VECTORCARDIOGRAPHIC RESULTS FROM SKYLAB MEDICAL EXPERIMENT M092: LOWER BODY NEGATIVE PRESSURE

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ABSTRACT

Vectorcardiograms were recorded via a modified Frank lead system from all crewmen of the three Skylab missions in conjuction with the Lower Body Negative Pressure - M092 Experiment. Data were analyzed by a specially developed computer program (VECTAN). Design of the test sequences allowed direct comparisons of supine resting, Earth based (reference) vectorcardiograms with those taken during lower body negative pressure stress and those obtained at rest in orbit, as well as combinations of these conditions.

Results revealed several statistically significant space flight related changes; namely, increased resting and lower body negative pressure stressed heart rates, modestly increased PR interval and corrected QT_c interval, and greatly increased P and QRS loop maximal amplitudes. In addition, orientation changes in the QRS maximum vector and the J-vector at rest in space seem quite consistent among crewmen and different from those caused by the application of lower body negative pressure. No clinical abnormalities were observed.

Etiology of these findings is conjectured to be, at least in part, related to fluid mass shifts occurring in weightlessness and attendant alterations in cardiovascular dynamics and myocardial autonomic control mechanisms.

INTRODUCTION

Electrocardiographic interval changes suggesting effects of increased vagal tone were observed early in some Gemini crewmembers (1). Preflight versus postflight amplitude differences appeard in electrocardiograms of several of the early Apollo crewmembers. In preflight and postflight crew evaluations of the last three Apollo flights, quantitative postflight vectorcardiographic changes were for the first time determined in American space crews. Changes not considered related to heart rate were mainly those of increased P and QRS vector

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magnitudes and orientation shifts. But since most of these post-flight findings resembled those observed with the orthostatic stress of lower body negative pressure, it was inferred then that upon their return from space, astronauts exhibited exaggerated responses to orthostasis in the vectorcardiogram as well as in measures of cardiovascular hemodynamics (2). No explicit information on in-flight vectorcardiographic changes or on in-flight influence upon postflight findings existed before Skylab. To help resolve the question, vectorcardiograms have been studied on all nine Skylab crewmen.

The M093 investigators have studied and reported on the vectorcardiograms of exercising Skylab astronauts (3); this M092 report extends our data base with extensive vectorcardiographic recordings on all nine, supine resting astronauts periodically subjected to lower body negative pressure stress.

METHODS

A specially designed Frank lead vectorcardiograph system (4) was used for all Skylab vectorcardiographic recordings (fig. 1). Safety and reliability features commensurate with other space hardware were added; the only other modification was the shifting of leg electrodes to the "presacral" area to obtain greater stability of signals during the exercise experiments M093 and M171. Body sites were permanently marked to assure consistency in repeated application of electrodes (fig. 2). System controls provided individual electrode impedance checks and continual digital heart rate readout selectable from either of the three leads since no onboard display of analog signal was available in the Experiment Support System for crew monitoring. Discrete gain settings for each lead allowed some degree of optimization for individual signal amplitude. All data were recorded primarily on digital magnetic tape with a sample frequency of 320 samples per second per channel (limit of Skylab capability); in-flight data were telemetered from onboard recordings to ground tracking stations as they became accessible. Real-time ground monitoring of in-flight data, therefore, could be randomly available for only relatvely short periods. Data from complete experiment protocols were rarely seen in real time.

Every test protocol consisted of 25 minutes of data recording, broken into five, 5-minute periods for vectorcardiographic analysis. This provided a resting supine control period, three graded levels of lower body negative pressure stress and a final period of recovery at ambient pressure (fig. 3). The first two minutes at lower levels of
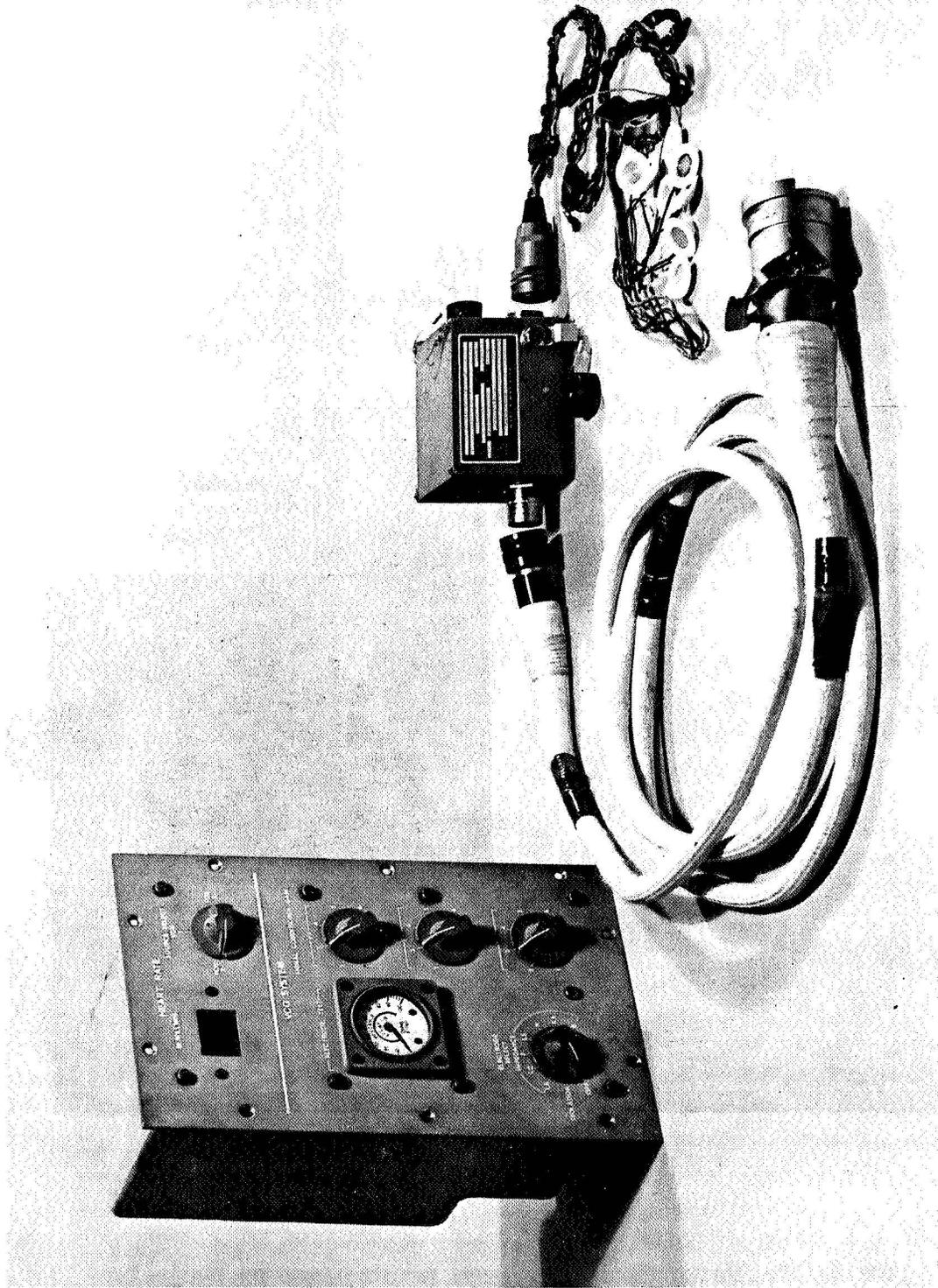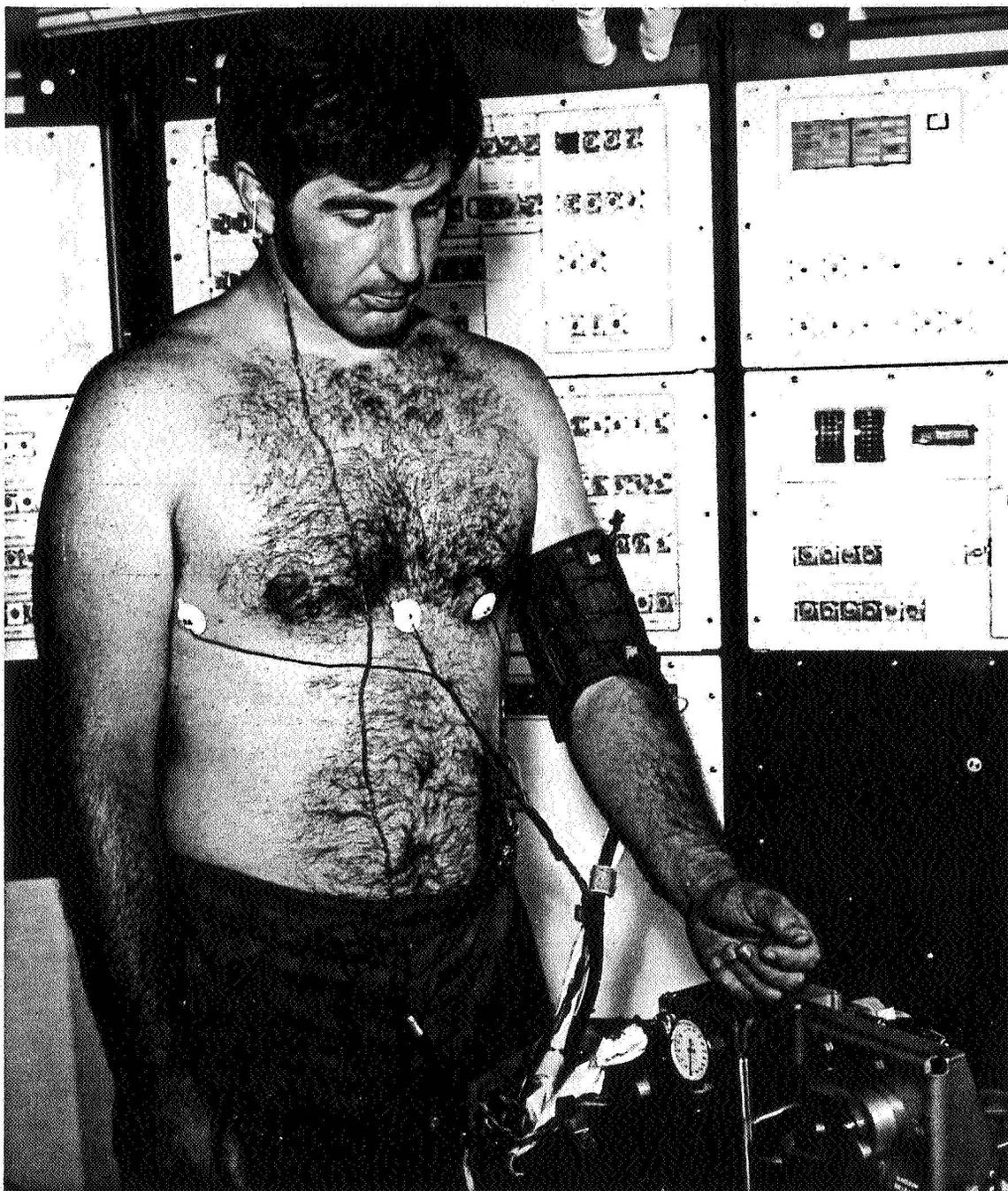
Figure 1.   Vectorcardiograph system hardware.

Figure 2. Vectorcardiograph system in place on subject.

lower body negative pressure were included as part of the first major stress period for vectorcardiographic analysis.
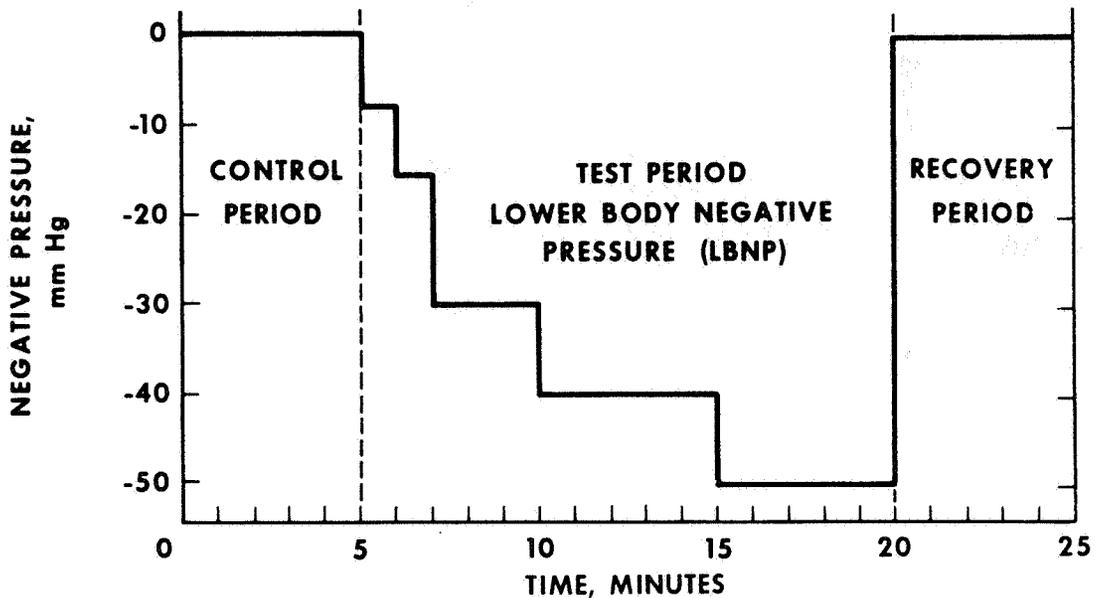

Figure 3. The lower body negative pressure protocol used for Skylab cardiovascular evaluations assessing orthostatic tolerance.

Each astronaut trained both as subject and observer in a one-g flight simulator of the Skylab Orbital Workshop beginning about six months before the launch of his flight. From each crewman, five to seven pre-flight vectorcardiographic recordings during the lower body negative pressure protocol were obtained during this period to establish his normal vectorcardiogram and variance. Three of these recording sessions were scheduled in the month preceding, with the last approximately five days before, launch.

The earliest in-flight lower body negative pressure tests (fig. 4) were performed on the fourth to sixth day of orbit for each crewman; thereafter in-flight tests were conducted approximately every third day. postflight tests were accomplished on recovery day aboard ship as soon as possible after splashdown and on the succeeding two days. Return to the Johnson Space Center usually occurred on the third day postflight. Subsequent postflight tests were done on fourth and fifth day postflight and on at least three additional days, as late as one to two months after recovery. Flight related test dates were not necessarily the same for all crewmen. All postflight tests utilized Skylab hardware outfitted in a mobile laboratory (fig. 5). The separate systems of hardware were of identical design and departures
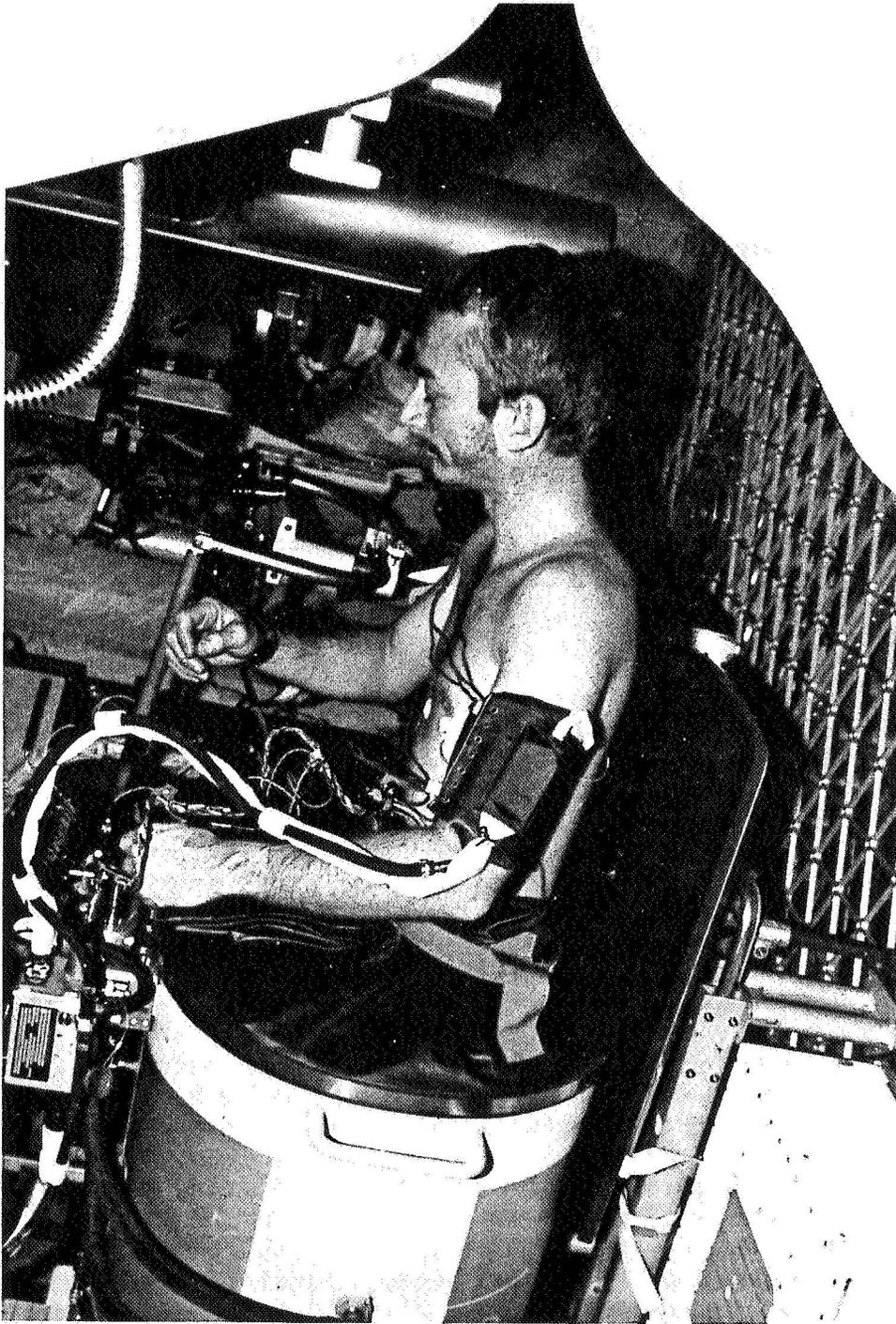
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Figure 4. Skylab 3 Scientist Pilot in Lower Body Negative Pressure device. Sensors in place for recording experimental data, including vectorcardiogram.

Figure 5. Skylab Mobile Laboratory. Cardiovascular facility for lower body negative pressure testing.

from equivalence lay only in necessary elements peculiar to one-g or zero-g environment operations, *e.g.*, one-g upper torso support dolly for lower body negative pressure.

All digital recordings were processed by a previously developed computer program called VECTAN (5) which analyzed the three-dimensional spatial entity rather than planar projections in order to obviate perspective distortions. It has been verified with ground-based studies as well as by Apollo and Skylab Medical Experiments Altitude Test usage. The program basically reconstructs the mathematical elements of the spatial P-QRS-T vector loops (fig. 6) which include standard time intervals, vector magnitudes and orientations, calculated areas and circumferences and other quantitative parameters. These data are computed from the spatial vector for every complex analyzed (one every five seconds) (fig. 7) and summarized statistically over discrete protocol periods for every lower body negative pressure test and subsequently for every subject according to flight phase (preflight, in-flight or postflight), test means and/or trends. Finally, group mean values for comparable flight phases have been calculated using the data from all nine crewmen.

Standard statistical procedures have been used to establish in-flight and postflight differences from preflight values for the most part two basic considerations are dealt with by selected vectorcardiographic parameters (table I):

° The effect of space flight itself. Answering this query has been attempted by calculating the in-flight (or postflight) minus preflight difference in the resting phase only, since it has been assumed that the vectorcardiogram recorded on resting, supine subjects in Earth gravity is likely the closest approximation obtainable to the vectorcardiogram recorded on the same resting subject in space. Each subject was thereby his own control; the paired t-test was used to test for statistical significance.

° The effect of lower body negative pressure orthostatic stress. Since the test subject experienced no alterations in body orientation, vectorcardiographic changes evidenced during application of lower body negative pressure should be fairly discretely ascribable to fluidic, footward shifts of body mass, in space or on Earth. Hence differences between -50 mm Hg of lower body negative pressure and resting vectorcardiographic measurements were also amenable to statistical analysis by the paired t-test and were used for these comparisons. Various combinations of condition effects are readily evident in table I which is the comparison matrix used to test for
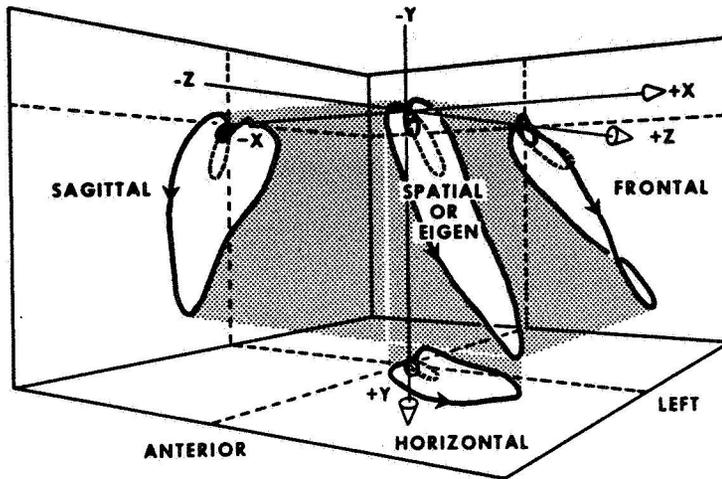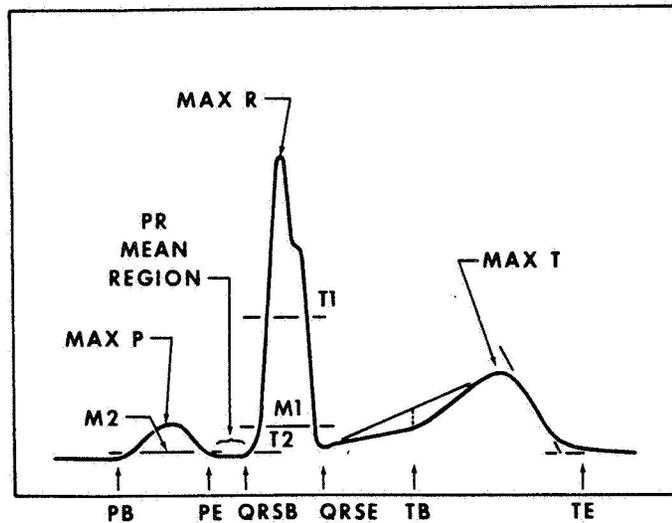
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Figure 6. Vectorcardiogram P-QRS-T loops in space with three planar projections.

This derivative from the three orthogonal scalar leads is the basis for all
computer analyses in this experiment (M092 VCG).
MAX P, MAX R, and MAX T are respective spatial maxima of the P,
QRS, and T loops. PR mean region is the computer null voltage reference.
PB, QRS B, and TB are beginning; and PE, QRS E, and TE are ending;
fiducial times for the respective loop components. T1, T2, M1 and M2
are respective threshold and modal voltage values employed in the computer
program. From these basic elements and the original orthogonal scalar data
essentially all aspects of the P-QRS-T complex may be described mathemati-
cally in three dimensional space.

Figure 7. Vectorcardiogram spatial vector length in scalar form for
one complete P-QRS-T cycle.

vectorcardiographic changes observed after the experimental
conditions of lower body negative pressure (LBNP) stress,
the space environment itself and entry.

TABLE I. M092 VECTORCARDIOGRAM COMPARISON MATRIX

Percent Change After Designated Condition

Reference Values	Condition = LBNP (LBNP Stress Values)			Condition = Flight (Resting Values)	
	PREFLIGHT	IN-FLIGHT	POSTFLIGHT	IN-FLIGHT	POSTFLIGHT
	LBNP	LBNP	LBNP	Space	Space
Preflight Supine Rest	(Alone)	+ Space	+ Space + Entry		+ Entry
In-flight Rest		LBNP (in space)			Entry
Postflight Rest			LBNP (After Space)		

Throughout these data analyses, it has been assumed that all three
Skylab crews, despite widely varying mission lengths and initally
high ambient temperatures for the Skylab 2 mission, experienced the
same space stresses and that their physiologic responses should have
been at least qualitatively similar. Using these premises, statistical
comparisons have been made primarily on group (nine crewmen) mean
values. In recognition of the differences in mission durations, how-
ever, and therefore of the possibility of trend changes, in-flight
means as well as single test values early and late in each orbital
period have been compared separately with preflight mean references.

RESULTS

Heart rate responses to lower body negative pressure (table II) are
presented in this report also. It is sufficient to reiterate here
that, compared to supine resting preflight values, resting heart rates
were elevated in-flight (18%) for the Skylab 3 and Skylab 4 crewmen,
and generally in the early postflight period (3%) for all nine
Skylab astronauts. The Skylab 2 crewmen, however, differed somewhat
in-flight by showing decreased resting heart rates. The average
difference between in-flight and preflight resting heart rates of
the Skylab 2 crewmen, all of whom showed decreases from preflight
values, was significantly ($P<0.001$) different from the same average
difference for the other six crewmen, who invariable exhibited higher
resting heart rates in-flight than preflight.

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During lower body negative pressure stress, heart rates were always elevated, 20 to 50% over their corresponding resting values, regardless of flight phase; however, a tendency toward greater than preflight stressed increases was evident in-flight and immediately postflight.

The PR interval (table II) exhibited moderate, reciprocal changes with heart rate, decreasing significantly (4 to 10%) during lower body negative pressure stress for all but two crewmen (Skylab 2 Commander and Pilot). Though changes in the resting PR interval in-flight were individually sporadic and averaged some 2% less than preflight values for the earliest in-flight tests, mean in-flight values were significantly greater (4%, $P<$ 0.025) than preflight. There was, however, no clear time trend throughout the missions nor distinct relationship to duration of flight.

For the QRS duration (table II), although in-flight resting values averaged slightly less than (2%) than the preflight counterpart, no consistent or significant pattern of change with respect to flight phase was seen. A modest but significant ($P<$ 0.02) decrease averaging about 5% in absolute value, however, occurred almost universally with the application of lower body negative pressure.

The absolute QT interval (table II) was also uniformly decreased (6 to 15%) during lower body negative pressure stress and whenever the heart rate was elevated, its response following the expected reciprocal relationship to heart rate. Corrected resting QT_c intervals by the Bazett equation (6), however, showed an average increasing trend in-flight, which became significantly different in the late in-flight period from preflight mean values (3% increase, $P<$ 0.05). Furthermore, QT_c intervals during lower body negative pressure were elevated (2 to 7%, $P<$ 0.05 to 0.001) over resting values at all phases of the mission.

Effects on vectorcardiograph component amplitudes (table III) were greater than those on temporal measurements. The P-wave maximum vector magnitude ($P_{max}MAG$) at rest significantly ($P<0.025$) increased in-flight, averaging about 25%. This increase was greater early than late in flight, was still present on recovery, although already attenuated, but quickly returned to preflight values. Even more marked, however, was the increase in $P_{max}MAG$ during lower body negative pressure (ranging 28 to 55%), again the greater changes being seen in-flight and immediately postflight.

The group average QRS maximum vector magnitude ($QRS_{max}MAG$)(table III) at rest also increased (12%) significantly ($P<0.001$) in-flight with an increasing in-flight trend, returning rather precipitously to preflight levels about three days postflight. Preflight during lower body negative pressure the $QRS_{max}MAG$ decreased from resting

TABLE II. TEMPORAL MEASUREMENTS OF THE VECTORCARDIOGRAM
Percentage changes from the nine crewmen group mean, preflight, supine resting values (as reference) of averages for heart rate, PR interval, QRS duration, and QT interval (basic and heart rate corrected, QT_C) during designated treatment condition.

CHANGE AFTER DESIGNATED CONDITION (%)

VECTORCARDIOGRAM MEASUREMENT	PREFLIGHT REFERENCE VALUES SUPINE, RESTING MEAN ± SD	CONDITION = LBNP					CONDITION = FLIGHT			
		PREFLIGHT		IN-FLIGHT		POSTFLIGHT R + 0		IN-FLIGHT		POSTFLIGHT R + 0
		$\bar{X}$	P	$\bar{X}$	*	$\bar{X}$	*	$\bar{X}$	P	$\bar{X}$	P
Heart rate (bpm)	56 ± 6	+20	<0.001	+54		+57		+9	NS	+2	NS
PR interval (ms)	148 ± 16	-11	<0.01	- 6		- 5		+3	<0.025	+2	NS
QRS duration (ms)	98 ± 8	- 6	<0.001	- 6		- 4		-3	NS	+2	NS
QT interval (ms)	419 ± 20	- 6	<0.001	-13		-14		-2	NS	-1	NS
QT_C interval (ms)	402 ± 13	+ 2	<0.001	+ 7		+ 7		+2	0.01	+0	NS

NS = not significant

*P values were not computed for these comparisons because percentage changes are reckoned from preflight resting references, and compound treatment effects ($i.e.$, LBNP, space and/or entry) are involved. Approximate significance may be judged in relation to the P values for the relatively "pure" treatments of preflight LBNP or flight itself.

TABLE III. AMPLITUDE MEASUREMENTS OF THE VECTORCARDIOGRAM
Percentage changes from the nine crewmen group mean, preflight, supine resting values (as reference) of averages for P-wave maximum vector magnitude ($P_{max}MAG$), QRS complex maximum vector magnitude ($QRS_{max}MAG$), QRS spatial Eigenloop circumference (QRS-E CIRC), and ST-wave maximum vector magnitude ($ST_{max}MAG$) during designated treatment condition.

CHANGE AFTER DESIGNATED CONDITION (%)

VECTORCARDIOGRAM MEASUREMENT	PREFLIGHT REFERENCE VALUES SUPINE, RESTING MEAN ± SD	CONDITION = LBNP					CONDITION = FLIGHT			
		PREFLIGHT		IN-FLIGHT		POSTFLIGHT R + 0		IN-FLIGHT		POSTFLIGHT R + 0
		$\bar{X}$	P	$\bar{X}$	*	$\bar{X}$	*	$\bar{X}$	P	$\bar{X}$	P
$P_{max}MAG$ (mV)	0.122 ± 0.0332	+27	<0.001	+78		+75		+24	<0.02	+16	NS
$QRS_{max}MAG$ (mV)	1.70 ± 0.373	- 6	<0.02	+13		+12		+12	<0.001	+18	<0.001
QRS-E circ (mV)	5.01 ± 1.027	+ 3	NS	+24		+32		+19	<0.005	+21	<0.001
$ST_{max}MAG$ (mV)	0.646 ± 0.206	-15	<0.01	-32		-37		-10	NS	- 6	NS

NS = not significant

*P values were not computed for these comparisons because percentage changes are reckoned from preflight resting references, and compound treatment effects ($i.e.$, LBNP, space and/or entry) are involved. Approximate significance may be judged in relation to the P values for the relatively "pure" treatments of preflight lower body negative pressure or flight itself.

values (7%, $P< 0.02$) but showed no significant response to lower body negative pressure in-flight. This appears to be a differential response to lower body negative pressure preflight versus in-flight, or perhaps an overriding dominance due to the effect of space flight alone.

Perhaps a better indicator of change in the overall QRS depolarization complex, the total QRS Eigenloop* circumference (table III) reflected highly significant in-flight increases also (19%, $P< 0.005$), which generally progressed during the in-flight phase. In-flight increases and precipitous postflight return to preflight values caused this measurement to exhibit a "square wave" phenomenon during the in-flight phase. Somewhat paradoxically, however, the QRS Eigenloop circumference also increased during lower body negative pressure, insignificantly preflight, but to around 10% in-flight ($P< 0.0025$).

The resting ST maximum vector magnitude ($ST_{max}MAG$) (table III) for the group underwent nonsignificant decrements in-flight ($\sim 10\%$). But here, as with the heart rate, a distinctly different pattern prevailed in the Skylab 2 crewmen compared to the other two crews such that the question of significantly different stressors may be considered a possible explanation. The effect of lower body negative pressure was always to increase $ST_{max}MAG$, 14% preflight ($P< 0.01$) up to 25% in-flight ($P< 0.001$) and 30% immediately postflight ($P< 0.0001$).

Alterations in orientation of the $P_{max}MAG$ vector at rest in space were quite variable and nonuniform; lower body negative pressure produced a slightly greater and more consistent effect of a general shift of the $P_{max}MAG$ vector terminus inferiorly and rightward.

In contrast to $P_{max}MAG$ orientation, the resting $QRS_{max}MAG$ vector terminus showed a rather consistent, though not large, shift toward more anterior orientation in-flight, with a nearly equivalent return on the day of recovery (fig. 8). Figures 8 and 9 depict the QRS maximum vector termini on a spherical surface (Aitoff equal area projection) representing the body thorax with equatorial azimuth at heart level, 0° being the left axilla, and minus and plus 90°, anterior and posterior, respectively. Negative elevation angles represent headward, and positive, footward, declinations from the horizontal reference plane. A slight superior component is also seen in this orientation shift. Almost universally the $QRS_{max}MAG$ vector terminus shifted in the opposite direction (posteriorly and inferiorly) upon application of lower body negative pressure (fig. 9). The net effect of lower body negative pressure in-flight, therefore, was less than either effect alone.

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*The QRS Eigenloop is that unique spatial entity representing the net summation of all instantaneous vectors throughout the QRS depolarization cycle. It is normally fairly planar and is quanti- fied and oriented within standard orthogonal reference axes.
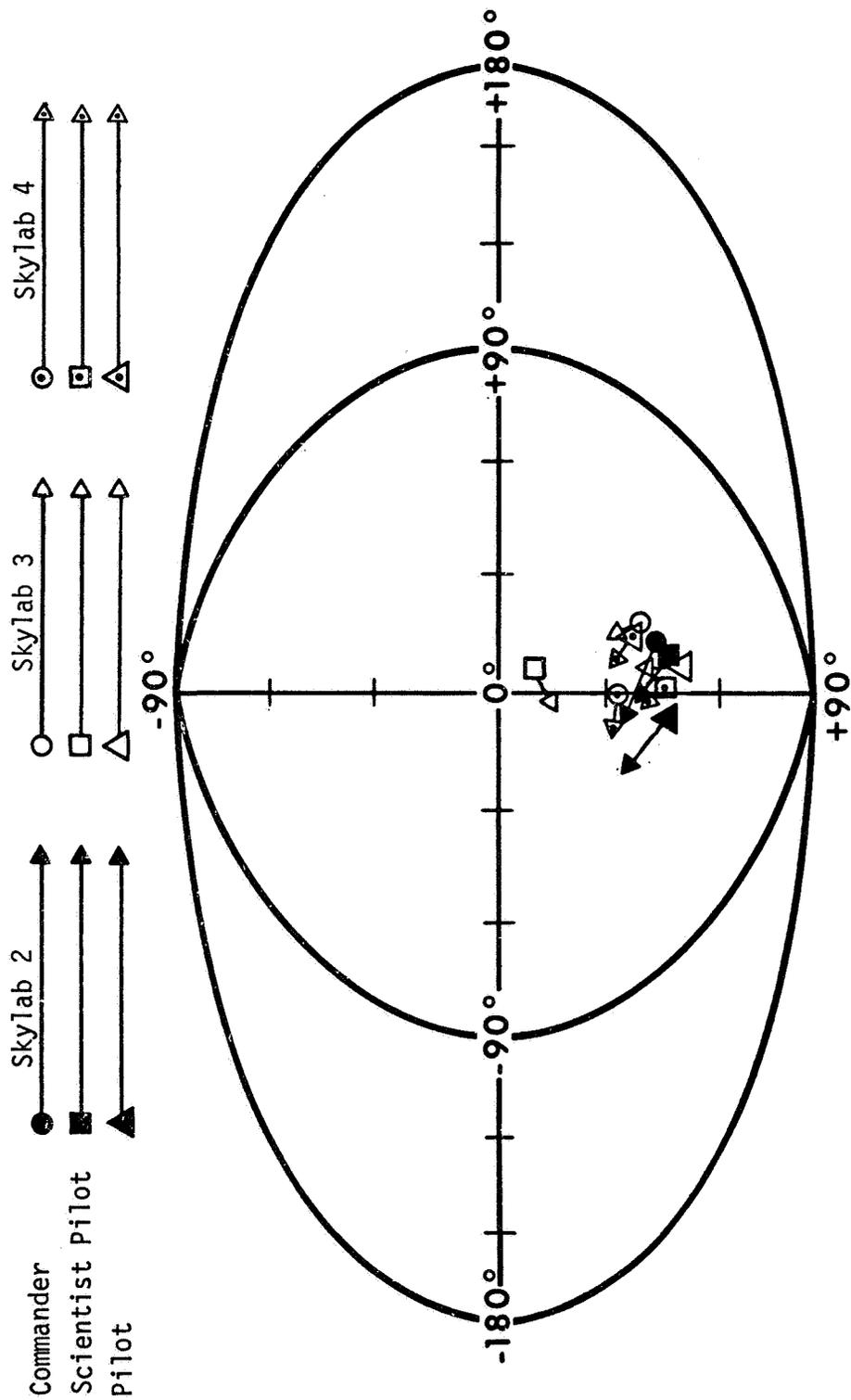
Symbols depict for each crewman his preflight mean supine control value with arrows ending at the first in-flight shifted location, still in the resting state.

The spherical grid (Aitoff equal area projection) represents the body surface where myocardial voltages are measured. The center (0°) is the left axilla, -90° is the right axilla; these azimuthal angles are in the horizontal plane at the level of the fifth intercostal space. Negative elevation angles from the horizontal reference plane represent superior (headward) direction and positive elevation angles, inferior (footward) direction.

Figure 8. Skylab M092 QRS$_{max}$ orthogonal orientation. The effect of space.
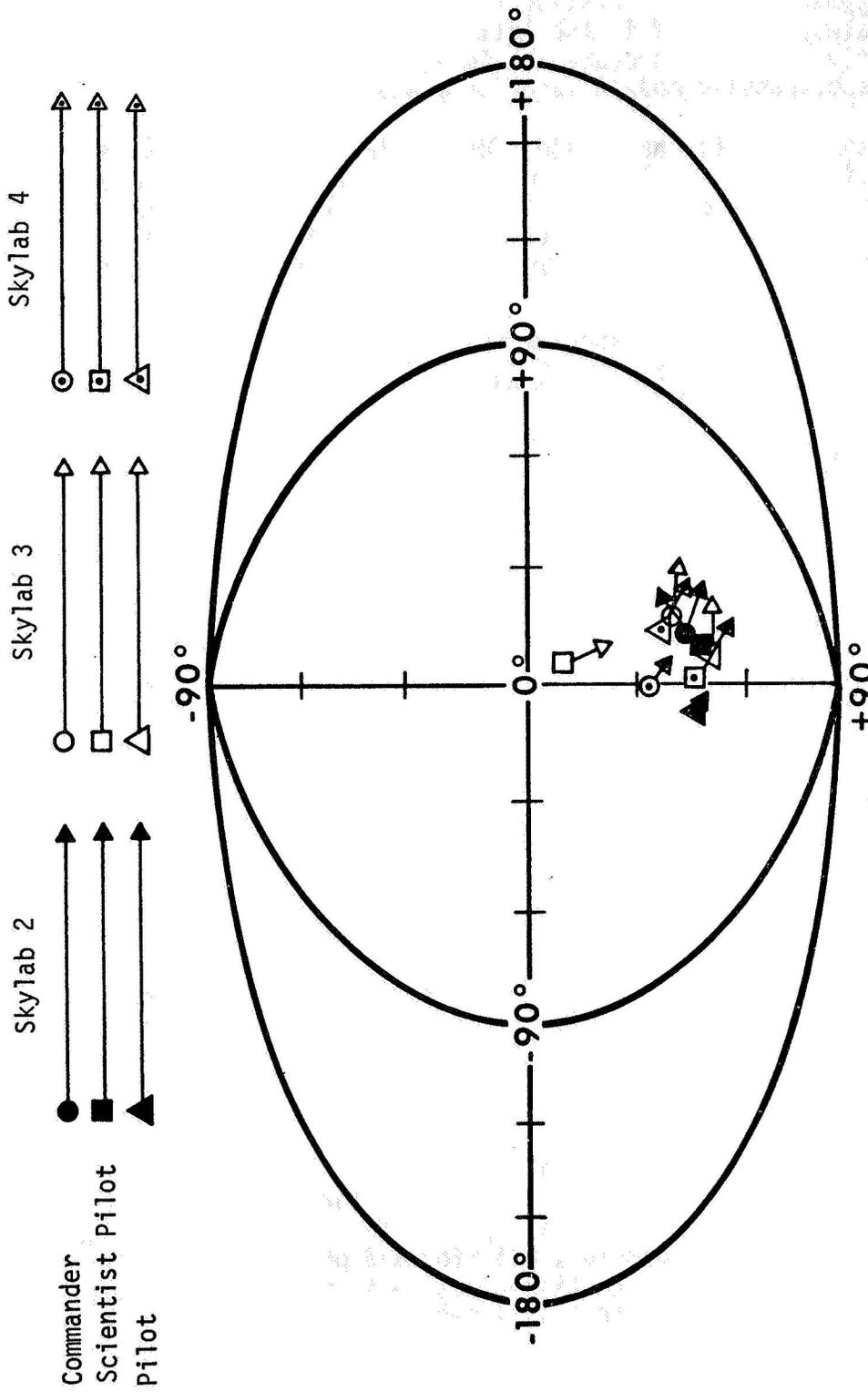
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Symbols depict for each crewman his preflight mean supine control value with arrows ending at his preflight shifted location under the stress of -50 mm Hg lower body negative pressure. Spherical grid is the same as for figure 8.

Figure 9. Skylab M092 QRSmax orthogonal orientation. The effect of lower body negative pressure.

The resting ST$_{max}$MAG vector orientation shifted slightly rightward in-flight, but always remained in the left anterior inferior octant. Lower body negative pressure produced a similar and somewhat larger shift, with an accompanying modest superior distortion.

In table IV resting J-vector magnitude (the spatial distance between origin and end of the QRS loop) shows no significant in-flight changes, but a postflight increase of 18% was significant at $P < 0.05$. Much greater augmentation occurred during lower body negative pressure stress preflight (30%, $P < 0.001$) and in-flight (up to 41% in the early part of the orbital phase).

TABLE IV. DERIVED MEASUREMENTS OF THE VECTORCARDIOGRAM
Percentage changes from the nine crewmen group mean, preflight, supine resting values (as reference) of averages for J-VECTOR magnitude, ST slope, and QRS-T spatial angle.

| VECTORCARDIOGRAM MEASUREMENT	PREFLIGHT REFERENCE VALUES SUPINE, RESTING MEAN ± SD	CHANGE AFTER DESIGNATED CONDITION (%)							
		CONDITION = LBNP					CONDITION = FLIGHT		
		PREFLIGHT		IN-FLIGHT		POSTFLIGHT R + 0	IN-FLIGHT		POSTFLIGHT R + 0	
		$\overline{X}$	P	$\overline{X}$	*	$\overline{X}$ •	$\overline{X}$	P	$\overline{X}$	P
J Vector (mV)	0.074 ± 0.024	+28	<0.001	+13		+26	+ 6	NS	+18	<0.05
ST Slope (mV/s)	1.28 ± 0.528	- 1	NS	-21		-18	+ 5	NS	+ 7	NS
QRS-T angle (deg)	38 ± 14	+61	<0.001	+13		+105	-17	NS	+12	NS

NS = not significant

* values were not computed for these comparisons because percentage changes are reckoned from preflight resting references, and compound treatment effects $i.e.$ lower body negative pressure, space and/or entry) are involved. Approximate significance may be judged in relation to the P values for the relatively "pure" treatments of preflight lower body negative pressure or flight itself.

Orientation changes of the J-vector terminus were perhaps the most consistent and striking. At rest early in-flight seven of nine crewmen (excepting the Commanders on Skylab 2 and 4) displayed considerable shift superiorly (figure 10). All nine crewmen by late in-flight produced a further leftward shift, while immediately on recovery day all resting J-vector orientations moved dramatically toward their respective preflight positions. Preflight lower body negative pressure stress produced very minor J-vector shifts (fig. 11), mostly rightward, but in-flight and postflight reorientations during lower body negative pressure were marked, especially in the superior direction; the terminus of several moved to the left superior, anterior and posterior octants, well separated from their normal resting position in the left anterior inferior octant. This was most striking immediately postflight.
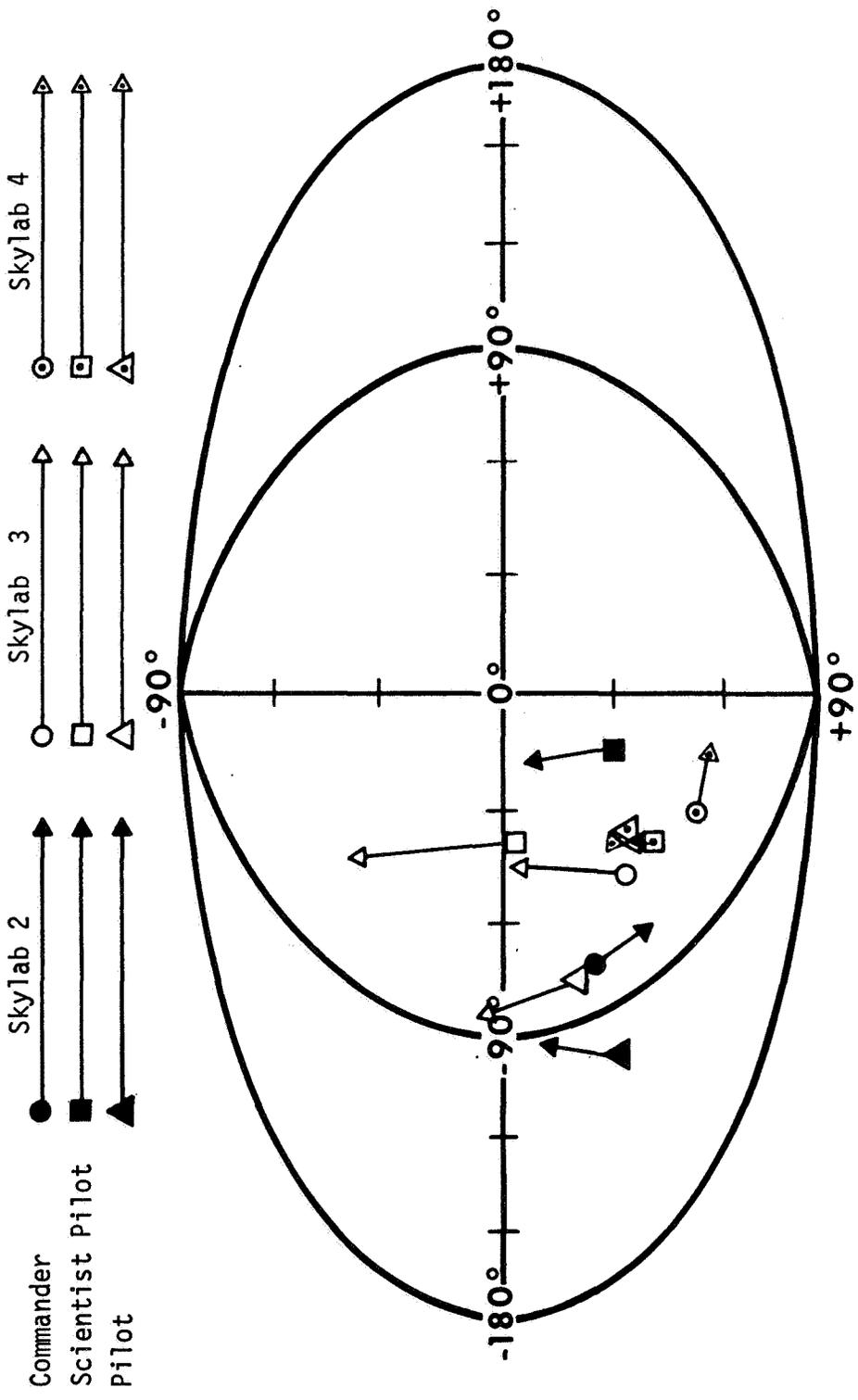
Figure 10. Skylab M092 J-Vector orthogonal orientation. The effect of space.
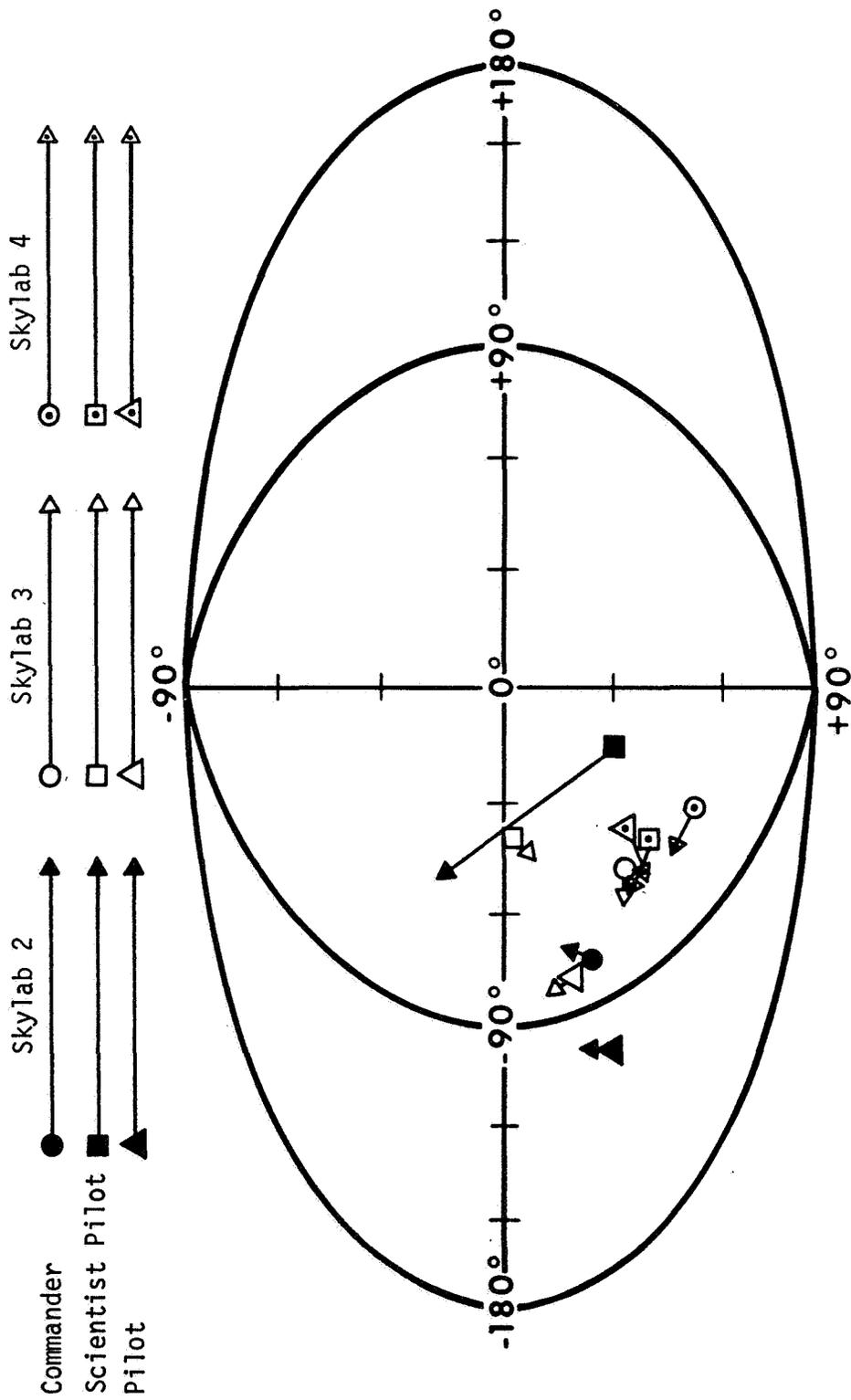
Symbols depict for each crewman his preflight mean supine control value with arrows ending at the first in-flight shifted location, still in the resting state. Spherical grid is the same as for figure 8.

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Symbols depict for each crewman his preflight mean supine control value with arrows ending at his preflight shifted location under the stress of -50 mm Hg lower body negative pressure. Spherical grid is the same as for figure 8.

Figure 11. Skylab M092 J-Vector orthogonal orientation. The effect of lower body negative pressure.

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Resting values for the ST slope (table IV) averaged 1.3 and ranged 0.5 to 2.1 millivolt/second. In-flight and postflight changes were rather variable and not statistically significant, though the group average was augmented in-flight above the preflight reference. Latest in-flight tests were on mission day 25 for Skylab 2; average values for all nine crewmen taken on or near mission day 25 in their respective flights were elevated only 1% over the preflight reference, while a corresponding average 4% increase occurred on the Skylab 3 and Skylab 4 six crewmen around mission day 58. The Skylab 4 crew did not show further increases later in orbit, but an average (nine crewmen) immediate postflight elevation of 7% required up to several days to disappear.

The effect of lower body negative pressure on the ST slope was likewise variable. A preflight increase of 2% was not statistically significant. An average, but not significant, decrease of 21% early in-flight augmented to a statistically significant 41% decrement ($P< 0.01$) late in-flight. On recovery day, however, this reduction in ST slope due to lower body negative pressure was already diminished to 15% with no statistical significance.

The spatial angle between $QRS_{max}MAG$ and $ST_{max}MAG$ vectors is a close approximation to the true QRS-T spatial angle. The average resting value of this QRS-T angle (table IV) decreased 17% in-flight (not statistically significant). A distinct mission trend in reduction of the angle was seen by an early in-flight decrease of only 3% progressing to an average 25% ($P< 0.005$) decrement in the late mission vectorcardiograms. Even so, on recovery day a complete reversal had already occurred with the group averaging a 12% increase over the preflight mean QRS-T angle.

The effect of lower body negative pressure was large and highly variable, but almost always caused an increase in the QRS-T angle which was greater preflight and postflight (69%, $P< 0.001$ and 96%, $P< 0.005$, respectively) than in-flight. The average in-flight increase due to lower body negative pressure was only 47% ($P< 0.02$); a trend toward a lesser in-flight increase due to lower body negative pressure was evident with longer orbital stay.

Concerning lower body negative pressure related arrhythmias, rare ectopic beats of both ventricular and supraventricular origin were noted at some time or other in all crewmen, but frequency appeared unrelated to mission phase. The only other notable occurrences were atrioventricular junctional rhythm seen primarily in all three Scientist Pilots and the Skylab 4 Pilot. These usually manifested themselves during higher levels of lower body negative pressure or immediately upon release, but occasionally were present even at initial rest. They

were seen preflight, in-flight and postflight, perhaps slightly more often in the Skylab 4 Pilot, a representative scalar strip of whom is shown in figure 12. No arrhythmias of clinical concern were ever recorded during lower body negative pressure tests, although the Skylab 3 Commander did exhibit a short episode of atrioventricular dissociation on mission day 21 at release of lower body negative pressure; this never recurred. Additionally, the Skylab 4 Pilot demonstrated considerable distortion of his ST-T waveform occasionally during lower body negative pressure, both in-flight and postflight; restoration was prompt after release of negative pressure.
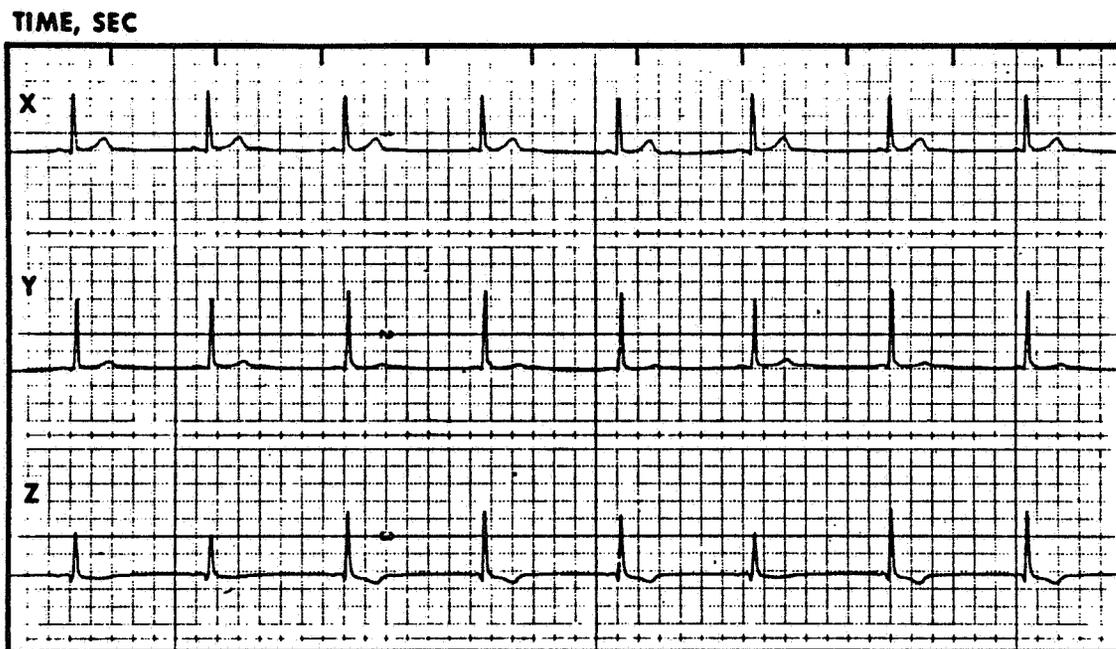
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Figure 12.   Scalar XYZ vectorcardiogram leads of Skylab 4 Pilot showing intermittent junctional arrhythmia shortly after release of lower body negative pressure on the day of entry.

It should be further pointed out that in no measurement described here did changes exceed the accepted clinical limits of the normal for that measurement. Changes are, therefore, not considered in the pathological context, but as normal physiologic variants of the cardiac electrical phenomena affected by the stresses of the Skylab space environment or of lower body negative pressure. As such they may shed light on basic physiologic mechanisms.

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DISCUSSION

Since heart rate is perhaps the best measure of orthostatic stress and is also a pivotal element in considering vectorcardiographic findings, the in-depth discussion of heart rate presented in another paper (7) is an essential to the understanding of the mechanisms involved. Uniformily lower body negative pressure stress produced heart rate elevations in one-g and in orbit, before and after flight. The normalized differential, however, is greater in-flight and immediately postflight than prior to flight. Average percentage increases in heart rate during lower body negative pressure over resting heart rate are: Preflight = 20%, early in-flight = 50%, around mission day 25 = 42%, around mission day 58 (six crewmen only) = 40%, late in-flight = 43%, and immediately postflight = 54%. Even though these differentials are significant in themselves, they are even further exaggerated by the fact that resting heart rates were generally elevated in-flight and postflight over preflight values. Of further importance is the high correlation of stressed heart rate with respective resting rates at any given test session. Therefore, whatever the conditions, stresses or events which affect an individual's resting heart rate must certainly reflect their effects in other physiologic and electrocardiographic measurements.

A modest reciprocal relationship between PR interval and heart rate is generally accepted (8). However, the data from Skylab indicate a more direct relationship; in-flight (especially late) resting heart rate elevations were usually accompanied by increases in the PR interval also. Conversely, the inverse response was observed during lower body negative pressure stress at all flight phases. This conceivably might indicate an in-flight alteration in cardiac autonomic control at rest which was overridden by the stress of lower body negative pressure. Altered autonomic control also might be related to the junctional rhythm observed not infrequently in several crewmen.

Since the only significant changes in QRS duration were seen during lower body negative pressure stress, little difference across the flight phases occurred, and resting differences were insignificant, it is inferred that space flight produced no noteworthy effects on this measurement.

Though the expected reciprocal relationship of QT interval and heart rate was evidenced throughout all flight phases, the trend tendency for the corrected QT_c interval to increase through the orbital phase favors a space related effect upon this measurement independent of heart rate. The effect was directionally the same as that due to lower body negative pressure, though of somewhat lesser magnitude. Since the QT interval represents total ventricular electrical systole

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(depolarization and repolarization) and the QRS duration (depolarization) was essentially unchanged, this in-flight lengthening of the QT_C interval must be chiefly due to prolongation of the repolarization process. This conceivably might be related to changes in autonomic balance, but could as likely involve basic cellular metabolic processes.

A seeming paradox in $P_{max}MAG$ is difficult to explain. Lower body negative pressure increases in this measurement have long been observed, sometimes attributed in part to more nearly synchronous depolarization of both atria with increased heart rate and relative adrenergic dominance. Experimental data on dogs by Nelson and co-workers (9) supports an increase in P-wave amplitude upon removal of blood. A space related increase in this measurement at rest, even for those crewmen of Skylab 2 who had decreased resting heart rates in-flight seems to address another mechanism. The fact that early in-flight vectorcardiograms exhibited the greater increases would point to a possible etiology related to fluid shifts which are felt to be operative early following orbital insertion. That fluid is shifted in the opposite direction during lower body negative pressure, when even greater $P_{max}MAG$ values are observed, compounds the paradox. Physiologically, positional changes in this vector do not appear relatively significant.

Even more striking were the $QRS_{max}MAG$ and QRS Eigenloop circumference changes. These measures of increased ventricular depolarization voltage imply a definite space effect, since lower body negative pressure produced actual decreases in the former and nonsignificant increases in the latter preflight. End diastolic ventricular blood volume is considered by Nelson, et al.(9) to be a major factor affecting the QRS complex. Manoach, et al.(10), and others (11) have demonstrated in dogs a significant direct correlation of blood volume and QRS amplitude during controlled hemorrhage, volume replacement, vena caval occlusion and direct intracardial infusion overload. One might also consider the potential effect in space of relative hemodilution (12) which, according to Rosenthal, et al.(13), augments QRS magnitude by lowering intracavitary blood resistivity.

In the hypothesized events occurring in space, a large fluid shift from the lower body centripetally would very likely produce initially a relatively increased intravascular and intracardiac volume. Subsequent transfer of fluid from other compartments to the vascular tree could dilute the original hematacrit as well as increase total blood volume. This interactive complexity could also account for the modest vector orientation shifts observed, particularly as the two ventricular chambers may experience nonidentical alterations. Trying to relate these vectorcardiographic findings to hemodynamic events is enticing, but difficult (14). Our data and the study by Brody (15), who asserted

That intracavitary blood exerts a powerful effect upon surface lead electrical potentials of the heart by differentially decreasing tangential while augmenting radial dipoles seem to give our hypothesis practical and theoretical support. Another perhaps less likely consideration is that these increased surface potentials in-flight do in fact represent increased myocardial work, which might logically be considered due to increased stroke volume and/or elevated systemic pressure.

Finally, since the J-vector and ST slope give important information on myocardial oxygenation, the absence of a significant space related alteration in these two measurements is encouraging. The increased J-vector magnitude and decreased ST slope during lower body negative pressure stress, however, need further investigation.

CONCLUSIONS

°Vectorcardiograms taken on all crewmen during the Lower Body Negative Pressure Experiment (M092) on the Skylab flights have shown several consistent changes apparently related to space flight. Principally involved among these changes are temporal intervals, vector magnitudes and their orientations, and certain derived parameters, presumably as a consequence of altered autonomic neural imputs upon the myocardial conduction system and/or of major fluid shifts known to have occurred in flight.

°Correlations of these electrocardiographic findings with other hemodynamic and related changes appear reasonable and consistent, especially as regards the concept of headward fluid shifts in space.

°All observed measurements have been well within accepted limits of normal and are considered to represent adaptative phenomena rather than pathological conditions.

°These findings have, in a predictable fashion, opened new questions which will direct future ground-based and in flight researches - particularly in the area of cardiovascular electro-hemodynamic studies for the Shuttle era.

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