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Final Report NASA SUP Grant

NGR-06-002-038

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COLORADO STATE UNIVERSITY

Fort Collins, Colorado

Project # 1912

ABSTRACT

Deconditioning effects of weightlessness on the cardiovascular system of astronauts is a problem recognized by authorities in aerospace medicine. Most cardio-physiologists believe that man cannot tolerate indefinite exposure to weightlessness without considerable circulatory deterioration. Analyses of data collected from space flights to date substantiate these beliefs, and confirm the fact that some form of compensation must be provided to keep the cardiovascular system of space travelers properly conditioned. As the duration of flights increase, the problem intensifies and becomes more critical.

Sequential pulsatile devices were investigated to produce periodic hydrostatic pressure gradients in the venous system of eight sub-human primates. Intermittent venous pooling of blood in the extremities triggers and stimulates the vascular reflex mechanisms of the cardiovascular system that may have significant benefits in maintaining the circulatory system in proper tone under weightless conditions. Electrocardiograms, blood pressure measurements, cardiac output and stroke volume determinations were used to evaluate the efficiency of the described technique.

Results were amazingly consistent, in this ground based experiment, to indicate an efficient system for intermittently exercising the heart within safe and medically acceptable limits.

The system's efficiency, operating in a weightless environment, can only be attested by investigations conducted in Sky Lab or other orbiting facility. The need for cardiovascular conditioners for space travelers has been verified during short tenures in space, that requirement, will undoubtedly become more apparant as space tours become longer in duration. The importance and priorities of biomedical investigations in space cannot be over emphasized or delayed in planning for future space ventures.

This final report summarizes the research carried out under project #1912 of NASA SUP Grant NGR-06-002-038.

STIMULATION OF CARDIOVASCULAR ADAPTABILITY
DURING PROLONGED SPACE EXPOSURE

by Harry A. Gorman*
Principal Investigator

One of the major physiological problems associated with long duration space flight is the effects of weightlessness on the cardiovascular system. Astronauts returning to earth's gravity after relatively short exposure to weightlessness have experienced circulatory problems including orthostatic hypotension, tachycardia, reduction in blood volume, lowered cardiovascular reflex response to shifts of blood to the extremities, and syncope or fainting.

Most cardio-physiologists believe that man cannot tolerate indefinite exposure to weightlessness without considerable circulatory deterioration. Many scientists have studied the effects of weightlessness in man and in subhuman primates to determine the causes of this problem. While the physiology of cardiovascular deconditioning in space maybe complex, in general, it develops as a result of reduced functional requirements of the circulatory system released of the gravity stress of earth's environment.

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Analyses of data collected from both Russian and U. S. space flights substantiate beliefs, and confirm scientific opinions that some form of cardiac exercise must be provided to keep the cardiovascular system of space travelers properly conditioned. As the duration of flights increase, the problem intensifies and becomes even more critical.

It appears then, that some form of periodic stimulation of the circulatory system is essential to maintain proper tone for rapid increased heart work loads, such as the sudden return to earth's 1 g environment. Such hypotheses may be investigated under ordinary laboratory circumstances but final proof must be accomplished in space under weightless conditions.

Attempts have been made to exercise the cardiovascular system by conventional tourniquets, tilt-table conditioners and lower body negative pressure equipment. All of these techniques were aimed at inducing a hydrostatic pressure gradient in the venous system sufficient to stimulate the vascular reflex mechanisms of the heart and great vessels. The degree of success, for one reason or another, has been less than satisfactory. Tilt-table training can only be employed under controlled laboratory conditions; conventional tourniquets, while occluding venous return of blood from the extremities are painful and their use was discarded in the Gemini flights. Lower body negative pressure equipment (LBNP) is bulky, requires a constant controlled vacuum source and must be accurately applied to prevent harm to abdominal viscera.

The purpose of the research under this grant was to investigate new and modified techniques for comfortably inducing periodic hydrostatic pressure gradients in the venous system of the arms and legs of subhuman primates (*macaca nemastrina*).

Intermittent venous pooling of blood in the extremities triggers and stimulates the vascular reflex mechanisms of the cardiovascular system and can have significant benefits in keeping the circulatory system in top performance tone.

Since a weightless state cannot be simulated in the laboratory, the results of these new techniques were evaluated by carefully monitoring changes in heart rate, blood pressures and cardiac output. Significant changes in these parameters indicate effectiveness to challenge the cardiovascular system.

Research Objective:

The objective of this research was to test the hypothesis that a mechanical pooling of blood in the extremities would trigger the cardiovascular reflexes and result in an active exerciser for the circulatory system.

Materials and Methods

Eight, adult, male, pigtail monkeys (*macaca nemastrina*) were purchased from Asiatic Imports Company of San Francisco, California for the experimental subjects. This sub-human species was selected

as the animal model of choice because the conformation and configuration of their arms and legs are closest to those of man. After a 30 day standardization period, during which the primates were tuberculin tested and given complete physical examinations, the animals were ready for the experiments.

The first experiment of this investigation was to apply rubber tourniquets to the arms and legs of the monkeys and to monitor changes in heart rate through ECG electrodes. The rubber tubing tourniquets were applied sufficiently tight to occlude venous blood returning from the extremities but not tight enough to stop arterial blood from going to the extremity. During this initial experiment, there was no device coupled to the tourniquets. The elasticity of the rubber tubing provided the constant pressure to occlude the venous return of blood.

Standard electrocardiogram leads were coupled to a Sanborn recorder for record of heart rate performance. The results were as predicted, the heart rate increased on a mean average of 17% during the time the tourniquets were employed. It was noted, however, that considerable tissue damage occurred beneath the tourniquets and considerable pain was evident after about 5 minutes of application.

Figures 1 through 8 are graphs of the results obtained when the simple tourniquets were applied to the primates over four test periods each.

FIGURES 1-8

Graphs of the results obtained when the simple tourniquets
were used on the primates through four tests.

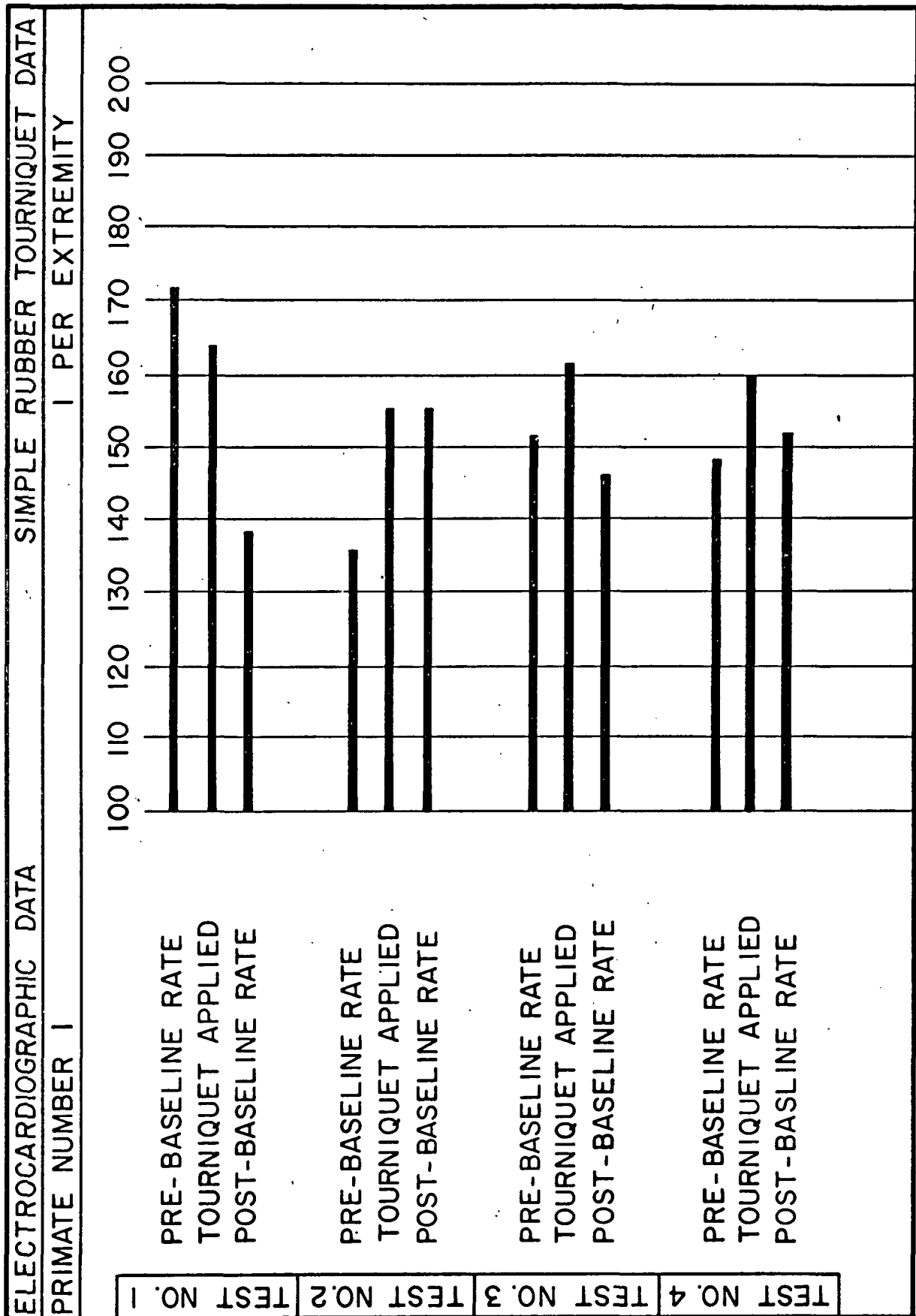


FIG. 1

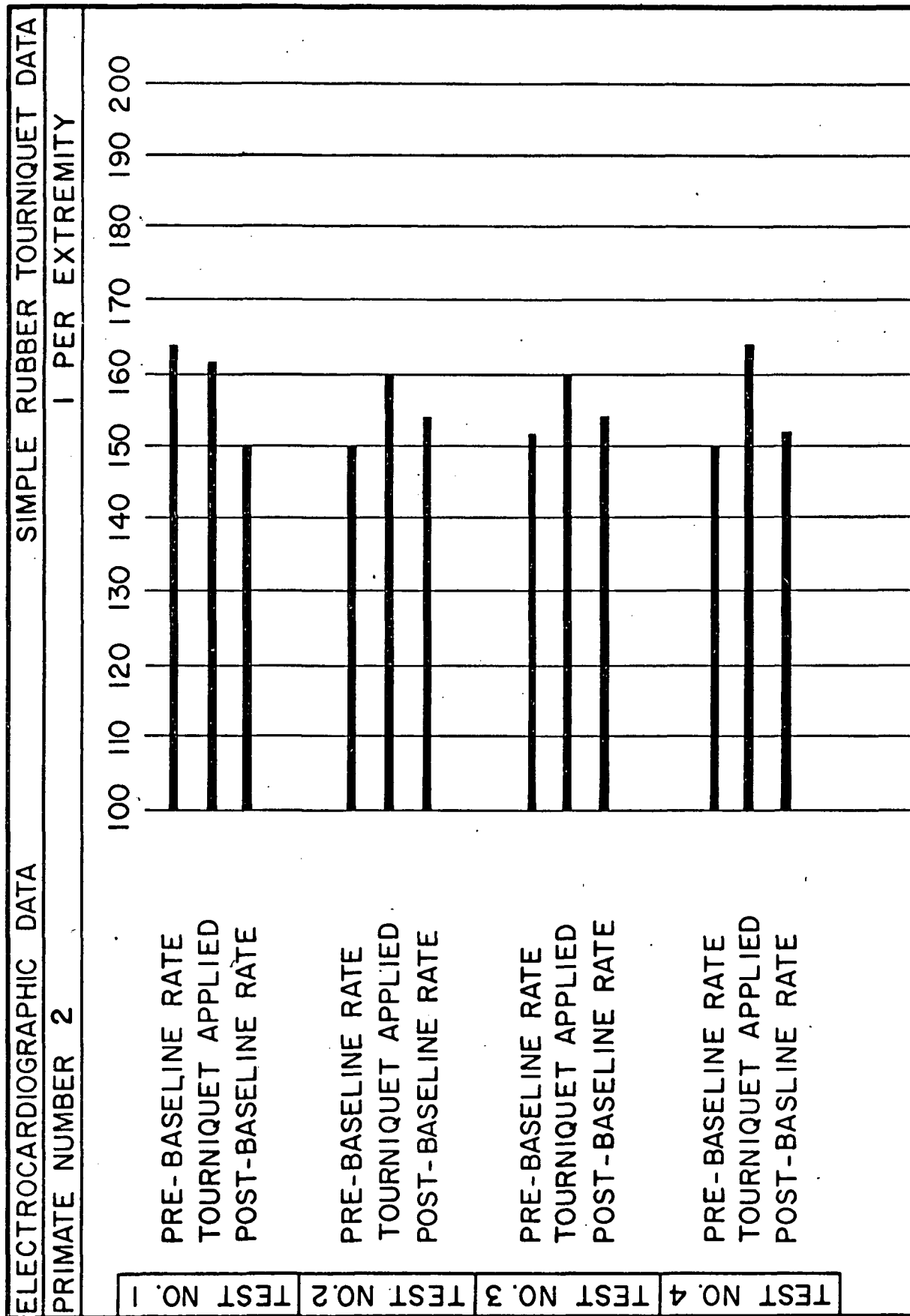


FIG. 2

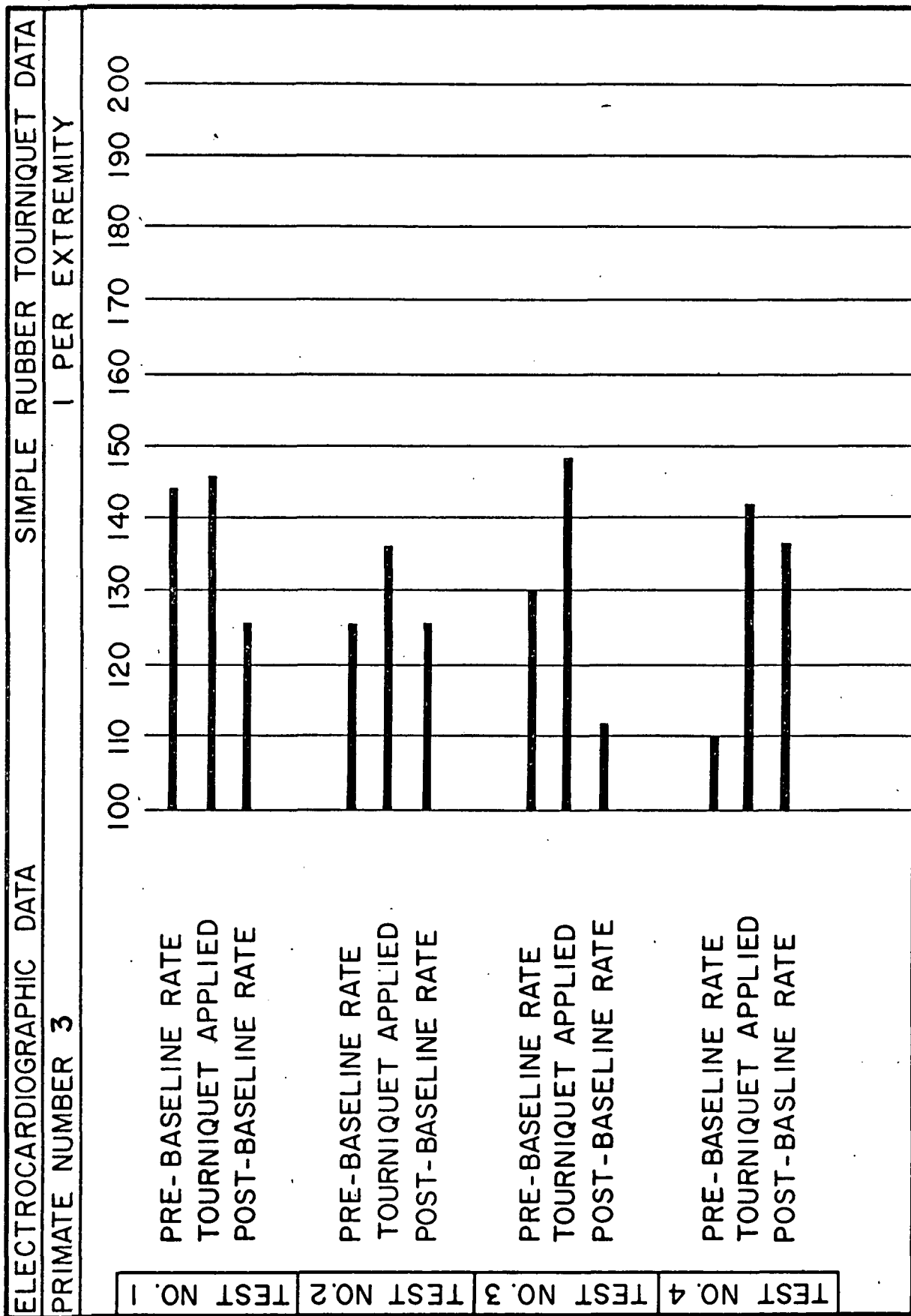


FIG. 3

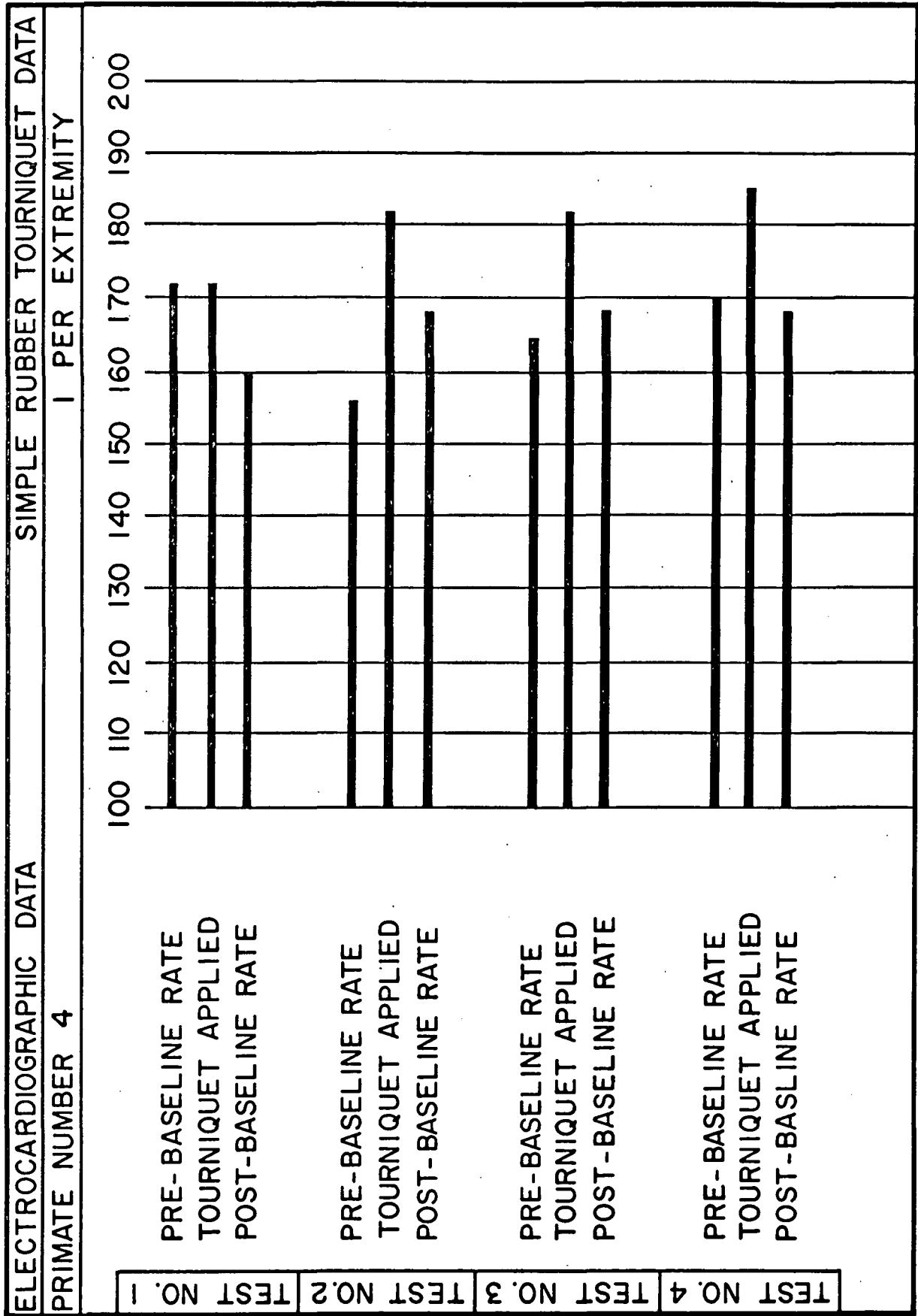


FIG. 4

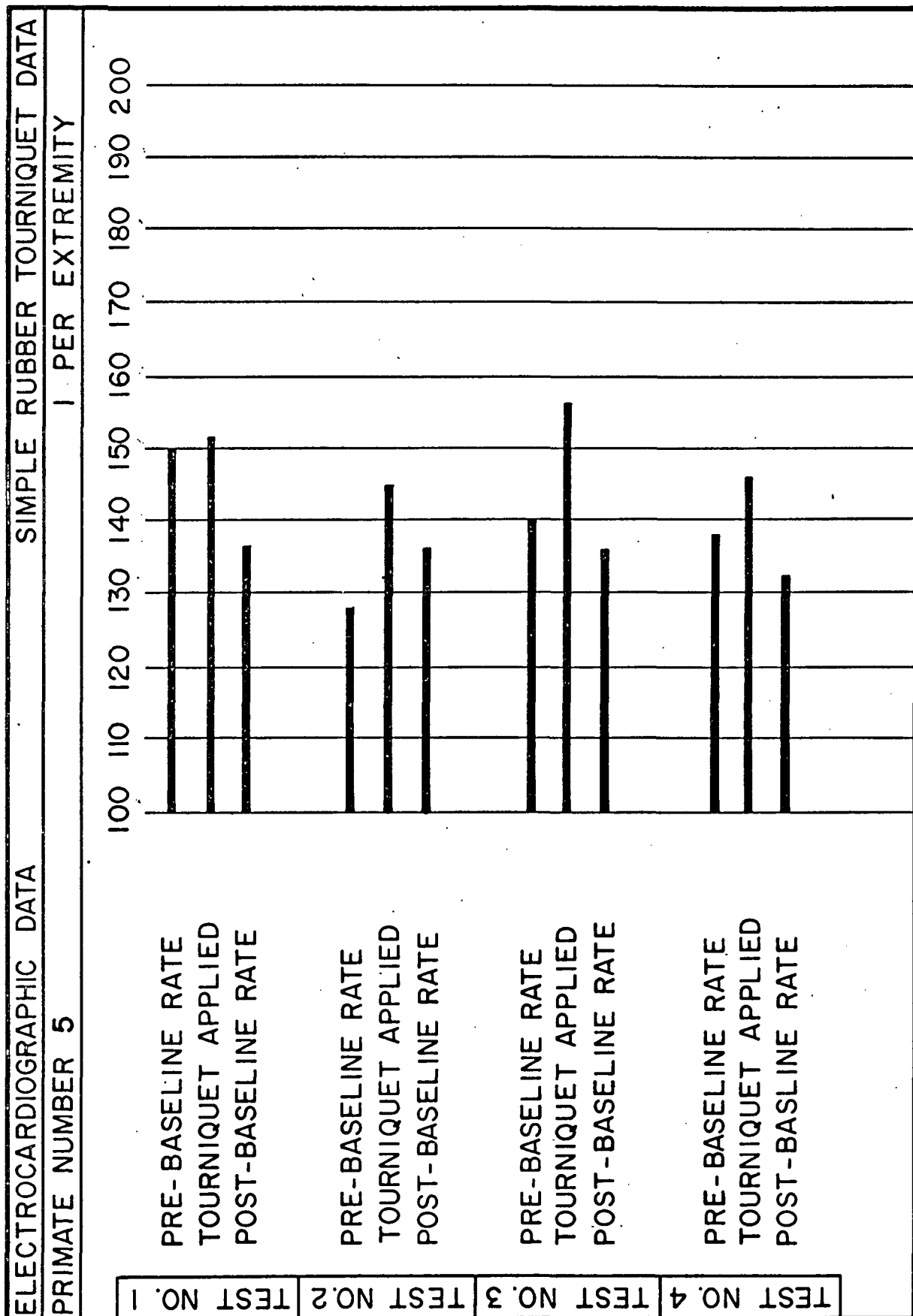


FIG. 5

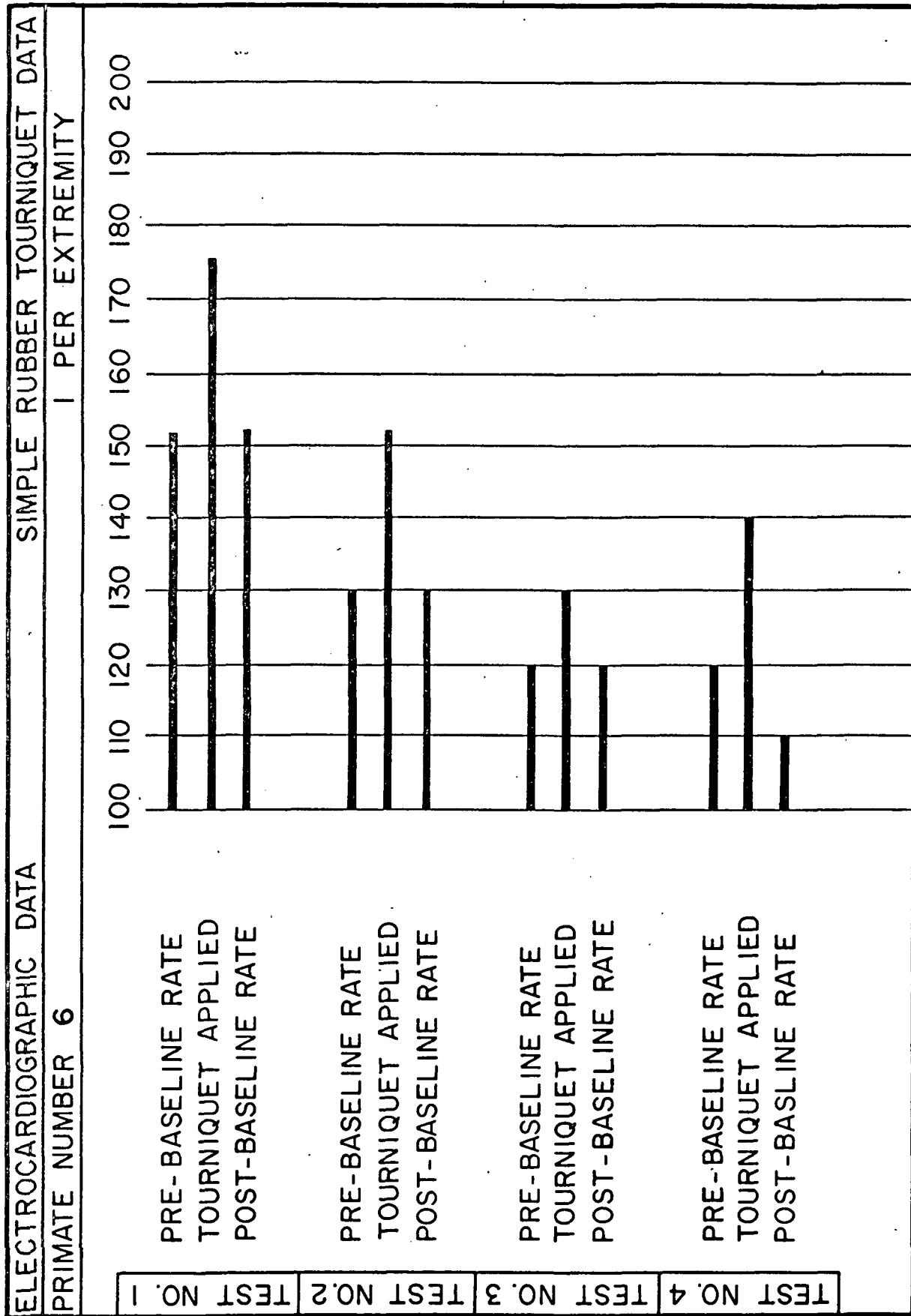


FIG. 6

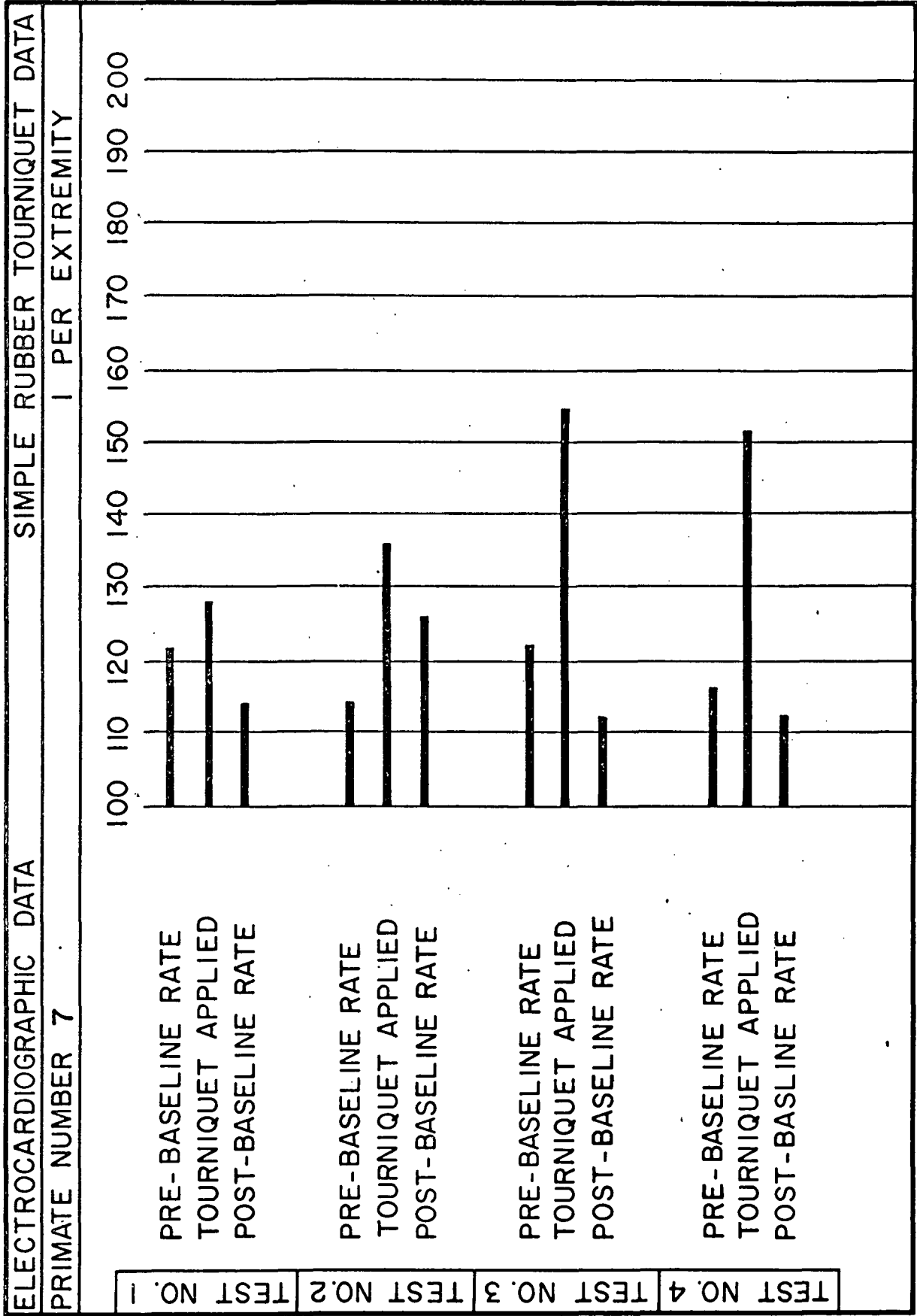


FIG. 7

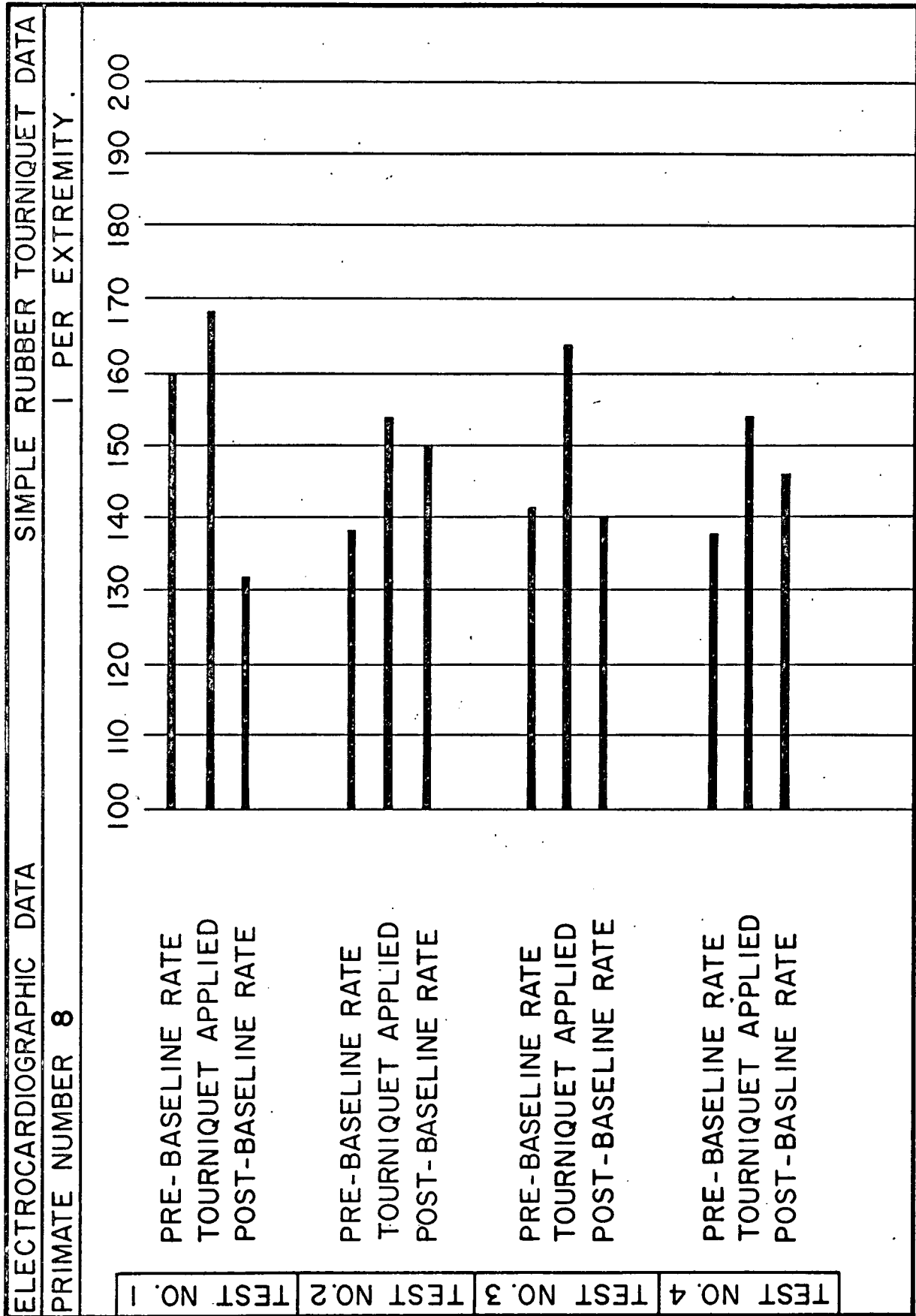


FIG. 8

While the application of tourniquets to pool blood gave significant increases of heart rate, the pressure on the arms and legs caused pain. To remedy this problem, a sequential "ripple" sleeve was developed. This was reasoned to be a new and novel idea for comfortably inducing periodic hydrostatic pressure gradients in the circulatory system.

Vinyl plastic sleeves were designed with four air compartments that when inflated would occlude the venous return from the extremity. (Figures 9-10-11) A device was designed for adequately inflating the top air compartments of each sleeve (both arms and legs) and then releasing the pressure as the second compartment filled. This inflating-deflating sequence was repeated through all compartments again to complete one cycle.

The pulsatile sleeves, fitting from the shoulder to the elbow on each arm and from the upper thigh to the knee of each leg, were activated by compressed air through a programmed pulsator. Figures 12-13 show application to limbs of the primate. Figures 14-15 show adaptation to man.

J. J. Monaghan Company of Denver, Colorado, fabricators of respirators and rubber specialty items, assembled the first pilot model of the pulsator and delivered it for testing on April 10, 1968. This model was a motor driven cam that actuated four separate valves in sequence. An adjustable bleed-off valve was between the actuated valve and the tippling cuff. Pressures were variable by valve adjustments but frequency adjustments required readjustment

FIGURE 9

Four compartment vinyl plastic portion of ripple sleeve.

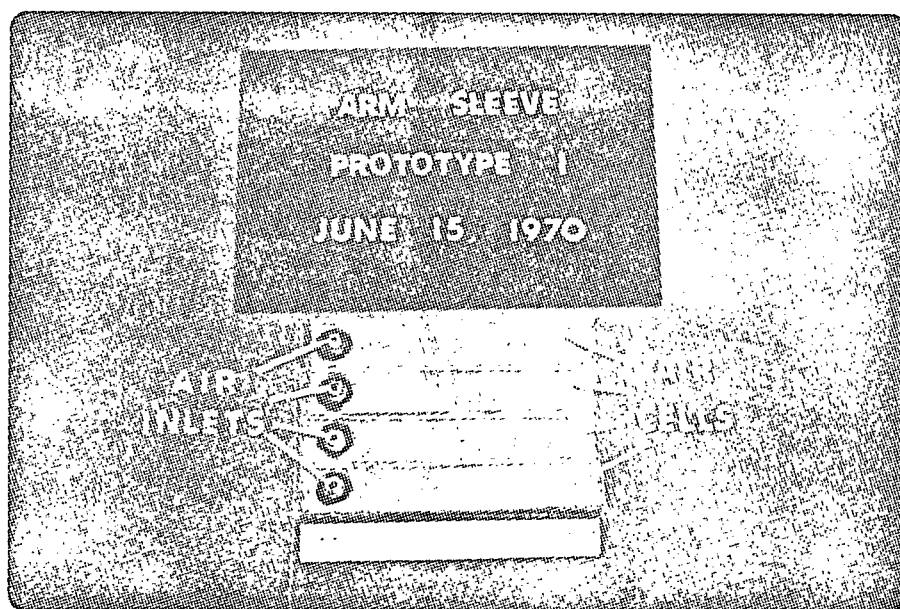


FIGURE 10

Arm and leg sleeves showing inflating compartments
and retaining part of sleeves.

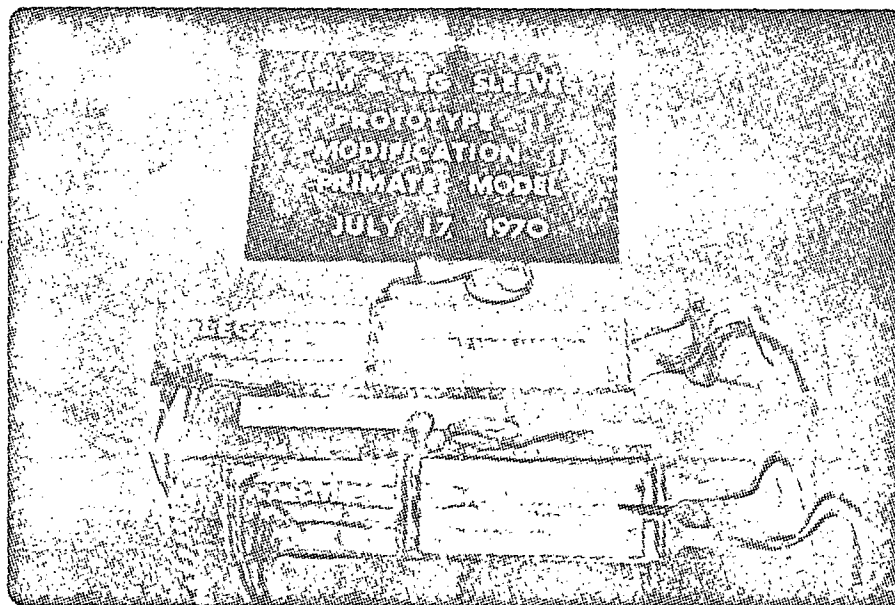


FIGURE 11

Vinyl sleeve showing segmental break down of parts.

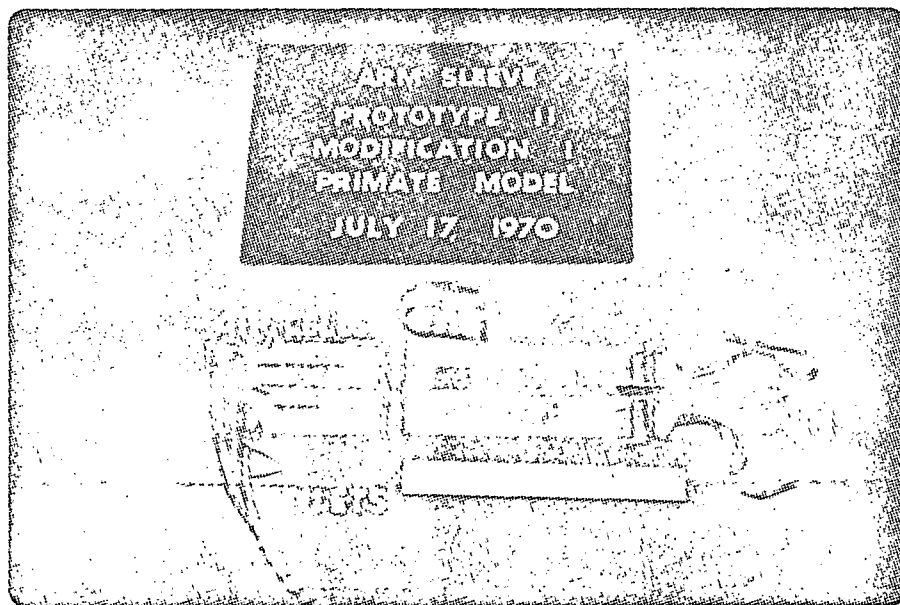


FIGURE 12

Vinyl sleeves applied to all four limbs of primate.

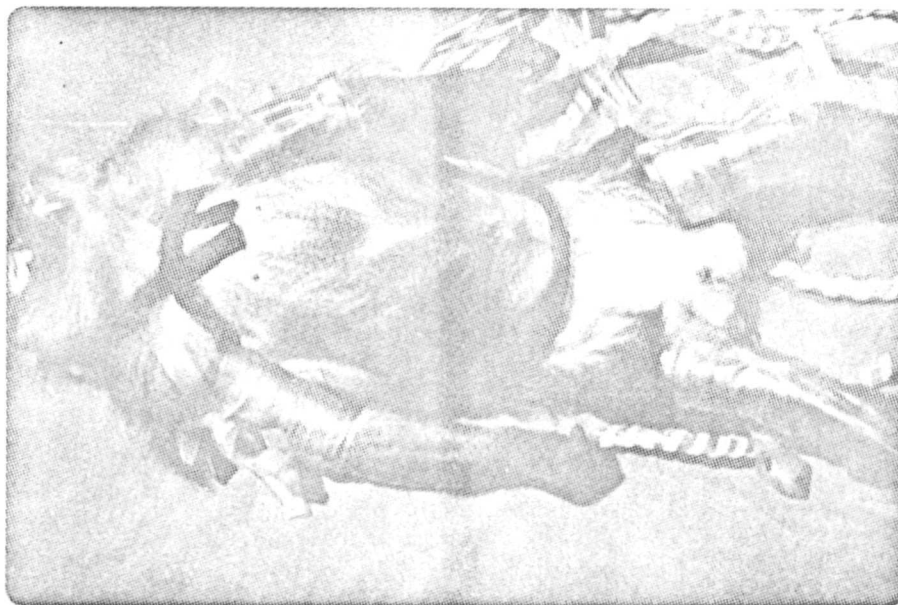


FIGURE 13

Sleeves applied to primate and coupled to air pulsator.

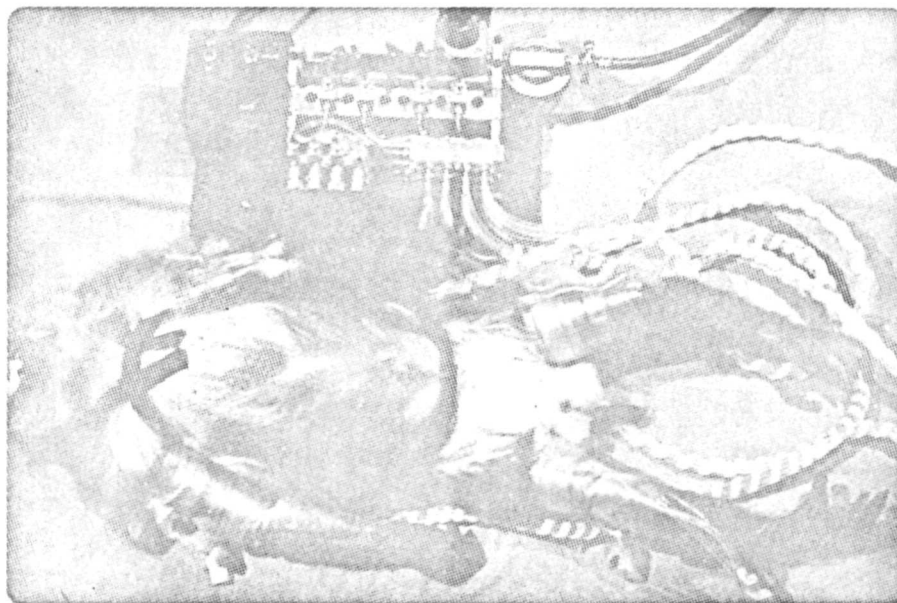


FIGURE 14

Plastic sleeve applied to forearm of man.

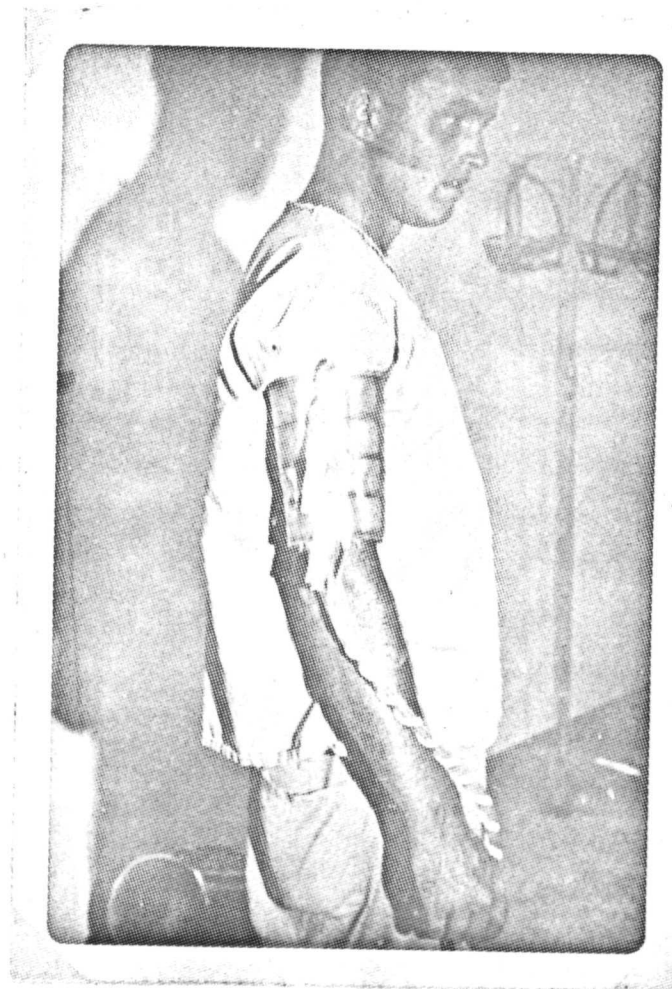
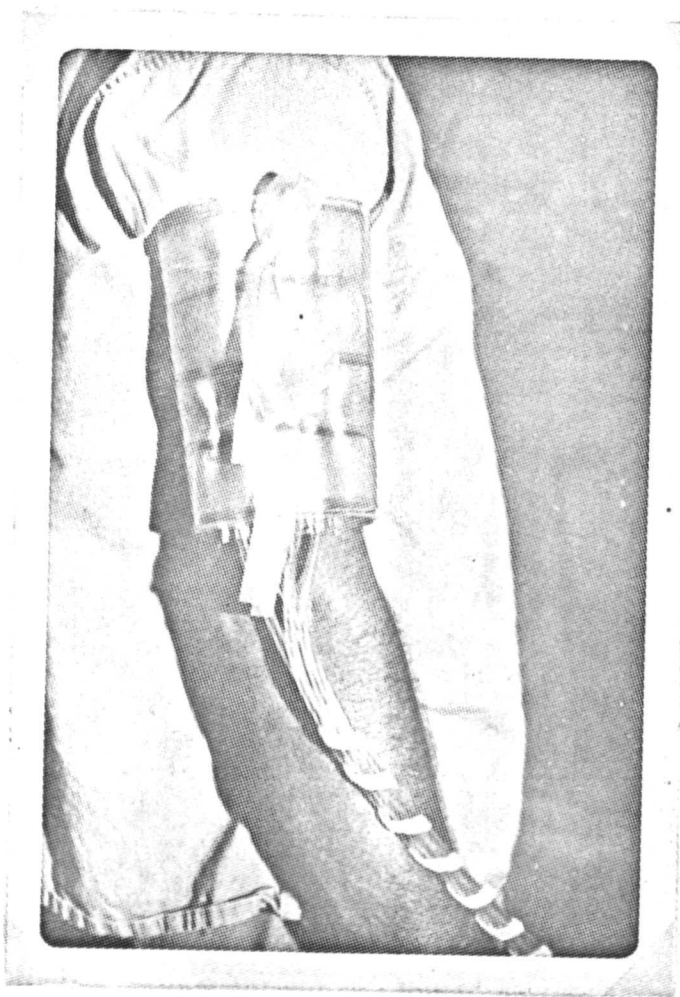


FIGURE 15

Close-up of plastic sleeve. Note: It is applied
similar to cuff of a sphygmomanometer.



of each cam. The actuating arms controlling the valves had a tendency to stick and the cams would slip. The pulsator as originally designed was used to pulse the sleeves on only one primate. It was then modified from a cam operated to an electronic solenoid type pulsator.

Modification of the pulsator from a mechanical operated cam to an electronic system included the following: A ring of four, ring counters, using SCR's was pulsed with a UJT relaxation oscillator. (Figure 16) is a diagram of the circuit.

Pulse rate was determined by the values of C_1 and R_1 . The pulse was then fed from point "A. to D_1 , D_2 , D_3 , D_4 . The SCR's were all forward biased while D_1 , D_2 , D_3 , D_4 , were reverse biased, in the static state. The circuit required a starting pulse (manual) which was provided through the resistive capacitive network R_5 , R_6 , and C_2 , by way of momentary switch S_1 . When S_1 closed, a pulse was applied directly to the gate of SCR_1 . It then was conducting and completing the circuit which activated solenoid So_1 , simultaneously forward biasing D_2 . The next pulse from the UJT, applied through D_2 to the gate of SCR_2 , momentarily deflected the current path away from the anode of SCR_1 through C_5 , and simultaneously activated So_2 , and forward biases D_3 to make ready for the next pulse. The cycle was repeated for each solenoid. Sequence was: power on, manual pulse, So_1 active, UJT pulse, So_2 active, UJT pulse, So_3 active UJT pulse, So_4 active, UJT pulse, So_1 active, etc.

FIGURE 16
Circuit Diagram

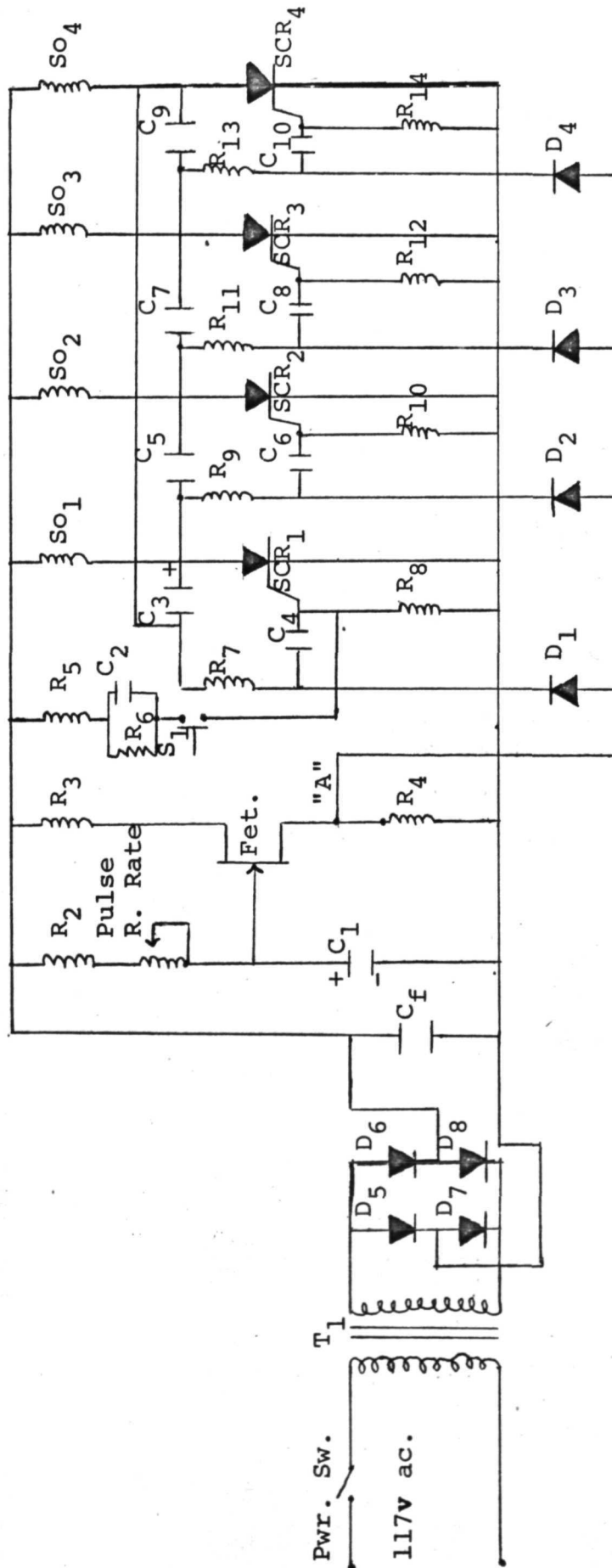


FIGURE 16

The cuffs containing the rippling air compartments were fabricated from an outside nylon (nonstretch) material with an inner cotton stockinette (stretch) material. Adjustments to the contour of each arm and leg was made possible by velcro belts. The pressure compartments were 1/2 inch in diameter of latex tubing, approximately 9" long with one end occluded and the other end attached to tygon pressure tubing leading to the pulsator.

Air Flow System:

The system operated on approximately 10 psi. air pressure. Air flowed through the regulator into a four-part manifold which fed four three-way poppet valves (clippard model (#MJV-3)). The exhaust was to atmosphere through a hollow stem. When the valve was actuated air flowed through a Mantrol Model #4F-200-B, flow control valve. Each flow control valve was fed into a four-part manifold which fed one cuff band on each limb. When the three-way valve was deactivated, deflation was controlled through the flow control valve; the cycle then repeated. Figures 17 and 18 show a schematic and photograph on this air flow system.

The challenge delivered to the cardiovascular system by the pulsating ripple sleeves was measured by evaluating the responses of heart rate to the blood pooling. The results are in graph form and are displayed as figures 19 through 26. Although the pulsatile sleeves distributed the occluding pressure constantly over the upper arm and leg areas, thus eliminating pressure pain caused by simple

FIGURE 17
Schematic of Air Flow Diagram

Band Cuffs

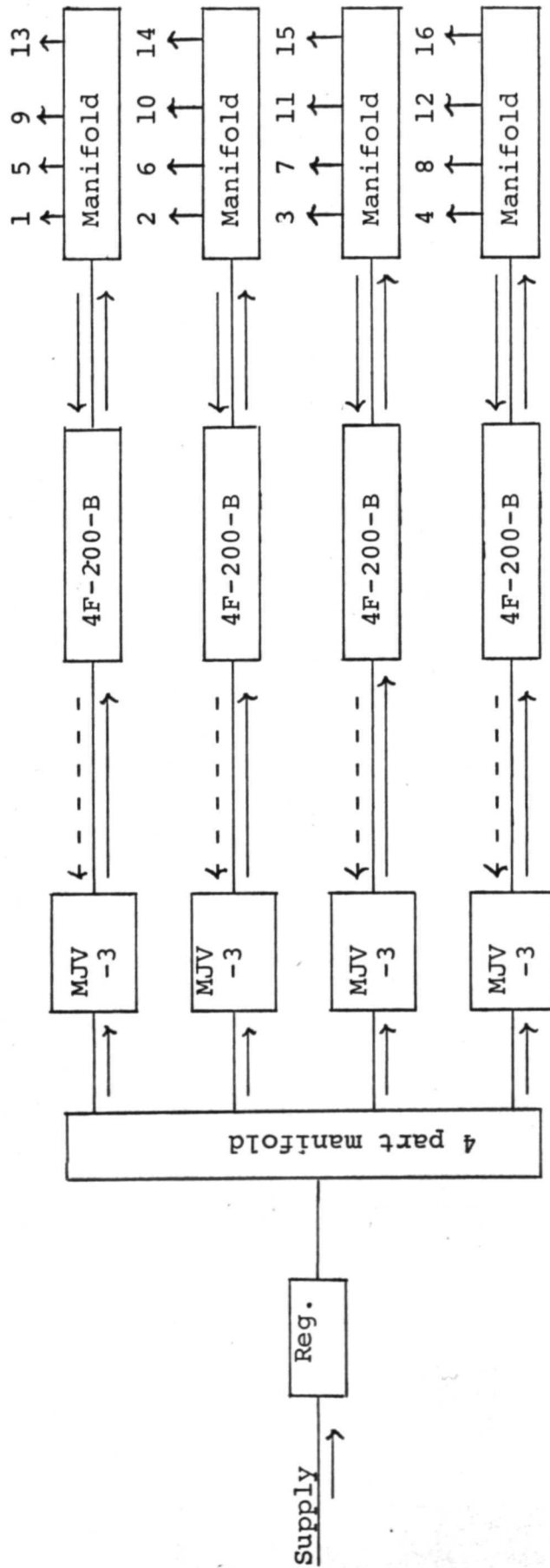
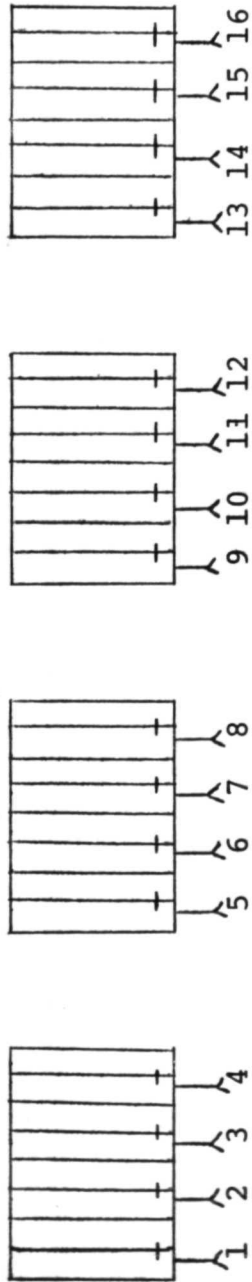


figure 17

FIGURE 18
Air Flow System

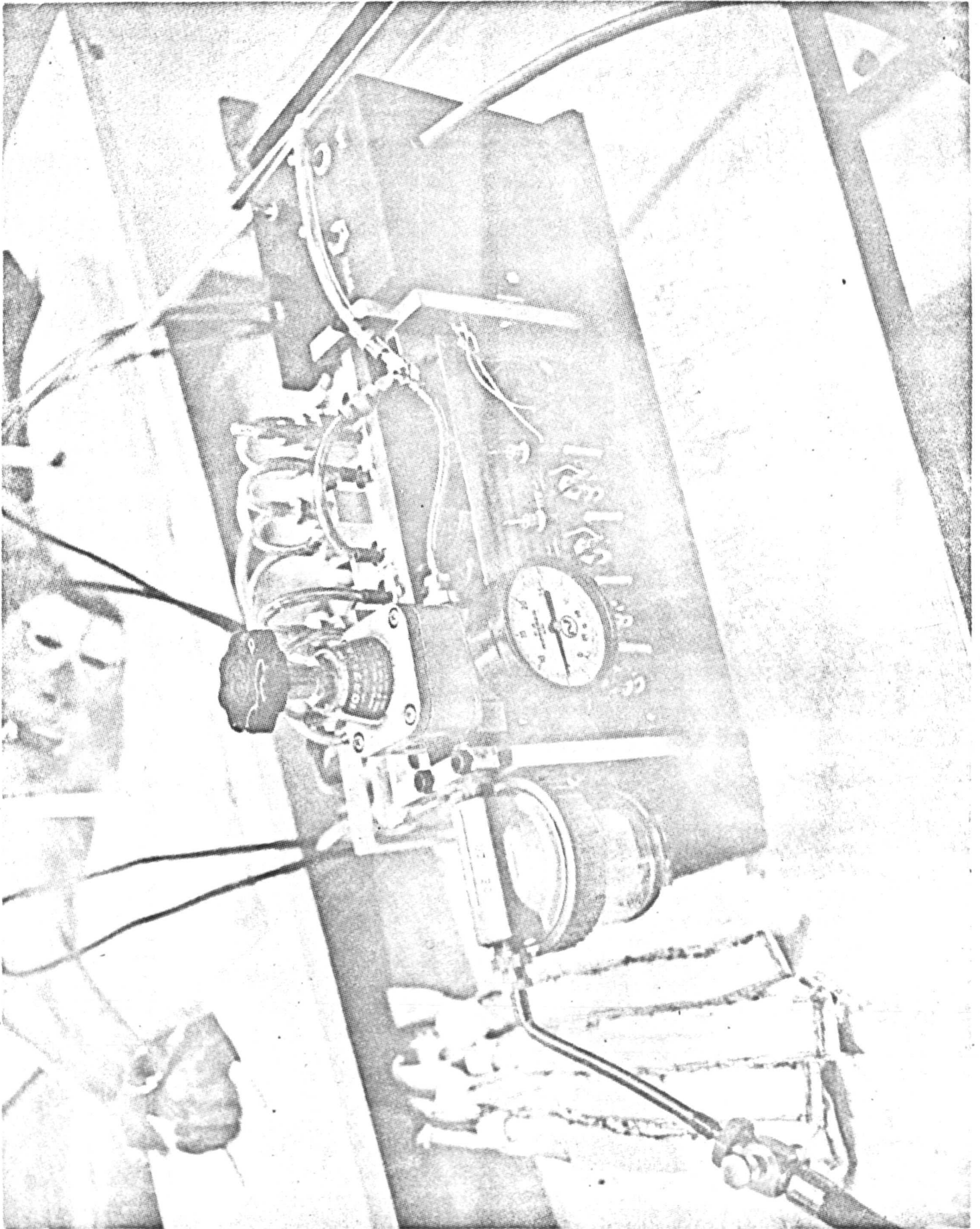


FIGURE 18

FIGURES 19-26

Graphs of the results obtained when the vinyl pulsatile sleeves
were used on the primates through four tests.

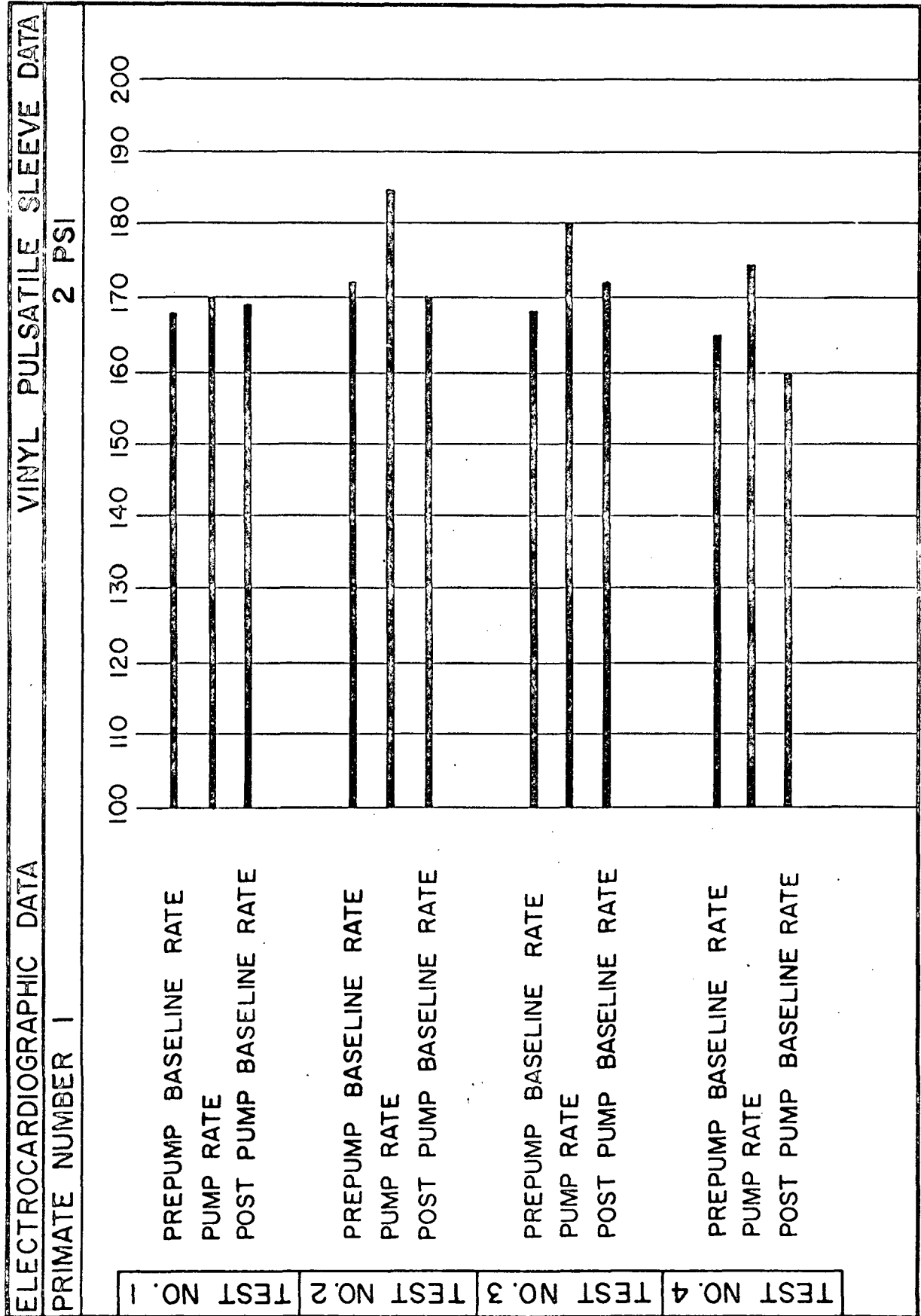


FIG. 19

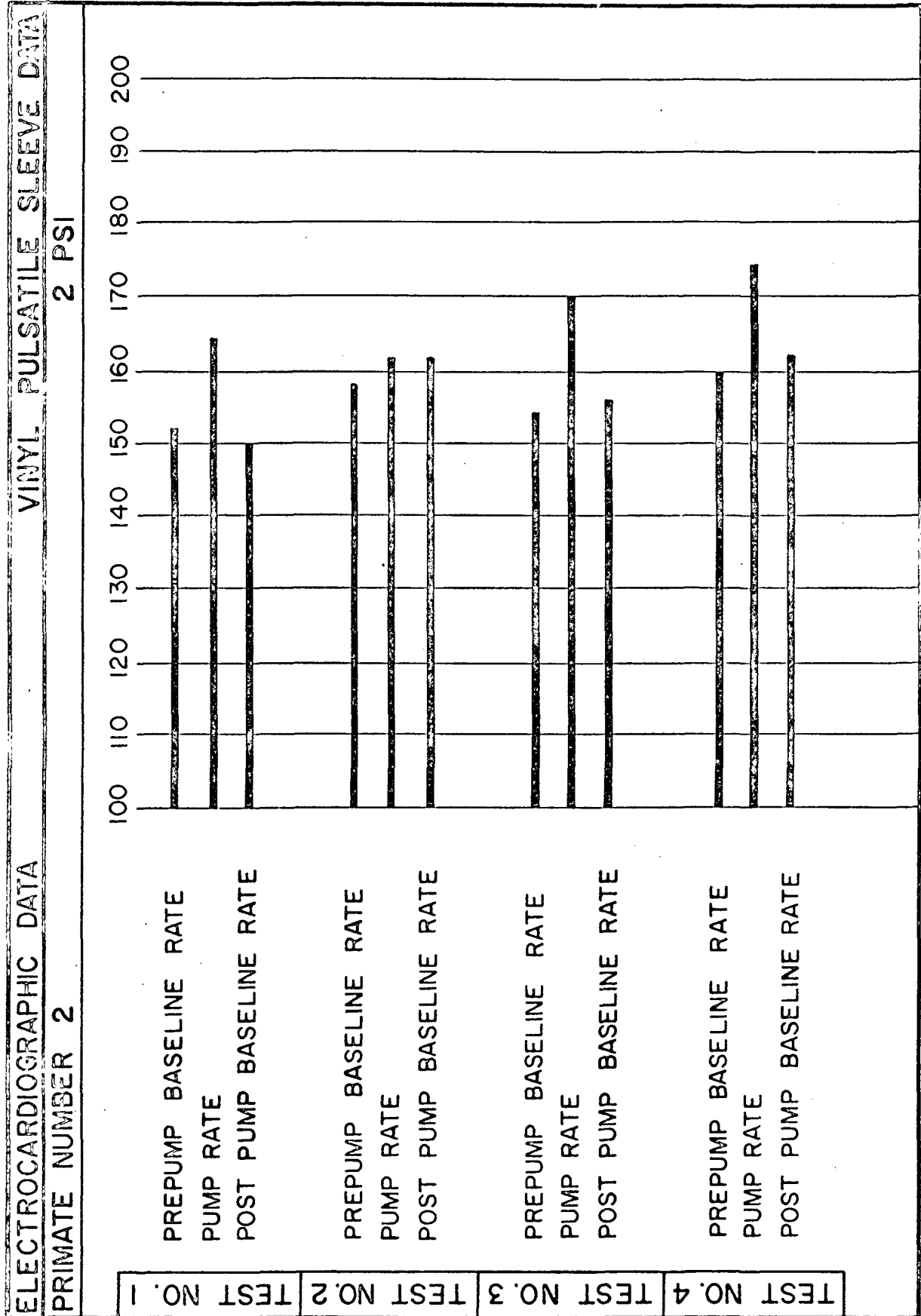


FIG. 20

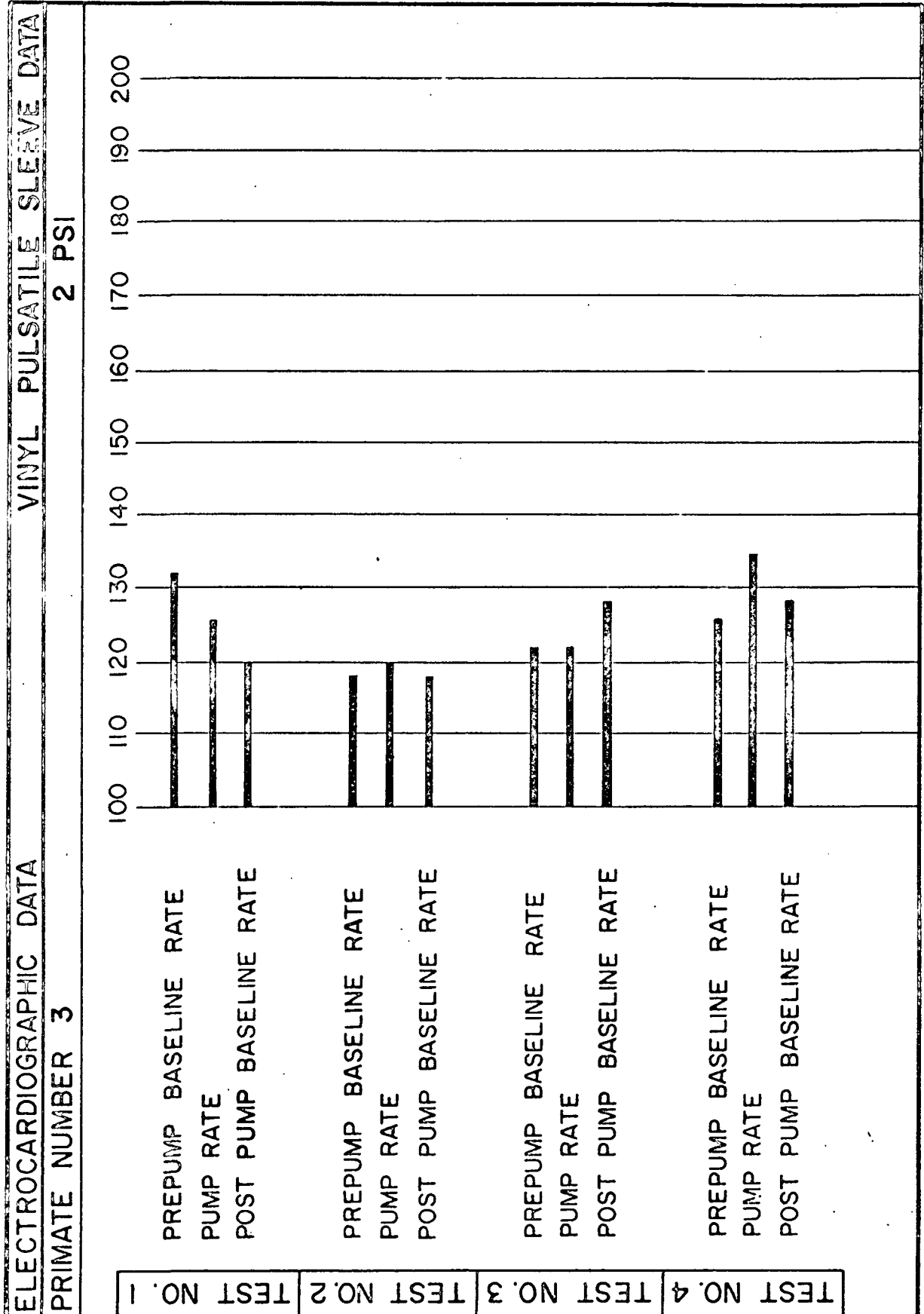


FIG. 21

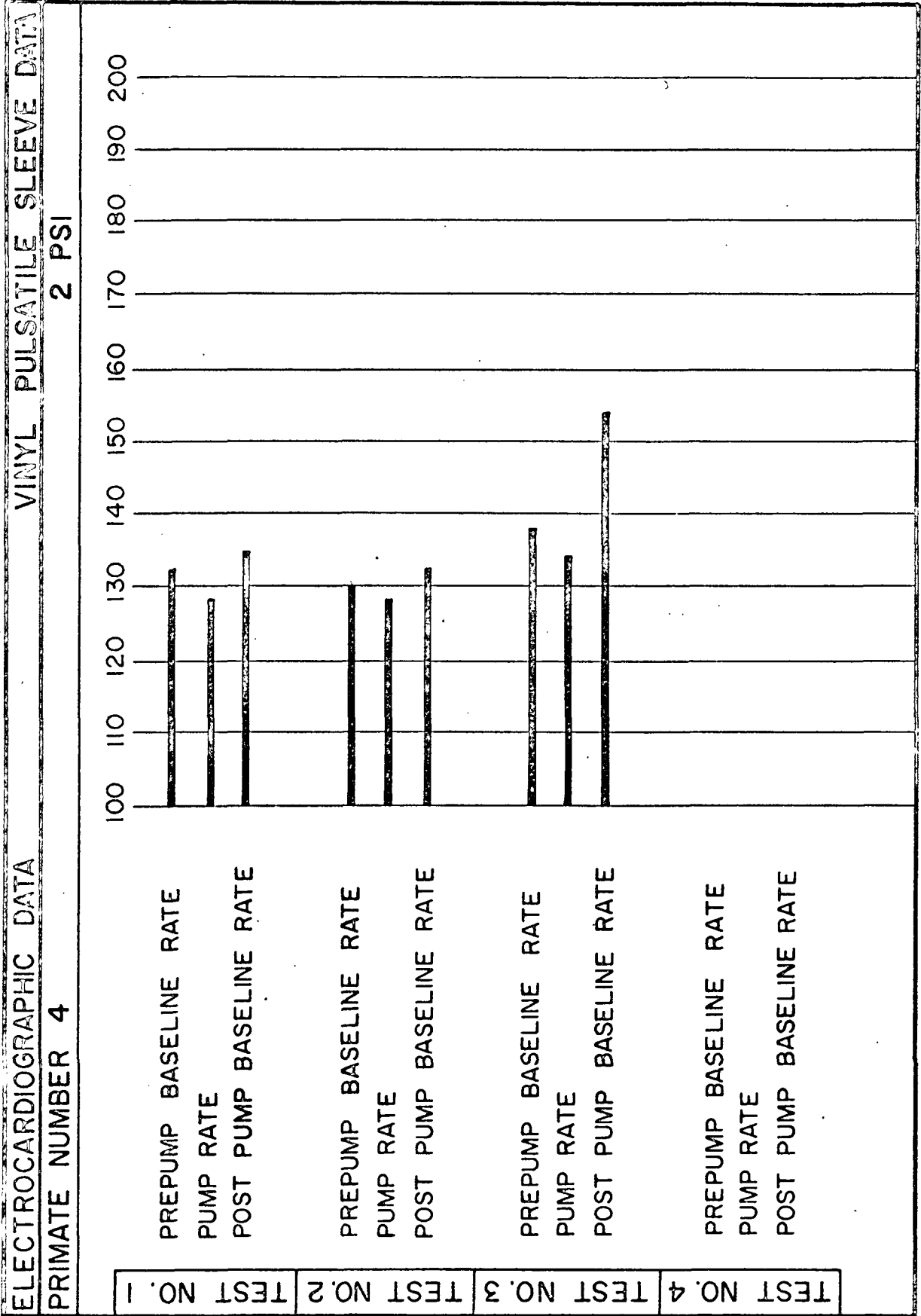


FIG. 22

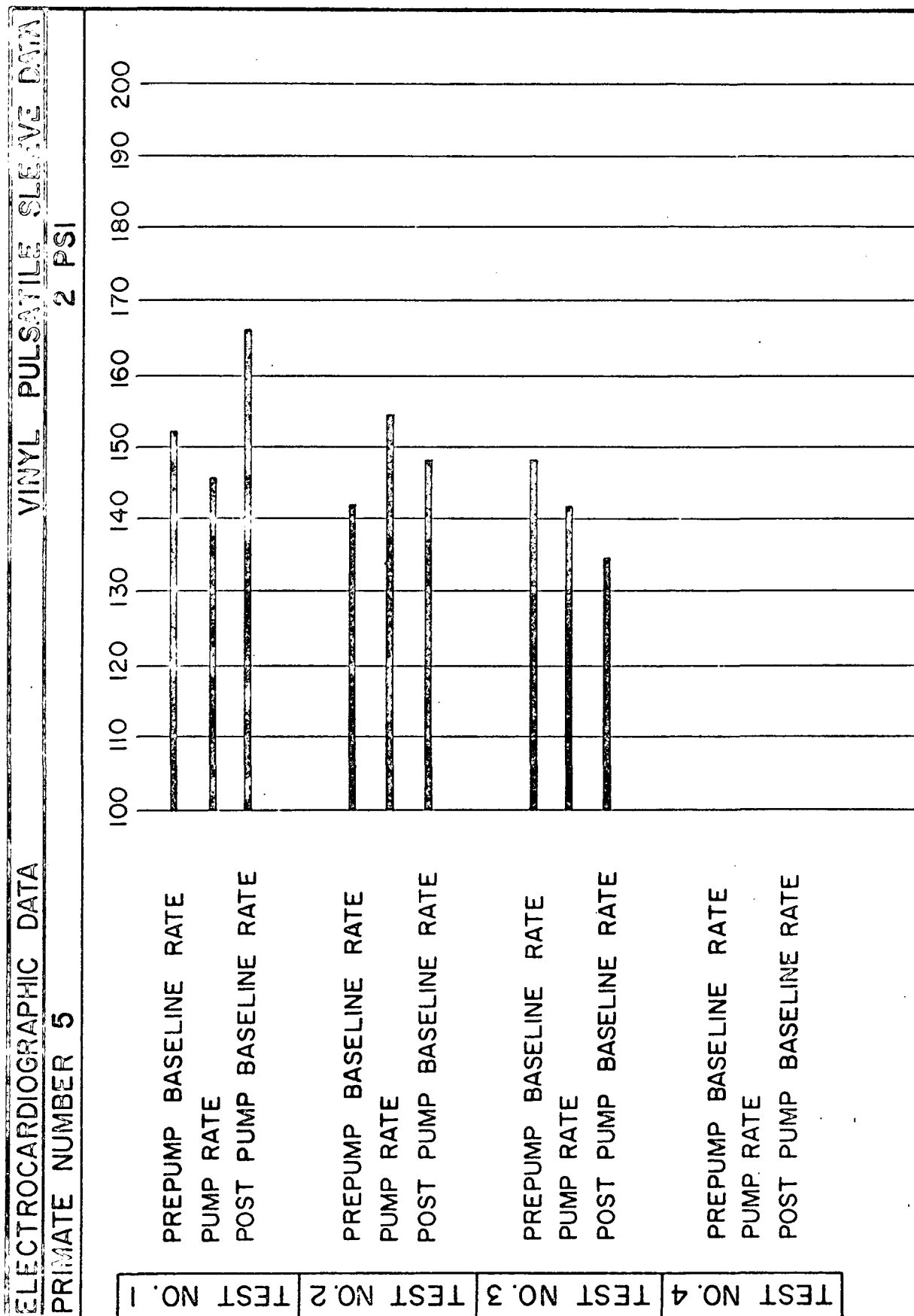


FIG. 23

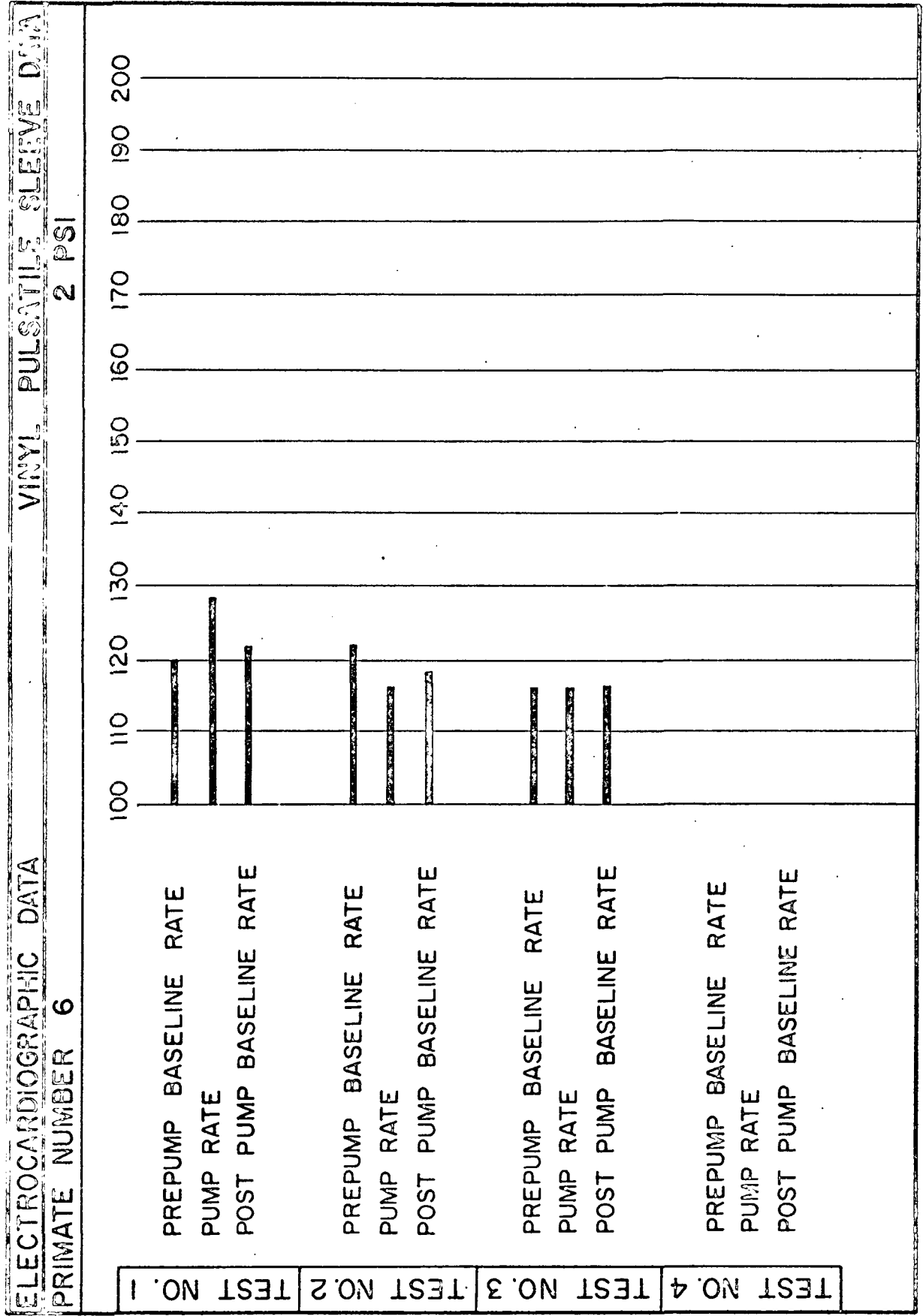


FIG. 24

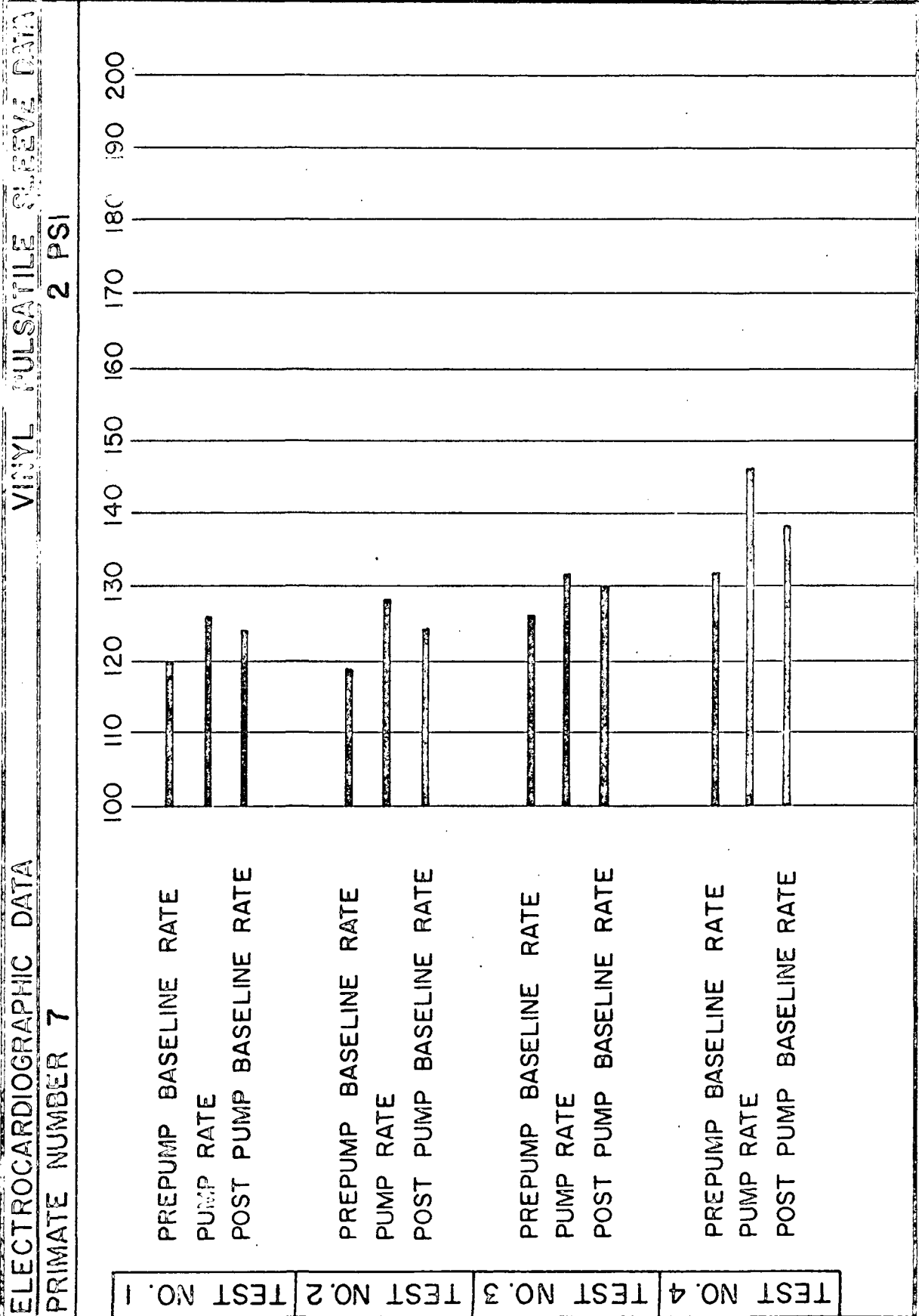


FIG. 25

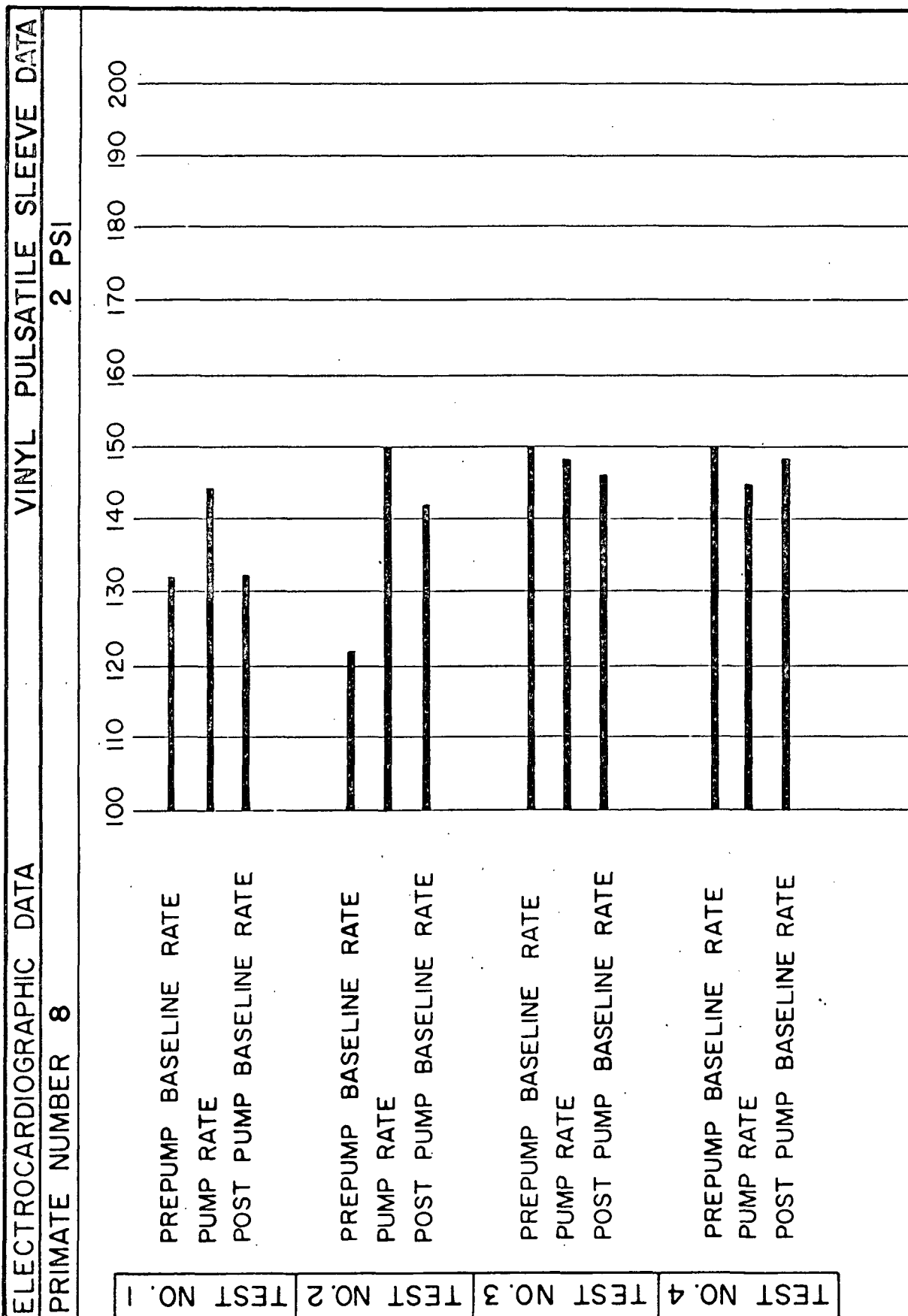


FIG. 26

tourniquets, the challenge elicited was not as great as that produced by the simple tourniquet technique. Later, the sleeves were fabricated from vinyl plastic material with four air compartments in each sleeve. Air pressures were programed to inflate each of the compartments in sequence at a rate of once every 5 seconds. The action produced was pleasing and comfortable but venous occlusion was difficult to maintain. The sleeve compartments under pressure had a tendency to "blow out" and this technique was abandoned.

Pulsatile Pneumatic Tourniquet Cuffs:

Venous occlusion was not considered sufficient to cause maximum cardiovascular response when the vinyl sleeves were utilized in early experiments. Therefore, pneumatic tourniquets coupled in sequence were investigated. Two infant size sphygmomonometer cuffs with rubber bladders were fastened together, with a separate air line running from the pulsator to each air chamber of the cuff.

Modification of the pulsator, to convert it from a 4 chamber electronic system to a 2 chamber electrical-timer system, were made. All of the solid-state electronic controls were removed except its driving power supply. The supply voltage was dropped to operate the 2 remaining chambers (solenoids). A 2 cam (switch) 3 minute recycling timer was installed and the cycle was divided so that switching took place as follows:

switch #1 - closed, #2 - open

switch #1 and #2 - closed

switch #2 - closed, #1 - open

switch #1 and #2 - closed

The closed switches actuated the solenoids sending air flow to the pneumatic tourniquet cuffs.

The system was programed to deliver cuff pressure to the superior cuffs of both arms and legs at the same time, and to maintain that pressure for 1 1/2 minutes before release. Within 8 seconds of the release time for the superior cuffs, another set of jets delivered cuff pressure to the inferior cuffs on both arms and legs. Thus, there was an 8 second overlap of top and bottom tourniquets to prevent the escape of blood past the occluding site during the change of the intermittent cuff pressures. When the bottom tourniquets were inflated, the top cuffs deflated for the 1 1/2 minutes of the cycle. This continually shifted the pressure points of the occluding tourniquets and prevented the painful sensations normally accompanying conventional tourniquets. The cycle pulsed, with the top tourniquets inflated and the bottom tourniquets deflated, and then the occluding action occurred in the bottom tourniquets and the top cuffs deflated.

Changes in the cardiovascular physiology became apparent almost immediately with the pulsator in operation. The heart rate increased, cardiac output decreased, stroke volume decreased but blood pressures were variable, sometimes remaining unchanged. There were considered indices of cardiac exercise even though the experimental subjects were at absolute rest, with a low metabolism.

Cardiovascular Measurements:

In the preliminary phases of this investigation and during the designing and testing of various occluding sleeves and tourniquets, the changes in heart rate was the sole parameter monitored.

Electrocardiograms were taken by skin needle electrodes taped in position in the scapula, ilium and chest regions for Leads I, II, and III as well as for leads AVR, AVL and AVF. The signals are recorded on a Sanborn recorder equipped with an ECG amplifier as analog data. Later, silver silver-chloride external ECG electrodes were used. They gave a much cleaner signal with a lower noise to signal ratio, and freedom of movement artifacts. Figures 27 through 34 show heart rate changes when the pneumatic tourniquets were employed through four tests on eight primates.

Blood Pressure Measurements:

Initially, blood pressure measurements were obtained by the indirect method using a piezoelectric crystal* transducer in a modified sphygmomanometer cuff. This device was applied to the tail, with the sensing crystal directly over the coccygeal artery. The transducer was calibrated at 160 mm Hg full scale. The cuff was inflated to occlude the artery and then air pressure bled off with systolic pressure recorded when the first pulse passed the

* Astatic type 13T

FIGURES 27-34

Heart rate changes when the pneumatic tourniquets were
employed through four tests on eight primates.

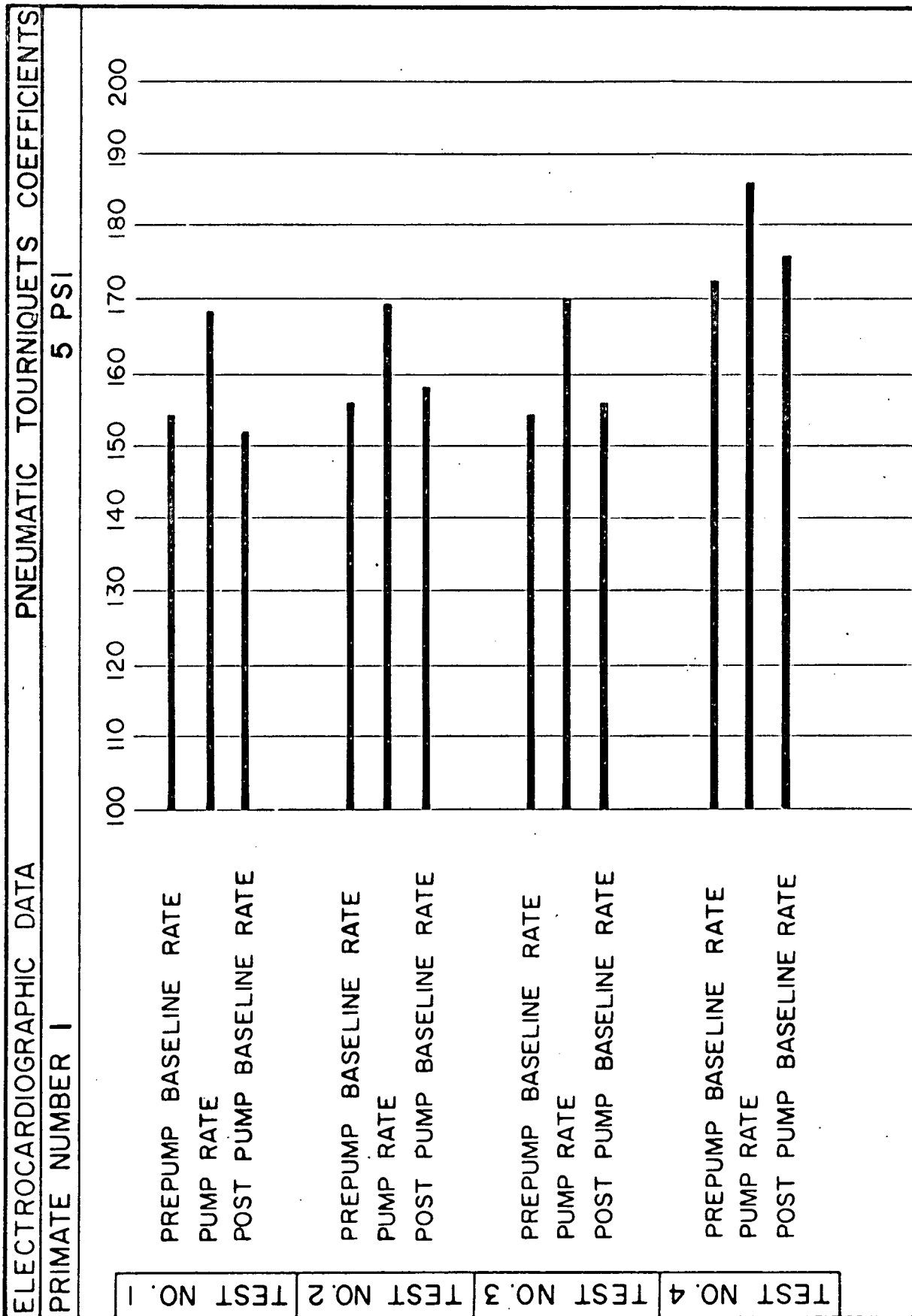


FIG. 27

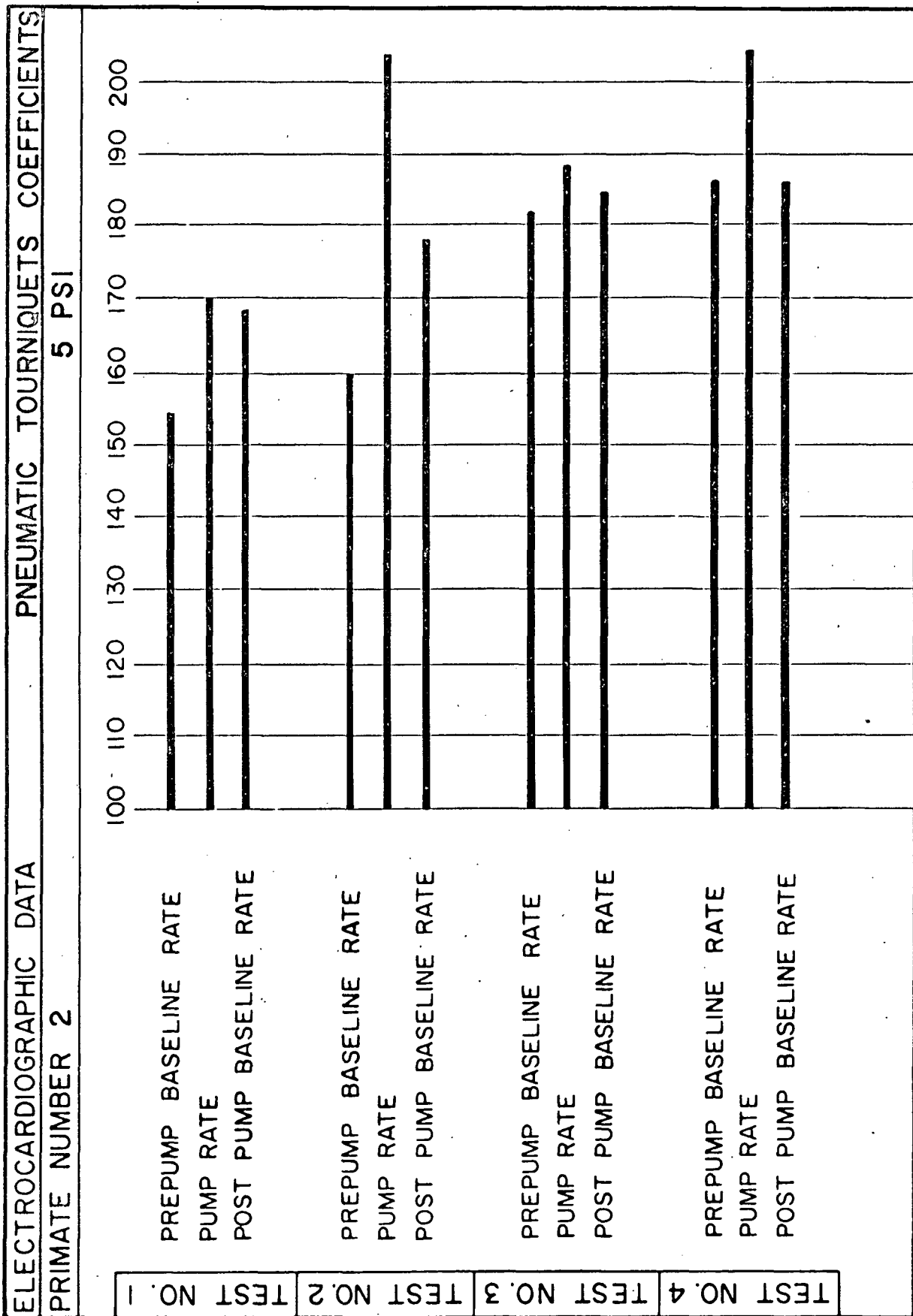


FIG. 28

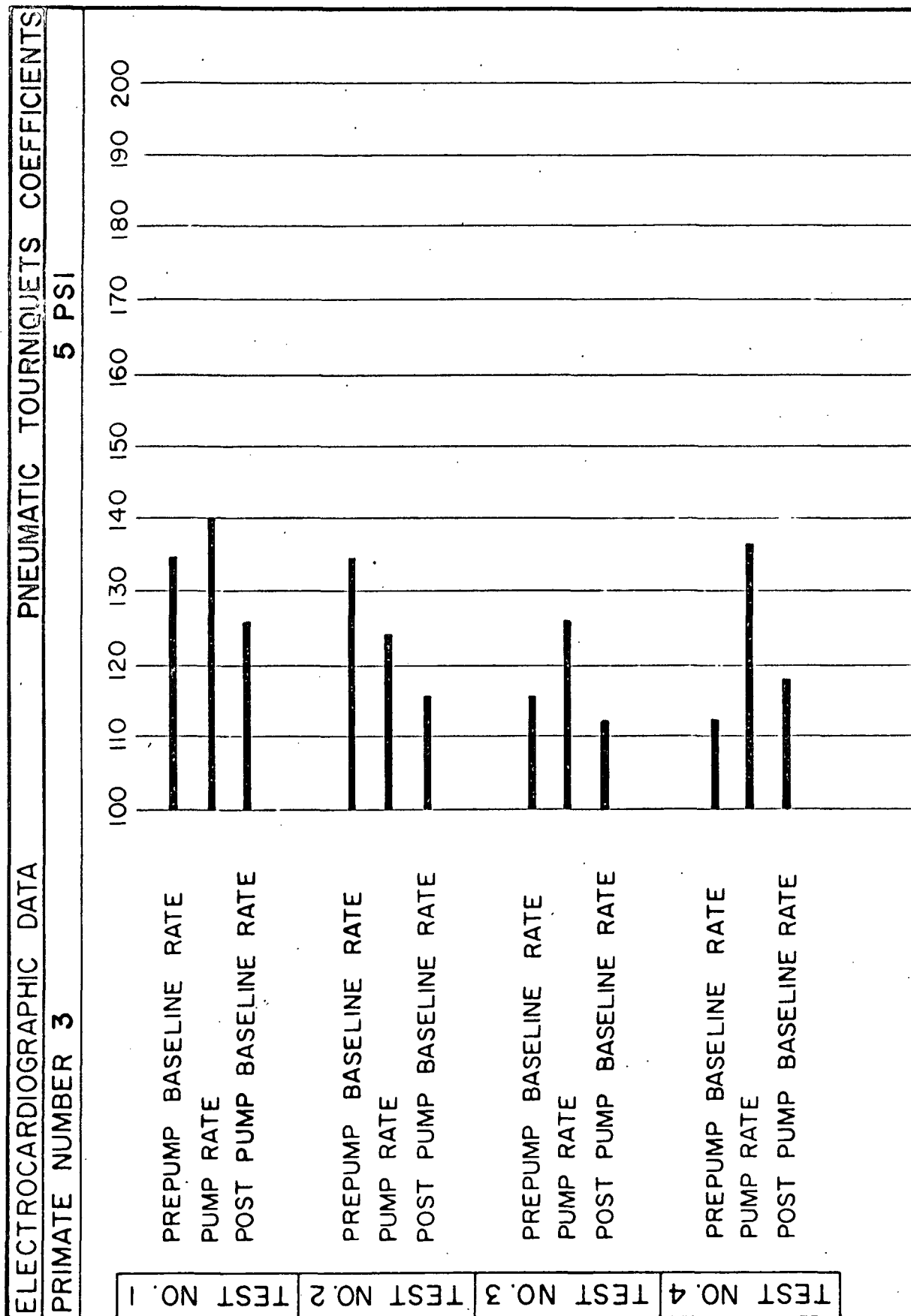


FIG. 29

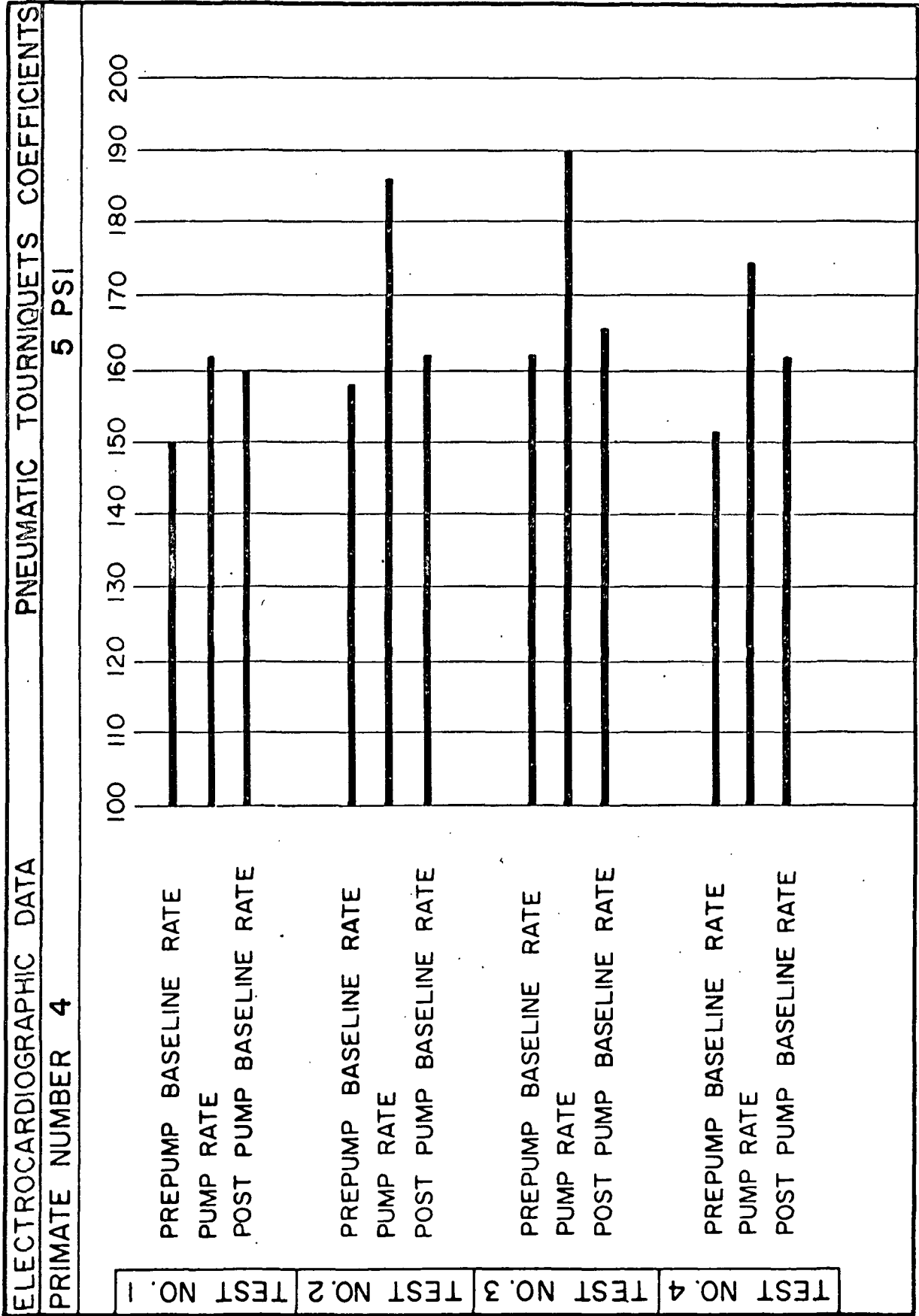


FIG. 30

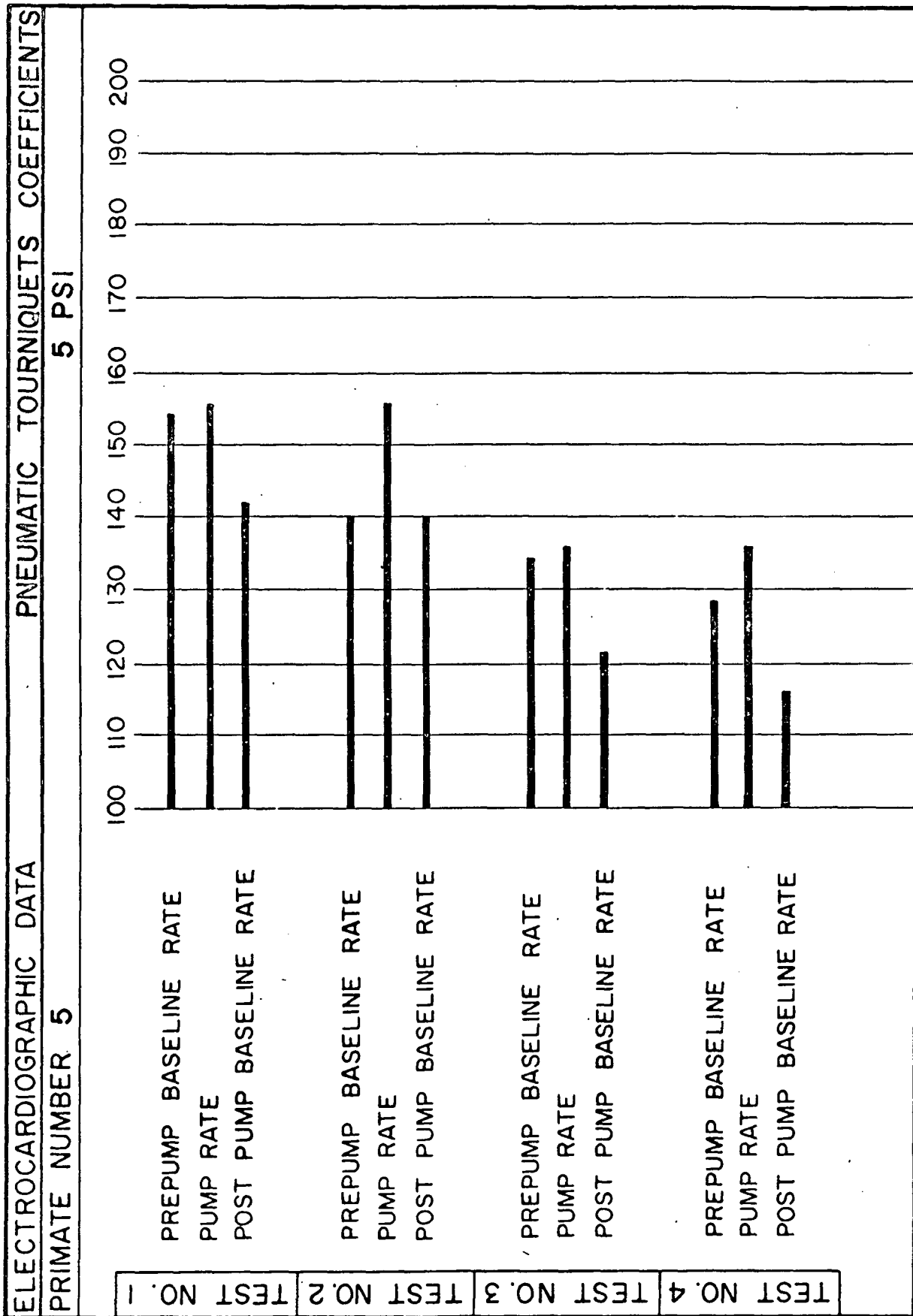


FIG. 31

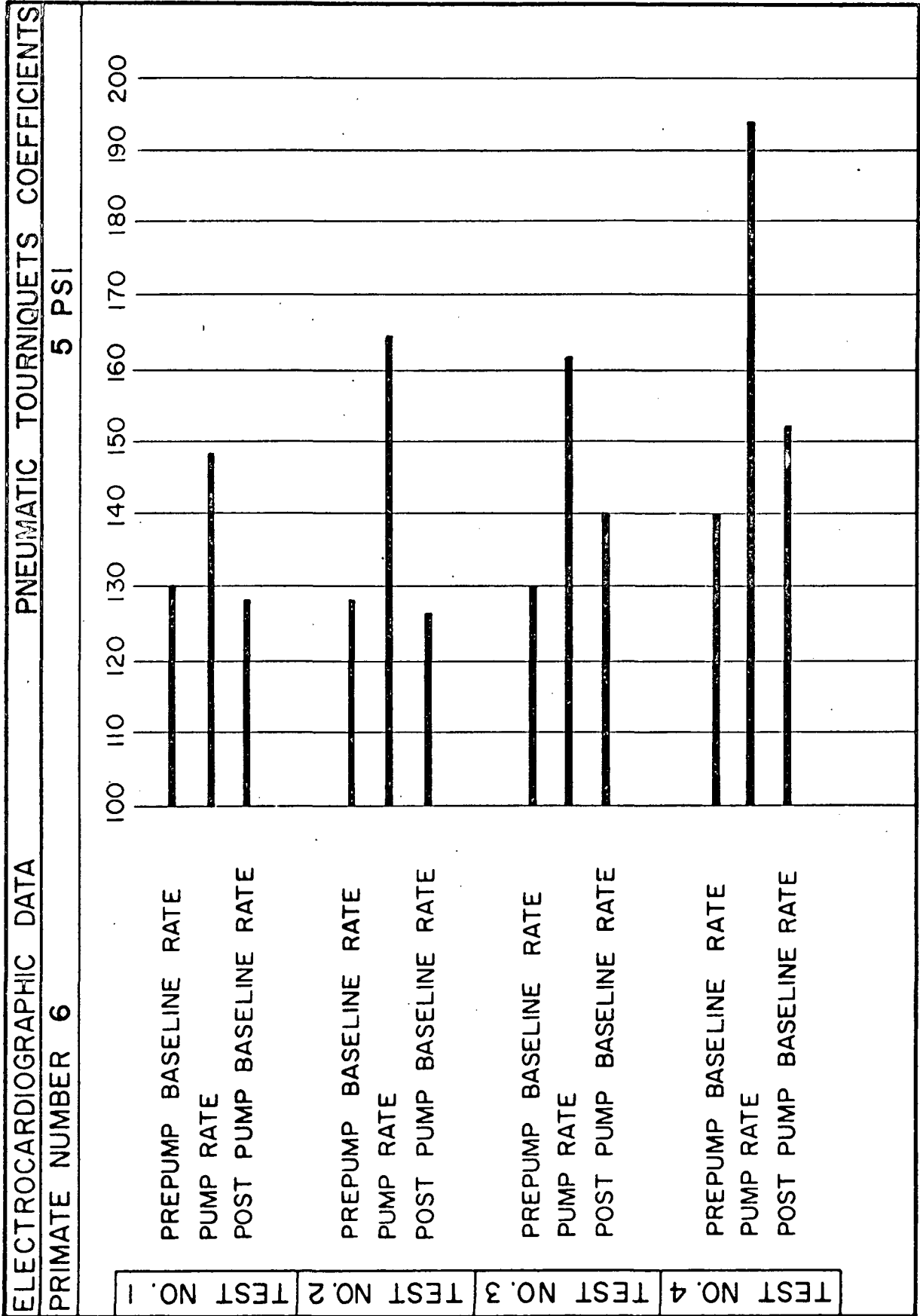


FIG. 32

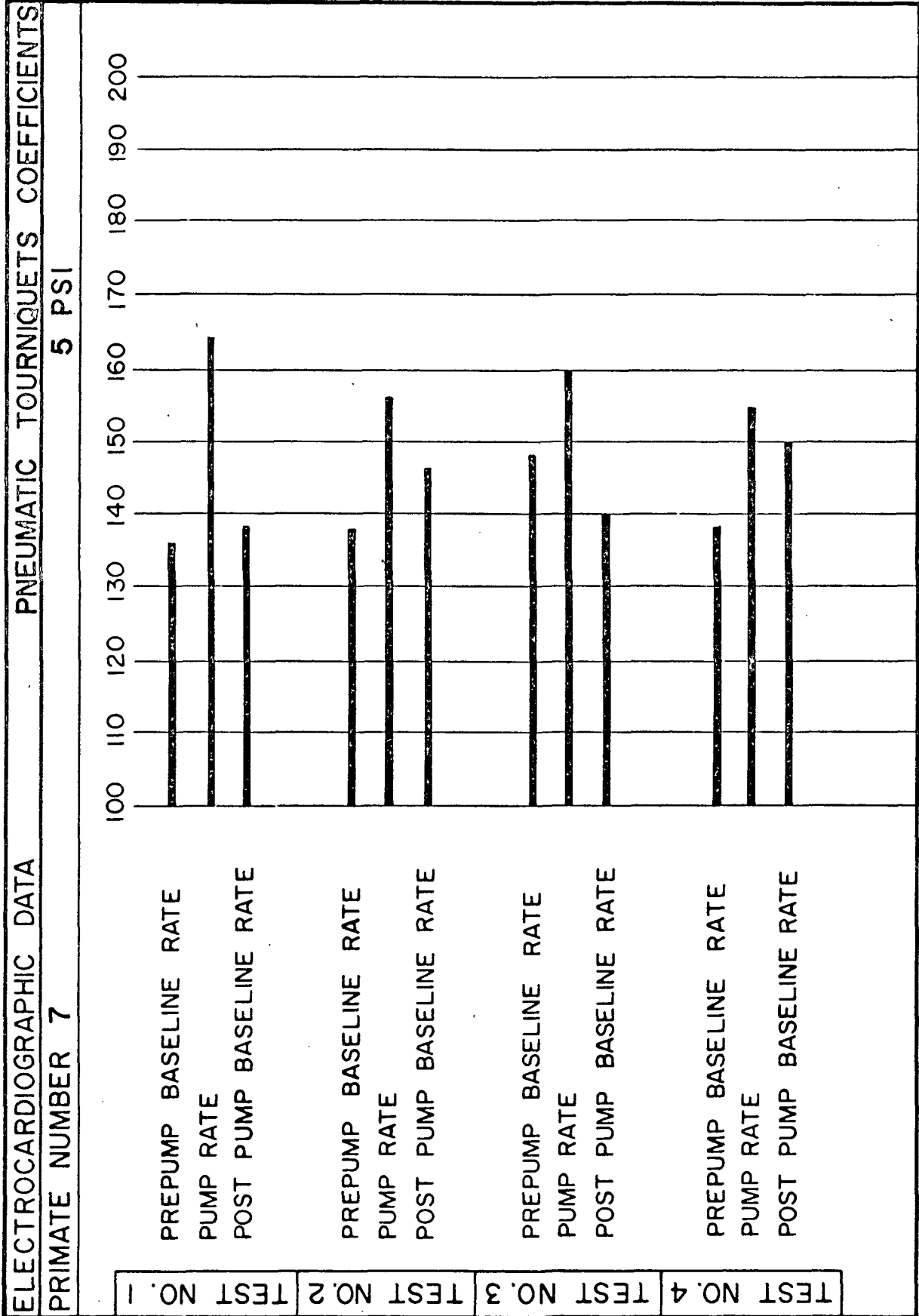


FIG. 33

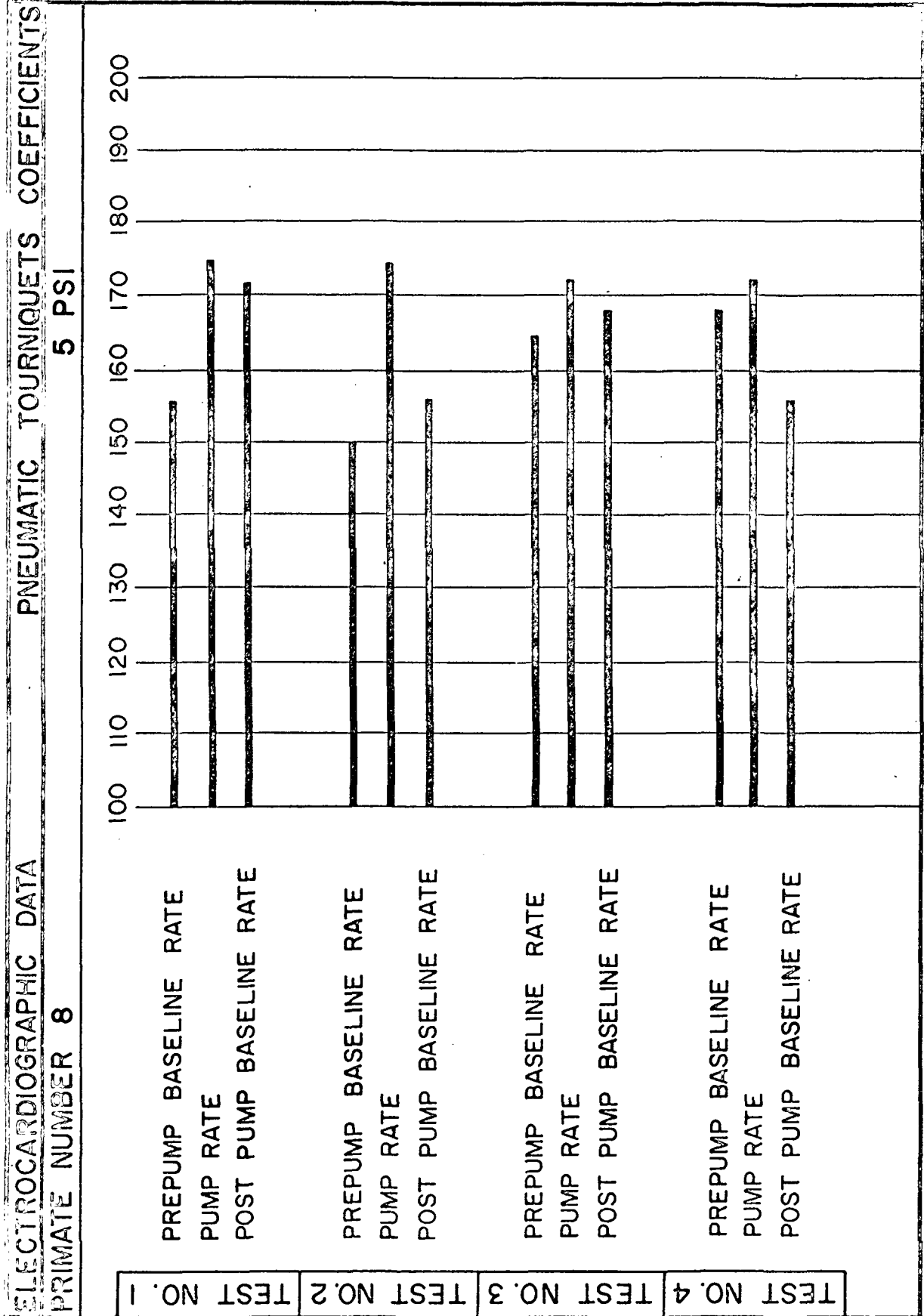


FIG. 34

occluding cuff. Diastolic pressure was recorded when the pulse wave first became constant in form. (Figure 35) Use of the tail to obtain blood pressures, freed the arms and legs for the sleeves and tourniquets to be applied.

Since indirect blood pressure measurements are not as accurate as direct measurements, the technique was changed over to the direct method. The femoral artery was cannulated with a .58 mm O D catheter coupled to a Statham blood pressure transducer (Model P 23 AA) and all further pressures were recorded through this system.

Cardiac Output Measurements:

Radioisotopes were originally considered for determining cardiac output. External scintillation probes were used to detect the Tc-99 m and I-131 labeled serum albumin injected intravenously as a bolus. The energy of the ionizing radiation emitted by the tagged albumin, as it was pumped through the heart was measured as a primary curve. Calculations of cardiac output by this technique was a modification of the Stewart-Hamilton method. Because of radioactive scatter and impossible shielding the results of cardiac output by this method did not prove satisfactory and were discontinued in favor of implanted electromagnetic flow probes.

Statham (Q-5000) flow probes were surgically implanted on the ascending aorta via left thoracotomy. The cable from the probe was brought out in the back region and secured in a pouch for accessibility at time of monitoring. After the primates had recovered from the

FIGURE 35

Diastolic pressure being recorded.

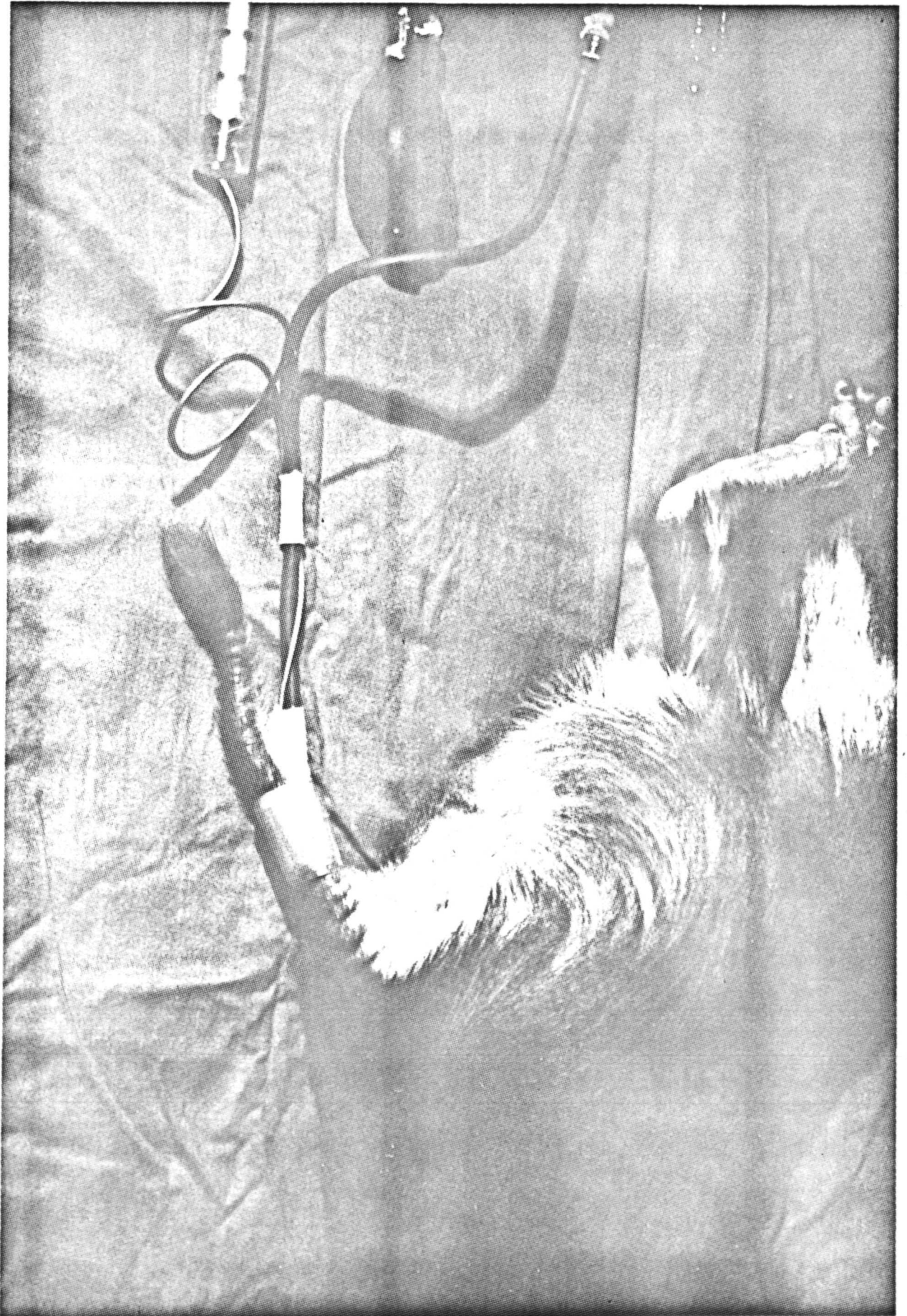


FIGURE 35

implant surgery, the flow probe cable was coupled to a Statham model 0-5000 blood flow meter.

A 4 channel model 7714 Sanborn recorder was used as a signal conditioning and "quick look" system in front of a Sangamo Model 3562 14 channel tape recorder. The analog tape generated on the Sangamo recorder was digitized on a Redcor A to D converter system and all of the data computations were accomplished by a CDC Model 6400 Computer.

RESULTS

The results obtained when simple rubber tourniquets were applied to both arms and legs of sub-human primates have been shown in graph form as figures 1 through 8. Although application of simple tourniquets produced responses in the cardiovascular system of increased heart action, the pain and tissue damage beneath the tourniquet proved intolerable and this method of occlusion of venous return was abandoned.

The application of pulsating ripple sleeves, applied to both arms and legs are shown in figures 9 through 15. Air compartments, inflated by a pulsator, occluded the venous return of blood in a sequential pattern to relieve pressure pain observed when simple tourniquets were used. The response of the circulatory system, as indicated by graphs in figures 19 through 26, was stimulated to produce increased heart rate. The amplitude and reliability of this response was quite variable. It is believed that the range of results

was in part due to the techniques used in applying the sleeves as cuffs. If the cuffs were tightly applied, the response recorded was greater than those from a loosely wrapped cuff. Compartment "blow outs" were a constant and discouraging problem with the sleeves as they were designed and after considerable experimentation, this technique was discontinued.

Because the pooling of blood in the extremities by tourniquets did produce responses by the heart, this principle was pursued by designing pulsating pneumatic tourniquet cuffs that were durable and positive in their application. The results obtained from electrocardiographic recordings are shown in graph form as figures 27 through 34.

In all but one test the heart rate increased quite measurably when the pulsating pneumatic tourniquets were applied and activated. The exception was a decline of heart rate during activation of the tourniquets and this decline continued after the tourniquets were removed. There was no plausible explanation for this effect and the cause remains unanswered.

These preliminary data indicated the feasibility and practical application of the pulsating pneumatic tourniquet technique. Not only was a significant heart response triggered by the venous pooling, but the slow pulsations of the inflating and deflating tourniquets on each limb, eliminated any lengthy pressure that might cause pain or tissue damage.

The amount of response was then measured by further instrumenting the animals to monitor electrocardiograms, blood pressures, cardiac outputs and stroke volumes. The methods on instrumentation have been described. Results are presented in table form as figures 36 through 43.

FIGURES 36-43

Results

PNEUMATIC TOURNIQUETS PRIMATE NUMBER 1

TEST 1			HEART RATE	CARDIAC OUTPUT	BLOOD PRESSURE	STROKE VOLUME
PREPUMP BASELINE RATE			163.80 / MIN	744.12 / MIN	$\frac{198.82}{87.35}$ mm. Hg.	4.54 ml
PUMP RATE			172.00 / MIN	645.00 / MIN	$\frac{207.49}{96.35}$ mm. Hg.	3.75 ml
POSTPUMP BASELINE RATE			169.20 / MIN	756.10 / MIN	$\frac{209.83}{96.55}$ mm. Hg.	4.46 ml
TEST 2			HEART RATE	CARDIAC OUTPUT	BLOOD PRESSURE	STROKE VOLUME
PREPUMP BASELINE RATE			158.00 / MIN	778.17 / MIN	$\frac{204.15}{81.73}$ mm. Hg.	4.92 ml
PUMP RATE			162.95 / MIN	639.63 / MIN	$\frac{203.87}{94.77}$ mm. Hg.	3.92 ml
POSTPUMP BASELINE RATE			160.00 / MIN	721.01 / MIN	$\frac{200.19}{91.07}$ mm. Hg.	4.50 ml
TEST 3			HEART RATE	CARDIAC OUTPUT	BLOOD PRESSURE	STROKE VOLUME
PREPUMP BASELINE RATE			159.16 / MIN	739.88 / MIN	$\frac{207.27}{95.83}$ mm. Hg.	4.64 ml
PUMP RATE			166.00 / MIN	620.10 / MIN	$\frac{213.83}{104.01}$ mm. Hg.	3.73 ml
POSTPUMP BASELINE RATE			161.05 / MIN	731.50 / MIN	$\frac{214.55}{102.69}$ mm. Hg.	4.54 ml
TEST 4			HEART RATE	CARDIAC OUTPUT	BLOOD PRESSURE	STROKE VOLUME
PREPUMP BASELINE RATE			162.00 / MIN	736.05 / MIN	$\frac{217.60}{102.57}$ mm. Hg.	4.54 ml
PUMP RATE			168.63 / MIN	602.94 / MIN	$\frac{218.90}{107.07}$ mm. Hg.	3.57 ml
POSTPUMP BASELINE RATE			164.84 / MIN	748.19 / MIN	$\frac{218.90}{102.07}$ mm. Hg.	4.53 ml

FIG. 36

PNEUMATIC TOURNIQUETS PRIMATE NUMBER 1

TEST 5

	HEART RATE	CARDIAC OUTPUT	BLOOD PRESSURE	STROKE VOLUME
PREPUMP BASELINE RATE	166.00 / MIN	747.00 / MIN	$\frac{215.76}{102.90}$ mm. Hg.	4.50 ml
PUMP RATE	172.42 / MIN	628.95 / MIN	$\frac{228.79}{112.11}$ mm. Hg.	3.64 ml
POSTPUMP BASELINE RATE	168.00 / MIN	743.19 / MIN	$\frac{218.88}{103.61}$ mm. Hg.	4.42 ml

TEST 6

PREPUMP BASELINE RATE	155.37 / MIN	728.25 / MIN	$\frac{207.17}{99.03}$ mm. Hg.	4.68 ml
PUMP RATE	162.00 / MIN	619.14 / MIN	$\frac{203.28}{106.71}$ mm. Hg.	3.82 ml
POSTPUMP BASELINE RATE	158.09 / MIN	672.27 / MIN	$\frac{203.12}{96.25}$ mm. Hg.	4.25 ml

TEST 7

PREPUMP BASELINE RATE	156.00 / MIN	686.51 / MIN	$\frac{206.78}{98.64}$ mm. Hg.	4.40 ml
PUMP RATE	166.00 / MIN	631.07 / MIN	$\frac{223.41}{116.50}$ mm. Hg.	3.80 ml
POSTPUMP BASELINE RATE	166.00 / MIN	758.52 / MIN	$\frac{235.10}{111.84}$ mm. Hg.	4.56 ml

TEST 8

PREPUMP BASELINE RATE	154.00 / MIN	741.35 / MIN	$\frac{215.57}{99.58}$ mm. Hg.	4.81 ml
PUMP RATE	160.00 / MIN	564.92 / MIN	$\frac{210.57}{103.85}$ mm. Hg.	3.53 ml
POSTPUMP BASELINE RATE	152.00 / MIN	698.62 / MIN	$\frac{215.84}{101.29}$ mm. Hg.	4.59 ml

FIG. 37

PNEUMATIC TOURNIQUETS PRIMATE NUMBER 3

TEST 1		HEART RATE	CARDIAC OUTPUT	BLOOD PRESSURE	STROKE VOLUME
PREPUMP BASELINE RATE		168.00 / MIN	640.37 / MIN	$\frac{180.38}{85.70}$ mm. Hg.	3.81 ml
PUMP RATE		174.00 / MIN	573.42 / MIN	$\frac{182.16}{88.42}$ mm. Hg.	3.29 ml
POSTPUMP BASELINE RATE		164.00 / MIN	582.24 / MIN	$\frac{159.00}{73.57}$ mm. Hg.	3.55 ml
TEST 2		HEART RATE	CARDIAC OUTPUT	BLOOD PRESSURE	STROKE VOLUME
PREPUMP BASELINE RATE		160.00 / MIN	569.68 / MIN	$\frac{163.05}{72.30}$ mm. Hg.	3.56 ml
PUMP RATE		162.95 / MIN	538.85 / MIN	$\frac{157.16}{73.30}$ mm. Hg.	3.30 ml.
POSTPUMP BASELINE RATE		154.00 / MIN	573.36 / MIN	$\frac{159.29}{70.80}$ mm. Hg.	3.72 ml
TEST 3		HEART RATE	CARDIAC OUTPUT	BLOOD PRESSURE	STROKE VOLUME
PREPUMP BASELINE RATE		152.00 / MIN	577.34 / MIN	$\frac{157.26}{70.00}$ mm. Hg.	3.79 ml
PUMP RATE		156.00 / MIN	496.05 / MIN	$\frac{156.42}{76.93}$ mm. Hg.	3.17 ml
POSTPUMP BASELINE RATE		150.00 / MIN	568.75 / MIN	$\frac{163.66}{76.93}$ mm. Hg.	3.79 ml
TEST 4		HEART RATE	CARDIAC OUTPUT	BLOOD PRESSURE	STROKE VOLUME
PREPUMP BASELINE RATE		150.00 / MIN	582.80 / MIN	$\frac{175.06}{81.51}$ mm. Hg.	3.88 ml
PUMP RATE		154.00 / MIN	515.15 / MIN	$\frac{166.01}{80.81}$ mm. Hg.	3.34 ml
POSTPUMP BASELINE RATE		148.00 / MIN	595.24 / MIN	$\frac{176.87}{81.51}$ mm. Hg.	4.02 ml

FIG. 38

PNEUMATIC TOURNIQUETS PRIMATE NUMBER 3

TEST 5			HEART RATE	CARDIAC OUTPUT	BLOOD PRESSURE	STROKE VOLUME
PREPUMP BASELINE RATE			144.00 / MIN	552.46 / MIN	$\frac{160.18}{71.85}$ mm. Hg.	3.83 ml
PUMP RATE			145.89 / MIN	471.33 / MIN	$\frac{152.77}{72.76}$ mm. Hg.	3.23 ml
POSTPUMP BASELINE RATE			142.27 / MIN	557.43 / MIN	$\frac{155.46}{75.80}$ mm. Hg.	3.91 ml
TEST 6			HEART RATE	CARDIAC OUTPUT	BLOOD PRESSURE	STROKE VOLUME
PREPUMP BASELINE RATE			140.21 / MIN	552.77 / MIN	$\frac{161.02}{73.64}$ mm. Hg.	3.91 ml
PUMP RATE			142.20 / MIN	503.02 / MIN	$\frac{162.71}{78.90}$ mm. Hg.	3.53 ml
POSTPUMP BASELINE RATE			141.92 / MIN	555.85 / MIN	$\frac{167.04}{79.61}$ mm. Hg.	3.91 ml
TEST 7			HEART RATE	CARDIAC OUTPUT	BLOOD PRESSURE	STROKE VOLUME
PREPUMP BASELINE RATE			140.00 / MIN	559.65 / MIN	$\frac{165.31}{79.05}$ mm. Hg.	3.99 ml
PUMP RATE			144.00 / MIN	528.47 / MIN	$\frac{176.30}{85.14}$ mm. Hg.	3.66 ml
POSTPUMP BASELINE RATE			144.00 / MIN	566.45 / MIN	$\frac{187.69}{88.95}$ mm. Hg.	3.93 ml
TEST 8			HEART RATE	CARDIAC OUTPUT	BLOOD PRESSURE	STROKE VOLUME
PREPUMP BASELINE RATE			144.00 / MIN	583.38 / MIN	$\frac{186.46}{87.70}$ mm. Hg.	4.05 ml
PUMP RATE			146.00 / MIN	531.99 / MIN	$\frac{175.13}{82.84}$ mm. Hg.	3.64 ml
POSTPUMP BASELINE RATE			145.77 / MIN	602.52 / MIN	$\frac{182.85}{85.33}$ mm. Hg.	4.13 ml

FIG. 39

PNEUMATIC TOURNIQUETS PRIMATE NUMBER 6

TEST 1		HEART RATE	CARDIAC OUTPUT	BLOOD PRESSURE	STROKE VOLUME
PREPUMP BASELINE RATE		148.11 / MIN	621.08 / MIN	$\frac{157.80}{84.59}$ mm. Hg.	4.19 ml
PUMP RATE		149.68 / MIN	484.51 / MIN	$\frac{142.43}{78.05}$ mm. Hg.	3.23 ml
POSTPUMP BASELINE RATE		146.00 / MIN	569.55 / MIN	$\frac{157.12}{89.35}$ mm. Hg.	3.90 ml
TEST 2		HEART RATE	CARDIAC OUTPUT	BLOOD PRESSURE	STROKE VOLUME
PREPUMP BASELINE RATE		144.00 / MIN	565.23 / MIN	$\frac{161.44}{92.34}$ mm. Hg.	3.92 ml
PUMP RATE		152.00 / MIN	479.57 / MIN	$\frac{163.01}{100.88}$ mm. Hg.	3.15 ml
POSTPUMP BASELINE RATE		148.00 / MIN	568.18 / MIN	$\frac{167.05}{98.84}$ mm. Hg.	3.83 ml
TEST 3		HEART RATE	CARDIAC OUTPUT	BLOOD PRESSURE	STROKE VOLUME
PREPUMP BASELINE RATE		146.00 / MIN	575.09 / MIN	$\frac{167.55}{99.35}$ mm. Hg.	3.93 ml
PUMP RATE		148.00 / MIN	412.42 / MIN	$\frac{138.47}{83.51}$ mm. Hg.	2.78 ml
POSTPUMP BASELINE RATE		144.00 / MIN	521.67 / MIN	$\frac{160.88}{95.17}$ mm. Hg.	3.62 ml
TEST 4		HEART RATE	CARDIAC OUTPUT	BLOOD PRESSURE	STROKE VOLUME
PREPUMP BASELINE RATE		144.00 / MIN	537.14 / MIN	$\frac{161.19}{95.05}$ mm. Hg.	3.73 ml
PUMP RATE		150.00 / MIN	433.22 / MIN	$\frac{151.54}{89.44}$ mm. Hg.	2.88 ml
POSTPUMP BASELINE RATE		144.00 / MIN	520.92 / MIN	$\frac{159.56}{95.89}$ mm. Hg.	3.61 ml

FIG. 40

PNEUMATIC TOURNIQUETS PRIMATE NUMBER 6

TEST 5

	HEART RATE	CARDIAC OUTPUT	BLOOD PRESSURE	STROKE VOLUME
PREPUMP BASELINE RATE	122.00 / MIN	462.63 / MIN	$\frac{117.24}{65.18}$ mm. Hg.	3.79 ml
PUMP RATE	133.93 / MIN	371.10 / MIN	$\frac{126.42}{77.16}$ mm. Hg.	2.77 ml
POSTPUMP BASELINE RATE	132.00 / MIN	500.14 / MIN	$\frac{157.79}{93.34}$ mm. Hg.	3.78 ml

TEST 6

PREPUMP BASELINE RATE	130.74 / MIN	496.33 / MIN	$\frac{157.10}{92.99}$ mm. Hg.	3.79 ml
PUMP RATE	136.00 / MIN	370.73 / MIN	$\frac{139.36}{86.62}$ mm. Hg.	2.72 ml
POSTPUMP BASELINE RATE	133.41 / MIN	495.42 / MIN	$\frac{158.36}{94.35}$ mm. Hg.	3.71 ml

TEST 7

PREPUMP BASELINE RATE	132.63 / MIN	494.93 / MIN	$\frac{160.89}{97.30}$ mm. Hg.	3.73 ml
PUMP RATE	148.50 / MIN	412.10 / MIN	$\frac{173.30}{114.23}$ mm. Hg.	2.77 ml
POSTPUMP BASELINE RATE	144.00 / MIN	536.76 / MIN	$\frac{168.93}{121.56}$ mm. Hg.	3.72 ml

TEST 8

PREPUMP BASELINE RATE	130.74 / MIN	462.56 / MIN	$\frac{133.60}{79.61}$ mm. Hg.	3.53 ml
PUMP RATE	133.41 / MIN	399.79 / MIN	$\frac{142.18}{85.34}$ mm. Hg.	2.99 ml
POSTPUMP BASELINE RATE	126.71 / MIN	472.72 / MIN	$\frac{157.82}{93.73}$ mm. Hg.	3.73 ml

FIG. 41

PNEUMATIC TOURNIQUETS PRIMATE NUMBER 7

TEST 1

	HEART RATE	CARDIAC OUTPUT	BLOOD PRESSURE	STROKE VOLUME
PREPUMP BASELINE RATE	164.00/MIN	810.30/MIN	$\frac{177.27}{87.35}$ mm. Hg.	4.94 ml
PUMP RATE	178.00/MIN	642.52/MIN	$\frac{206.72}{107.39}$ mm. Hg.	3.60 ml
POSTPUMP BASELINE RATE	172.00/MIN	710.34/MIN	$\frac{216.30}{111.02}$ mm. Hg.	4.12 ml

TEST 2

PREPUMP BASELINE RATE	174.00/MIN	706.99/MIN	$\frac{218.68}{115.19}$ mm. Hg.	4.06 ml
PUMP RATE	180.00/MIN	586.45/MIN	$\frac{213.07}{114.00}$ mm. Hg.	3.25 ml
POSTPUMP BASELINE RATE	170.00/MIN	706.05/MIN	$\frac{210.23}{107.31}$ mm. Hg.	4.15 ml

TEST 3

PREPUMP BASELINE RATE	164.00/MIN	567.84/MIN	$\frac{198.85}{108.01}$ mm. Hg.	3.46 ml
PUMP RATE	172.42/MIN	574.35/MIN	$\frac{211.29}{121.50}$ mm. Hg.	3.33 ml
POSTPUMP BASELINE RATE	154.59/MIN	663.29/MIN	$\frac{193.28}{99.86}$ mm. Hg.	4.29 ml

TEST 4

PREPUMP BASELINE RATE	172.00/MIN	637.32/MIN	$\frac{232.62}{119.43}$ mm. Hg.	3.70 ml
PUMP RATE	177.88/MIN	585.52/MIN	$\frac{236.88}{119.69}$ mm. Hg.	3.29 ml
POSTPUMP BASELINE RATE	176.21/MIN	726.84/MIN	$\frac{233.46}{119.64}$ mm. Hg.	4.12 ml

FIG. 42

PNEUMATIC TOURNIQUETS PRIMATE NUMBER 7

TEST 5

	HEART RATE	CARDIAC OUTPUT	BLOOD PRESSURE	STROKE VOLUME
PREPUMP BASELINE RATE	152.47 / MIN	608.65 / MIN	$\frac{216.07}{114.19}$ mm. Hg.	3.99 ml
PUMP RATE	153.47 / MIN	494.10 / MIN	$\frac{203.23}{107.31}$ mm. Hg.	3.21 ml
POSTPUMP BASELINE RATE	138.00 / MIN	606.64 / MIN	$\frac{210.23}{114.00}$ mm. Hg.	4.39 ml

TEST 6

PREPUMP BASELINE RATE	184.00 / MIN	609.22 / MIN	$\frac{204.15}{91.73}$ mm. Hg.	3.31 ml
PUMP RATE	181.89 / MIN	607.10 / MIN	$\frac{203.87}{84.77}$ mm. Hg.	3.33 ml
POSTPUMP BASELINE RATE	172.42 / MIN	699.36 / MIN	$\frac{205.19}{97.07}$ mm. Hg.	4.05 ml

TEST 7

PREPUMP BASELINE RATE	172.42 / MIN	519.43 / MIN	$\frac{207.27}{98.53}$ mm. Hg.	3.01 ml
PUMP RATE	170.00 / MIN	494.69 / MIN	$\frac{213.38}{101.04}$ mm. Hg.	2.90 ml
POSTPUMP BASELINE RATE	158.00 / MIN	576.49 / MIN	$\frac{214.55}{106.29}$ mm. Hg.	3.64 ml

TEST 8

PREPUMP BASELINE RATE	159.16 / MIN	618.45 / MIN	$\frac{200.91}{97.10}$ mm. Hg.	3.88 ml
PUMP RATE	178.10 / MIN	518.24 / MIN	$\frac{207.49}{95.36}$ mm. Hg.	2.90 ml
POSTPUMP BASELINE RATE	174.32 / MIN	695.61 / MIN	$\frac{198.28}{87.35}$ mm. Hg.	3.99 ml

FIG. 43

The data was collected in analog form on magnetic tape, converted to digital by an A to D converter, and processed through a CDC Model 6400 computer. Results are displayed in digital form for each parameter. Significance is evident in heart rate, cardiac output and stroke volume. Each of these parameter measurements followed not only a set pattern but were repeatable through eight different testing experiments. Heart rate increased, cardiac output decreased and stroke volume decreased each time blood was pooled in the extremities by activating the pulsating pneumatic tourniquets. Blood pressures did not show any pattern, trend or consistency. In some tests both the systolic and diastolic pressures were elevated by the action of the tourniquets. In other cases there was a spread or a narrowing between systolic and diastolic pressures. There was no significance therefore given blood pressure as a measurable parameter. Four primates were carried for 8 experiments each for a total of 32 tests.

DISCUSSION

In man, efficient reflex circulatory mechanisms respond to hydrostatic pressure gradients produced by gravity. This pressure influence acts as a stimulus to the circulatory system to assure adequate blood supply to all areas despite changes in posture. A weightless environment produces no gravity and thus no hydrostatic pressure effects that demand circulatory reflex regulation. Loss of cardiovascular adaptability, due to weightlessness has been well

documented by aerospace physiologists and verified by both astronauts and cosmonauts. With prolonged space flights and exposure to longer periods of weightlessness, the problem of cardiovascular adaptability becomes increasingly important to meet the sudden stresses of reentry, landing and readjusting to earth's constant gravity influence. Some means of maintaining cardiovascular adaptability during weightlessness is therefore most essential.

Despite programs of exercise that keeps the skeletal muscles in tone, cardiovascular reflex adaptability responds principally to stimuli of hydrostatic pressures imposed on the circulatory system. When loss of hydrostatic pressure influences exist, reflex control of circulation deteriorates from disuse. In the experiments described using sub-human primates (because of their conformation being more similar to man), three different methods were tested to increase peripheral venous pressure, decrease venous return to the heart and thus, in effect, create a mechanical hydrostatic pressure gradient that would trigger the compensatory reflex mechanisms of the cardiovascular system. Periodic and systematic triggering of these mechanisms facilitates and maintains the tone integrity of the heart so that adaptability is preserved.

The use of tourniquet type devices to occlude the venous return of blood from the limbs to the heart were tested, not only for their efficiency of occlusion but for patient comfort during their application. By intermittent inflation and deflation of a double set of tourniquets coupled to a pulsator, the venous return was obstructed, peripheral

venous pressure was increased as evidenced by dilated surface veins and blood was pooled in the extremities. Hydrostatic pressure effects were simulated and the cardiovascular system responded by the changes in the parameters of heart rate, cardiac output and stroke volume. The venous occluding cuffs were inflated to a pressure sufficient to occlude venous return but not great enough to preclude arterial flow into the extremities. The pulsation cycle was 3 minutes with an 8 second overlap during which both cuffs were inflated before one released (cuff #1, on for 1 1/2 minutes [8 seconds both on] then #1 deflated, repeated for cuff #2.)

This type of cardiovascular exerciser could be readily built into space suits and activated by plug-in or turn-on switching. It is most probable that cardiovascular conditioning could be programmed to coincide with the rest periods of astronauts without interference with their duty cycles. The frequency and exposure period with such a device is another series of animal experiments that should be conducted in a laboratory such as Sky Lab. If these results prove consistent and efficient, then the system should be considered for application of human space travelers.

SUMMARY

Exercisers for the musculoskeletal system, although important to astronauts, will not maintain cardiovascular adaptability which responds to hydrostatic pressure stimuli.

Simulating hydrostatic pressure effects that trigger cardiovascular reflex mechanisms, was accomplished by applying pulsating pneumatic tourniquets to the arms and legs of sub-human primates. The amount of stimulation to the cardiovascular system was measured and recorded as changes in heart rate, cardiac output and stroke volume.

Additional research in a weightless environment now needs to be accomplished. Optimum pressures under which the pulsating tourniquets will best challenge the cardiovascular system; the amount of time each individual animal or astronaut must be challenged to keep circulatory dynamics as near normal as possible and many other related aspects germane to maintaining cardiovascular adaptability, must be studied in space under actual weightless conditions.

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