The University of Texas
M. D. ANDERSON HOSPITAL AND TUMOR INSTITUTE AT HOUSTON
Department of Biomathematics
Section of Bioengineering

A CARDIOVASCULAR SYSTEM MODEL FOR LOWER-BODY NEGATIVE PRESSURE RESPONSE

FINAL REPORT

Prepared Under Contract NAS 9-11119

by

Baker A. Mitchell, Jr.
Chief, Section of Bioengineering

and

Robert P. Giese

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

September, 1971

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1. INTRODUCTION

One method for studying complex physiological control systems is through the use of mathematical modeling. This approach permits investigators to identify gaps in present knowledge of a subject as well as permitting a basis upon which to place new findings. The ultimate goal of these simulation systems is to provide a source of predictions for those situations when costly and timely research is prohibitive. Therefore, this type of effort finds wide application in dealing with physiological problems and space flight.

The purpose of this effort was to modify, for lower-body negative pressure studies, a mathematical model of the cardiovascular system which this contractor has previously developed. Since the mathematical model was about twice as large as the capacity of the EAI 680 computer available, an all-digital computer model was written for installation on the Univac 1108. This all-digital computer model was specifically written to allow orderly, straightforward expansion to include exercise, metabolism (thermal stress), respiration, and other body functions, the accuracy of which are highly dependent on a good cardiovascular fluid dynamics model.

2. TERMINOLOGY

Since the word Model is so ambiguous, an explanation of its usage in this paper is in order.

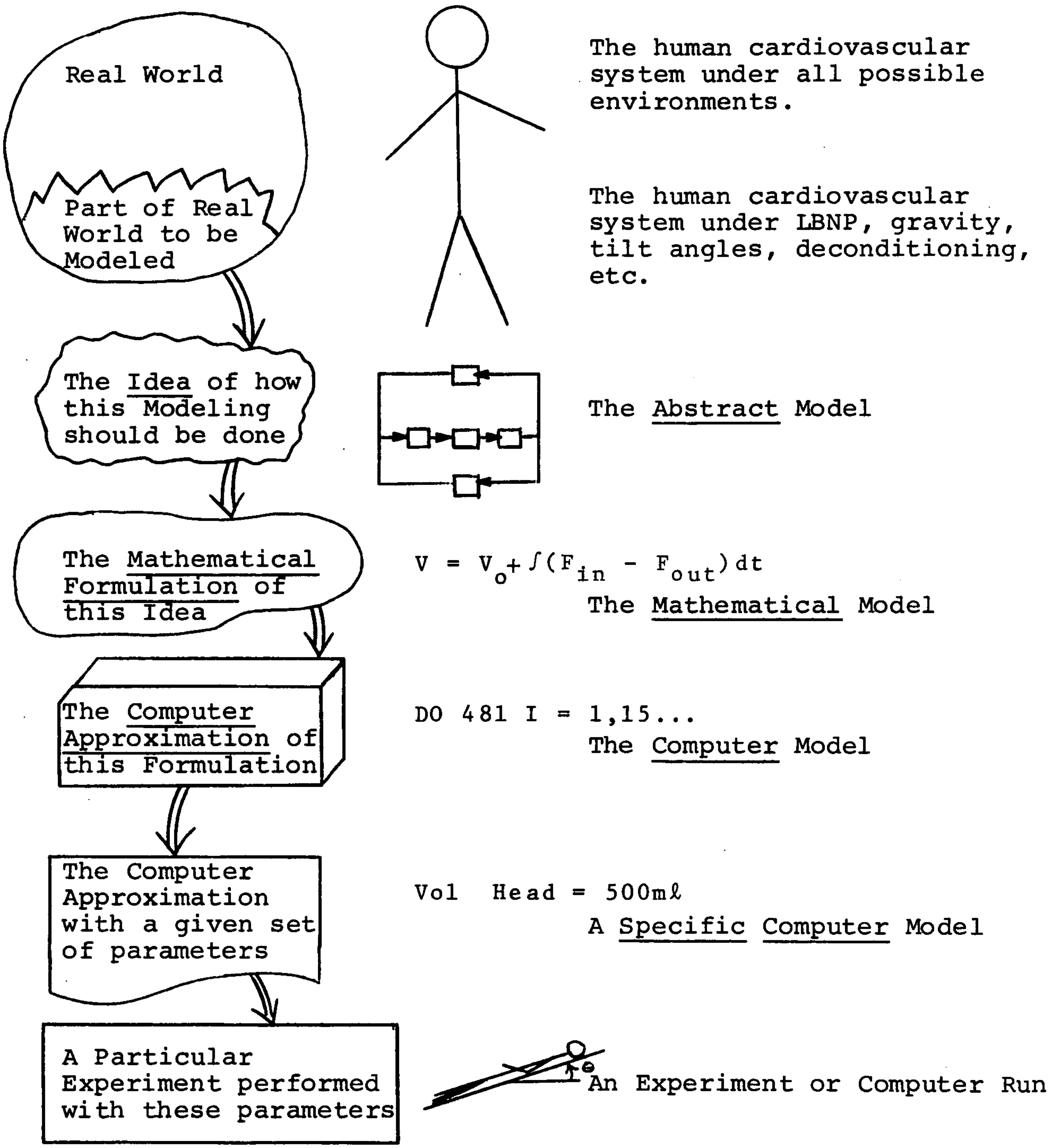


Figure 1a

Figure 1b

Figure 1a represents the modeling process in general. Each step is a further abstraction of the step above. Figure 1b represents the corresponding steps in the cardiovascular modeling project. Whenever the word model is used in a place that could be ambiguous, the appropriate modifier abstract, mathematical, computer or specific computer will be used.

3. THE HUMAN CARDIOVASCULAR SYSTEM

We cannot hope to model every function of the human cardiovascular system. We can, however, choose a sufficiently large subset of its functions so that certain experiments on the model will be predictive of the behavior observed when the same experiment is performed on the human being.

4. THE PART OF THE CARDIOVASCULAR SYSTEM MODELED

Only the relatively short term changes of the cardiovascular system are to be modeled. There are longer time constants not accounted for, such as:

A. Vena Cava stress relaxation with time constant in the order of 12 minutes.

B. Intravascular and extravascular fluid shifts with time constants of the order of 90 minutes.

C. Metabolic and biochemical stress with various time constants.

5. THE ABSTRACT MODEL

The abstract model configuration is shown in figure 2. It attempts to match the behavior of the fluid dynamics of the following anatomical elements. The number associated with each element is the same as is used in the computer model to follow.

A. Fluid Compartments

1. Heart Chambers

    8. Right Ventricle

    11. Left Atrium

    12. Left Ventricle

2. Aorta

    13. Ascending

    14. Carotid

    15. Thoracic

3. Other Fluid Compartments

    1. Head

    2. Arms

    3. Trunk

    4. Kidney

    5. Gut

    6. Legs

    7. Vena Cava

9. Right Lung

10. Left Lung

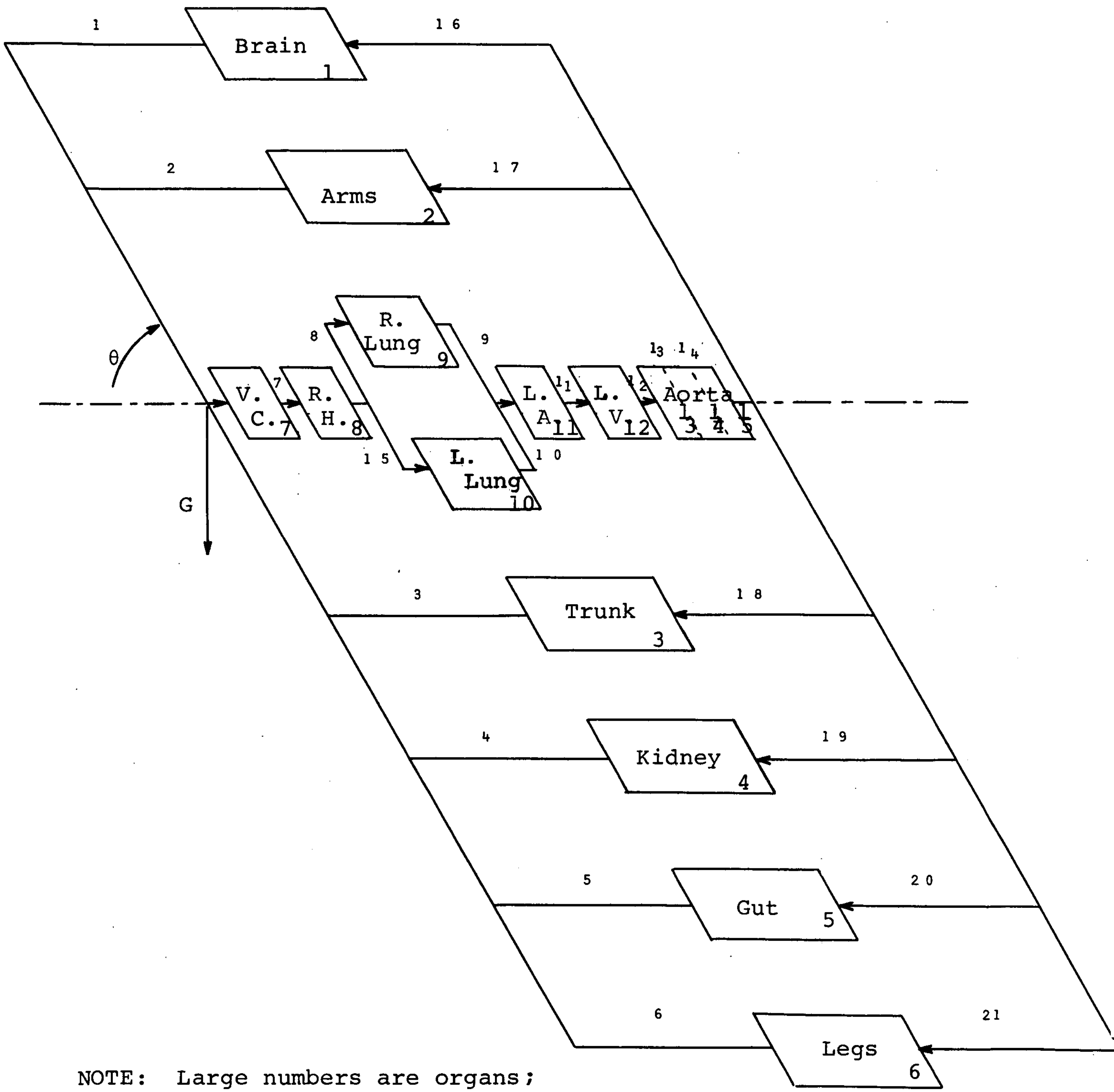
B. Other Active Elements

1. Carotid Baroreceptor

2. Cardiac Pacemaker

Figure 2

ABSTRACT MODEL



NOTE: Large numbers are organs;
Small numbers are flow paths.

This abstract model considers the cardiovascular system to consist of 15 separate compartments with the 21 associated flow paths interconnecting them as in figure 2. All of the body or model fluid is considered to be in these 15 compartments, and no blood loss (bleeding) or intra-vascular or extra-vascular fluid shifts are considered. Since respiration and energy usage are not explicit in this model, there is no oxygen and CO_2 content of the blood considered. Thus, heart rate for the model is entirely determined by pressure in the second aortic chamber (baroreceptor), and not secondarily by O_2 and CO_2 concentration at chemoreceptor sites as is the case in the real world.

Since only one pressure is associated with each compartment, some simplifications are necessary. For example, while one pressure is sufficient in the description of a heart chamber or a section of the aorta, it is not totally sufficient in the description of the legs, head, etc. Thus, the pressure computed is that in the arterioles supplying those organs. This convention will be especially useful for future secondary control of heart rate by O_2 and CO_2 and for regulating of blood flow by the various organs.

6. THE MATHEMATICAL MODEL

The equations which describe certain aspects of the behavior of each compartment of the abstract model will be described along with the behavior characteristics pertinent to the simulation. Symbols, units, and expressions for physiological constants are all contained in the appendix.

A. General Fluid Compartments

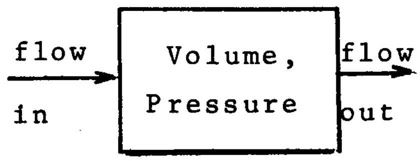


Figure 3a

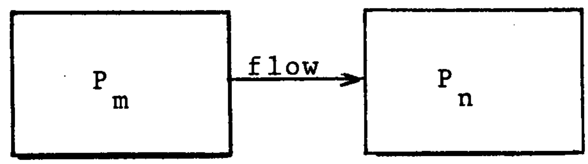


Figure 3b

Figure 3 illustrates the basic equations for flow, pressure and volume.

1) $V = V_0 + \int (F_{in} - F_{out})\,dt$ *

2) $P = \frac{V}{C} - P_r$

3) $F = \frac{P_m - P_n}{R_{m,n}}$

If gravity is considered these become:

4) $P = \frac{V}{C} - P_r + G$;

5) $F = \frac{P_m - P_n - G}{R_{m,n}}$.

*See Appendix V for a description of these symbols.

Equation 5) can be further refined to consider the inertia of the blood by using the following relationship from Mitchell, converted here to our notation:

6) $$P_m - P_n = R_{m,n} * F + L * \frac{dF}{dt} ,$$ which becomes after adding gravity,

$$P_m - P_n - G = R_{m,n} * F + L * \frac{dF}{dt} \qquad \text{or,}$$

$$F * R_{m,n} = P_m - P_n - G - L \frac{dF}{dt} \qquad \text{or,}$$

7) $$F = \frac{P_m - P_n - G - L \frac{dF}{dt}}{R_{m,n}} .$$

Thus, equations 1), 4), and 7) become the basic equations of the model. Equation 1) maintains fluid mass conservation in the compartments. Equation 4) describes the pressure - volume relationship of the tissue mass forming the organ, and equation 7) is the classical pressure-flow relationship considering gravity and inertia.

B. Heart Chambers

Heart chambers are described by equations 1), 4), and 7), with C and R as variables. Varying C as a function of time to simulate "pumping" has become common practice and seems to yield qualitatively satisfactory results.

$$8) \quad C = C(t)$$

Resistance of a valve is determined by the direction of flow through the valve.

$$9) \quad R(F) = \begin{cases} R & F \geq 0 \\ \infty & F < 0 \end{cases} \quad \text{for perfect valve.}$$

All heart chambers are governed by equations 1), 4), 7), 8), and 9), with the appropriate values of R and C(t) for each chamber being determined empirically.

<u>Aorta</u>

Beginning with the stress-strain relationship for a thin-wall cylinder:

$$10) \quad P\frac{\delta}{r} = E\frac{\Delta r}{r} \quad ,$$

the following equation governing incompressible fluid flow in elastic tubes may be derived:

$$11) \quad P = E_s(A - A_0) + G + \frac{Ed}{A} \frac{dA}{dt} \quad ,$$

where E_s is static elasticity and Ed is dynamic elasticity. The derivation of their equation is found in appendix I.

Note that 11) is simply 4) with the addition of dynamic term (Ed/A) * dA/dt.

Equation 1) for conservation of mass and equation 7) for pressure versus flow together with 11) complete the description of the aorta.

The aorta was discretized into three 10cm segments and the constants in equations 1) and 7) were calculated accordingly.

Carotid Baroreceptor

The vagus nerve impulse rate is related to aortic wall strain which may be obtained from equation 11). The exact nature of the transfer function between wall strain and impulse rate is presently under investigation.

Cardiac Pacemaker

Again, exact relationships which are physiologically justifiable are presently lacking. Here again "empirical curve fitting" is a more apt description than is the word simulation.

External Forces

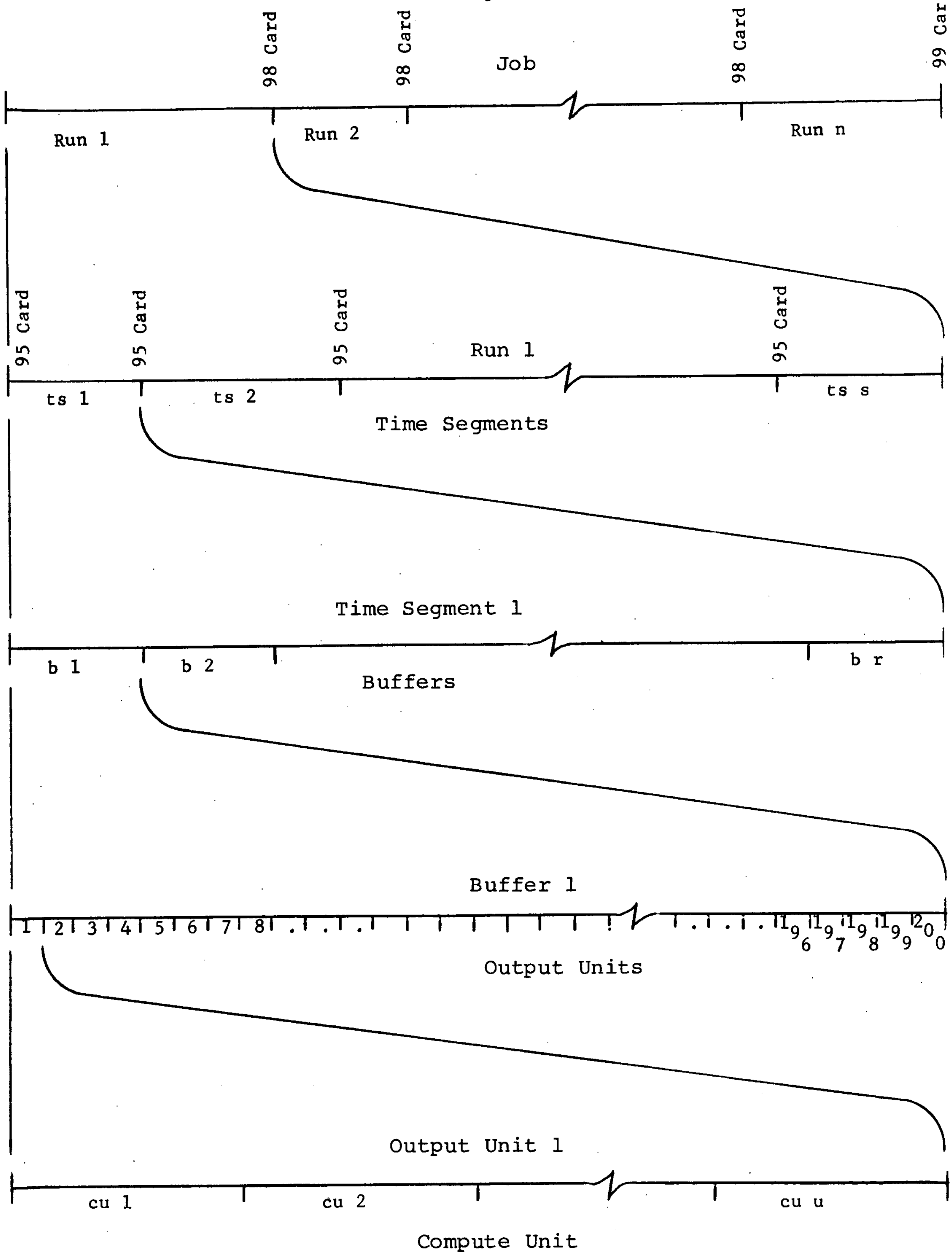
Hydrostatic pressures are added to all fluid compartments; the heights of the pressure heads are based on the body being in a straight posture. Additional acceleration terms may be easily added.

7. THE COMPUTER MODEL

A. Program Design

The LBNP Program is structured in levels of activities, most of which are nested as shown in figure 3. A computer job is a complete unit and may contain one or more runs. Each run is self contained, but is broken down into one or more time segments. The time segments represent intervals of time during which the model is using a fixed set of parameters. Body parameters such as resistance, LBNP, compliance, etc., may only be changed between time segments. Thus, to simulate an experiment, several time segments, or even several runs, may be required. Each time segment contains one or more buffers of 200 sets of output variables. For example, if 100 sets of output variables per second were desired, then the length of a buffer would correspond to two seconds of model time. Each time segment must then be an even number of seconds, and there will be $\frac{t}{2}$ buffers in a time segment of length t. As mentioned above, there are always exactly 200 output units in a buffer. Each output unit contains one or more compute units. In general, the stepsize Δt between compute units is considerably smaller than the resolution of the output device.

Figure 3


98 Card
98 Card
Job
98 Card
99 Car
Run 1
Run 2
Run n
95 Card
95 Card
95 Card
Run 1
95 Card
ts 1
ts 2
ts s
Time Segments
Time Segment 1
b 1
b 2
b r
Buffers
Buffer 1
1 2 3 4 5 6 7 8 . . . 196 197 198 199 200
Output Units
Output Unit 1
cu 1
cu 2
cu u
Compute Unit

The above levels of activity are all nested as shown in figure 3. There is one activity that does not nest with these other units; i.e., the cardiac cycle. The heart begins to beat at time=0 with the beginning of atrial contraction. Since there is essentially a continuum of heart rates, and heart rate may change after each beat, there is no assurance that the beginning of any heart beat except the first will coincide with the beginning of any other time segment, buffer, output unit, or even a compute unit. Thus, the cardiac cycle can not nest with the other units since it is not properly contained in any other unit, nor does it properly contain any other unit. *

B. Subcomponent Detail

For clarity, the subcomponent description will begin with the innermost level of activity and work outward.

1. The Compute Cycle

The compute cycle is controlled by an internal "clock" which runs continuously for each submitted job. This clock is represented internally by several variables within the program to insure: 1) no floating point found off or "drift"; 2) no integer overflow or "involuntary resetting"; 3) accurate subdivision as small time units to insure accurate integration; 4) separate timing of each heart beat

*See Appendix III for flowcharts.

so that no parameter change can occur in the middle of a heart beat. This "clock" may seem more complex than necessary, but each part is necessary to insure 1) and 4). Both integer and real variables are used, and the basic units of the clock are seconds and milliseconds. In addition, many variables that are used often in the program such as $\frac{1}{\Delta t}$, $\frac{1}{2*\Delta t}$, Δt, $2*\Delta t$, are pre-computed to minimize computation time and to use multiplication whenever possible instead of division. In-line comments in the program define both the working of the "clock" and the units of these associated variables.

The compute cycle as flowcharted in Appendix III uses the equations:

1) $$V = V_0 + \int (F_{in} - F_{out})dt \quad ,$$

2) $$P = \frac{V}{C} - P_r + G \quad ,$$

and

7) $$F = \frac{P_m - P_n - G - L\frac{dF}{dt}}{R_{m,n}} \quad ,$$

along with the associated equation of the heart and aorta stated previously, to compute new valves for each V, P, and F, from the values of the last compute step. *

*Derivation of Aortic pressure volume equations is found in Appendix I.

In equation 4) the value of C is a function of time for the heart chambers to simulate pumping. For the other organs, C is actually a function of volume; although it is often considered a constant for small volume changes. Computation speed was increased considerably by writing a FORTRAN function that returns a value of P for a given volume. In the function C, the value of P is computed by linear interpolation of a table of five pairs of values of F and V.

Equation 7) is restated as follows:

$$F = \frac{P_m - P_n - G - L\,\frac{dF}{dt}}{R_{m,n}} \quad ;$$

Substituting: $\dfrac{\overset{n}{F}\ \overset{n-1}{F}}{\Delta t}$ for $\dfrac{dF}{dt}$,

$$\overset{n}{F} = \frac{P_m - P_n - G - L\,\dfrac{\overset{n}{F} - \overset{n-1}{F}}{\Delta t}}{R_{m,n}} \quad ;$$

Rearranging:

$$R_{m,n}\overset{n}{F} = P_m - P_n - G - \frac{L}{\Delta t}\overset{n}{F} + \frac{L}{\Delta t}\overset{n-1}{F} \quad ,$$

$$R_{m,n}\overset{n}{F} + \frac{L}{\Delta t}\overset{n}{F} = P_m - P_n - G + \frac{L\overset{n-1}{F}}{\Delta t} ,$$

$$\overset{n}{F} = \frac{P_m - P_n - G + \frac{L\overset{n-1}{F}}{\Delta t}}{(R_{m,n} + \frac{L}{\Delta t})} .$$

This last formula turned out to be acceptable in actual computation.

All variables are computed in standard medical units. Several subroutines are included with the program to convert between scientific and medical units if this becomes desirable. A symbol table and list of included functions and subroutines are included with this report. In-line comments in both the calling program and the subprogram explain the use of each subprogram.

Valves were placed in the same flow paths as in the human body. A valve simply prevents reverse flow through a flow path. The valves in this program are "perfect" in the sense that they allow no back flow in closing. Similiarly, all volumes are constrained to be positive. If the computed flow is found to drive a volume negative, the volume is set to zero and the flow recomputed.

Stepsize can be a critical factor in this program, especially if relatively unrealistic body constants are used. In general, 200 steps per second are sufficient, and in most cases the results are indistinguishable from a higher compute frequency. In varying only stepsize, the most striking difference between 200 and 3200 steps per second is that in the latter case the compliance function of the heart is more nearly correct. This yields a slightly more efficient heart, resulting in about four beats per minute decrease in heart rate. If a stepsize is too large because of a compute frequency of 100 or less, then a cyclic ringing often occurs in the aorta. This will be especially evident with larger than realistic flow rates in the aorta, very high cardio-vascular output, or larger than real-life inertia term for the blood flow. To some extent this ringing can be artificially dampened by introducing a more elastic aorta using a different compliance curve or by increasing the inertia term on the aorta wall. However, using a higher compute frequency, and thus smaller stepsize, is probably the most accurate way of handling this difficulty. Note, however, that over 90% of the executive time of this program is within this loop, so doubling compute frequency nearly doubles running time. Thus, the indiscriminate use of a very high compute frequency to eliminate any chance of this ringing will use up large amounts of computer time.

2. The Output Cycle

Since the desired compute frequency may not be the same as the desired display frequency, the program allows the user to specify an output frequency different from the chosen compute frequency.

To simplify the program we require that the output frequency be an integer power to two times the buffer size of 200. Thus, acceptable output frequencies are ---, 50, 100, 200, 400, ---, points per second. Output frequency should always be adjusted considering the resolution of the output device. Compute frequency must always be a non-negative, power-of-two multiple of the output frequency. Thus, for a frequency of 100, a compute frequency should be 100, 200, 400, ---. In many cases it is desirable to have a relatively small output frequency (such as 50) and a relatively large compute frequency (such as 400).

3. The Output Buffer

All 51 output values of pressure, volume, and flow terms are stored in a 51 x 200 output buffer, and are output to magnetic tape as a single unit. This allows for: 1) separation of compute logic from graphical output logic so that graphical output units may be changed at any time with a minimum of effort; 2) the display of as many or as few output parameters as is desired; 3) re-play of a job utilizing different scaling factors or outputting different variables without the overhead of re-running the entire compute program; 4) minimize core requirement of the program without using an overlay structure.

The current value of each of the 10 derived variables are also written out at the end of this 51 x 200 buffer. The computation of these variables is discussed in the following section.

After each buffer is written to tape, a check for constant blood volume is performed. This check is made for accumulated truncation and round-off errors; and the excess or shortage of blood in the entire system is distributed over all 15 organs in the same proportion as the original blood volume in those organs. For example, if there is a 1mℓ excess in a 5000mℓ system where the arms originally contained 500mℓ of blood, then the arms would loose 0.1mℓ of excess blood. The total blood volume before each update is printed on the computer listing. In most cases, the accumulated error at time of update is about 1 or 2mℓ, or considerably less than 0.1%.

4. Cardiac Cycle

Circulation is produced in the model in the following manner. For the pressure formula of the heart chamber, $P = \frac{V}{C} - P_r + G$, the compliance, C, is a function of time. The following flow diagram illustrates the logic that determines the heart rate (figure 4).

Note that in all cases the heart is allowed to complete its current beat before starting the next beat. The maximum rate allowed with this model is 180 beats per minute, since above that point the heart does not fill rapidly enough and stroke volume is decreased to the point that cardiovascular output drops beyond that point.

No minimum heart rate is imposed on the model, except that no negative rate is allowed. Under some

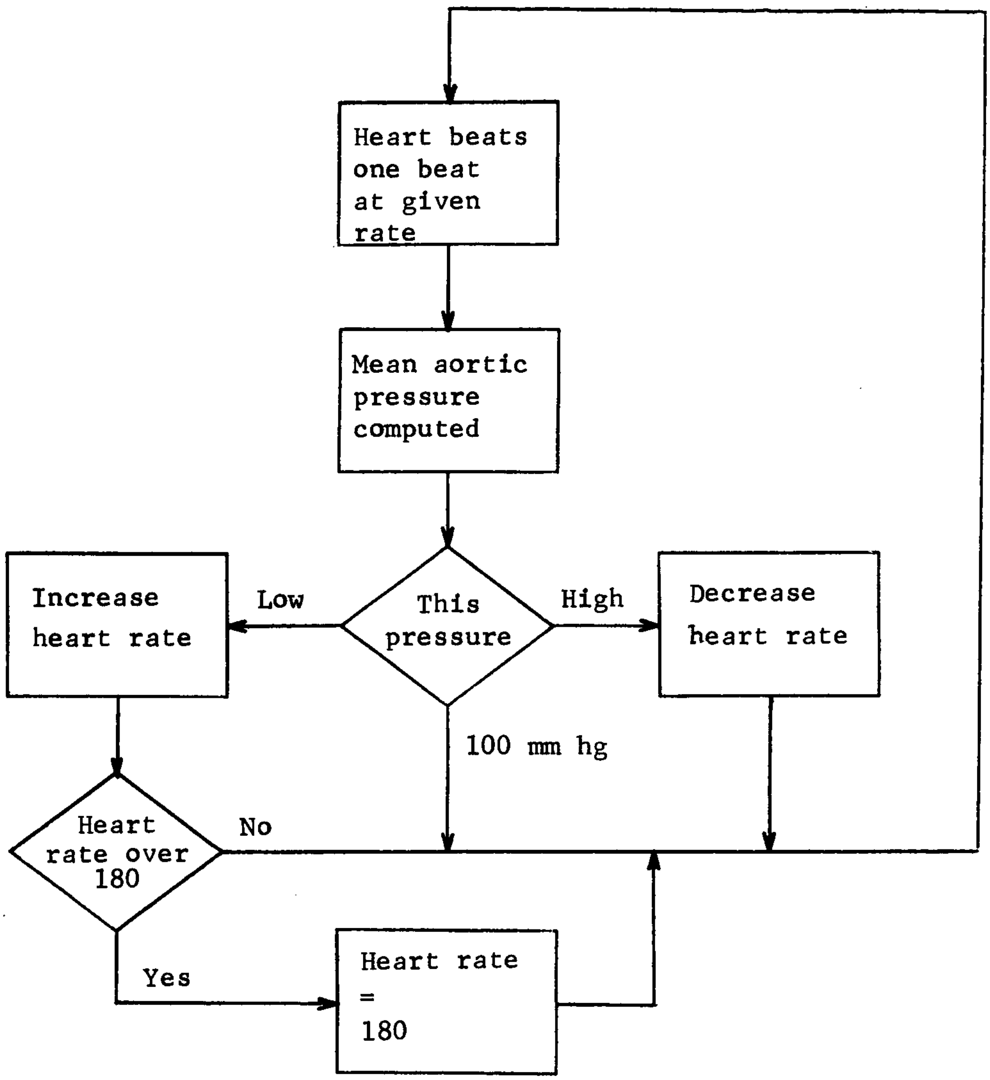

Heart beats one beat at given rate
Mean aortic pressure computed
Increase heart rate
Low
This pressure
High
Decrease heart rate
100 mm hg
Heart rate over 180
No
Yes
Heart rate = 180

Figure 4

gravity conditions with certain body angles the heart can be made to stop. This is physiologically as correct as is possible without carrying oxygen and CO_2 content to the blood.

5. Derived Variables

Systolic, diastolic, and mean aortic pressure are computed in the following manner. The heart rate is converted to number of compute steps per beat. Then the heart is allowed to complete a beat with that number of compute steps. For example, if we have 200 steps per second compute rate and a heart rate of 60 beats per minute, this one beat is 200 steps. Pressures are computed as follows:

$$\text{Systolic pressure} = \max_{i=1}^{n} \text{(Pressure at step i);}$$

$$\text{Average pressure} = \frac{\sum_{i=1}^{n} \text{(Pressure at step i);}}{n}$$

$$\text{Diastolic pressure} = \min_{i=1}^{n} \text{(Pressure at step i);}$$

where pressures are measured in the second 10cm of the aorta (P_{14} in the notation of the computer model). *

*See Appendix II for description of computer variables.

6. Time Segments

A time segment is the basic interval of the program used for specifying a sequence of events in simulating an experiment. Since there is no requirement for this all-digital program to be run real-time as in the case of most analog or hybrid models, a system was designed to allow the program user to design an experiment in advance of the computer run, in much the same way as a programmer lays out the logic of his computer program.

Each time segment is preceded by the reading of any number of parameter cards to define a physiological personality and the external forces to be applied to the model. When a "time card"

```
95      20.
```

such as the above example is read, the time segment will start and will run for the designated number of seconds. At the end of that time segment, new parameter cards are read until another "time card" is read.

Since a parameter change can affect the heart compliance, there is a delay factor in the time segment loop that will not use the new parameters until the beginning of the first complete heart beat within the time segment. Note that each time segment is exactly the length specified on the "time card", and no error accumulates because of this delay.

7. Runs

Each run may simulate an individual experiment or portion of an experiment. The results of the simulation are then stored on an intermediate magnetic tape, and can then be displayed at any time without requiring the entire simulation to be rerun each time. An example of the use of this feature follows. The user wishes to vary the compliance of one organ (without loss of generality, say the legs) and observe the effects on heart rate and flow to the brain.* He may then display only a few desired variables such as flow to brain, heart rate, and leg volume. He then repeats the simulated experiment several times using the same deck setup until the desired behavior is observed. The user may then want to display all variables requiring several passes from the same intermediate tape without rerunning the entire simulation. Finally, if he is satisfied with the results, he may again play back the intermediate tape and display the parameters at a scale suitable for publication. In this way, the investigator may

*See Appendix IV for a description of compliance cards.

display at ½ sec or 1 sec per inch to show fine details of a wave form, or compress long periods of time into a short space by using a display of 20, 60, or even 600 seconds per inch.

The deck setup for both the experiment and the display is explained in the User's Guide which is enclosed with this report. Full multi-job capability is included in the program for the user who wishes to run several experiments with the same computer job.

C. Input-Output

1. LBNP Program

a. Input

Control cards and deck setup are discussed in the User's Guide.* The entire set of cards that generated the output sample included in the user's guide is also attached to that document. All initial pressures, volumes, compliance, heart rate, resistance, inertia values, body angle, gravity, compute and output frequency, and body dimensions must be input to the program. In general, there are no default options for these parameters. However, since data cards may

*See Appendix VI for User's Guide.

be read into the LBNP Program in any order, and since duplicate cards may be read retaining only the value of the last card, there is an easy way to avoid such omissions. One needs only to input the entire data deck supplied with the program and add modifications at the end of that deck. For example, if more conditioned legs were desired, a second card 6 could be included behind the enclosed deck.

b. Output

All input data constants are output at the beginning of each run. Run number, time segment number, and length of time segment in seconds is output for each time segment. Heart rate, cardiovascular output, systolic, mean, and diastolic pressures are output for each heart beat. For the first time segment of each run, the flow, volume, and pressures 11 through 15 are output in their entirety. This is to allow the user to see accurately computed values of this critical part of the cardiovascular system without waiting for the plot to be returned.

After each output buffer is written out on tape, the following information is output: first line, segment number and total accumulated time within run; next 21 lines, flow, pressure, and volume of the model at the last compute step; last line, total volume in system before automatic volume update.

2. DISPLAY Program

a. Input

The first 62 cards of this deck must be included in the order given for each run. These cards labeled starting with 101 to 411 are scaling factors for all output variables. The hundred's digit of 1 is for flow, 2 is for volume, 3 is for pressure, and 4 is for special output parameters as discussed in the user's guide. The field 5-8 is for starting value of the graph, and field 9-12 is scaling factor of data to plot dimension. Examples of usage are given on the following page.

Field								Minimum	Maximum
5	6	7	8	9	10	11	12	Value	Value
			0		.	0	1	0	100
			0	.	0	0	5	0	200
			0	-	.	0	1	0	-100
		5	0		.	0	1	50	150
		9	0		.	0	5	90	110

Minimum Value is field (5-8)

Maximum Value is field (5-8) + $\frac{1}{\text{field}(9-12)}$

For each job on the intermediate tape to be read by this program, the user must submit cards to indicate what fields are to be displayed, and which vertical and horizontal scaling factors to use. The user's guide explains the necessary format and usage. This display program may be used on either a XDS Sigma 5 computer or a Univac 1108 computer, with either a 12 or a 22 inch plotter. Alteration between these computers and plotters is accomplished by adding a C in column 1 of some program cards, and removing a C in column one of others. In-line comments locate those areas and explains the needed changes. There should be little or no difficulty changing this program to other computers or other size plotters.

b. Output

The complete printer output may be ignored since it contains information of little use to the program user. The output contains only a listing of the values on the scaling cards, plus the value of the parameters G(1) through G(10) for each output buffer. These variables are:

```
G(1) IS LBNP
G(2) IS SYSTOLIC PRESSURE
G(3) IS DIASTOLIC PRESSURE
G(4) IS MEAN BLOOD PRESSURE
G(5) IS HEART RATE
G(6) IS BODY ANGLE
G(7) IS CARDIOVASCULAR OUTPUT
G(8) IS GRAVITY
G(9) TO G(10)  ARE CURRENTLY NOT USED.
```

An example of the plotter output is included in the enclosed user's guide. Up to 20 graphs may be displayed per computer run (up to 40 with a 22 inch plotter). The graphs may be displayed in any order and the time scale is continuously variable. The graphical display is especially easy to read if it is plotted on graph paper divided either 10 divisions per inch or 10 divisions per half inch.

8. THE SPECIFIC COMPUTER MODEL

The set of input data constants and functions that compose the specific computer model are realistic for an 80kg man 180cm in height, in good physicial condition. Total blood volume is just under 5½ liters and cardiovascular output prone and at rest is about 80mℓ/sec, or about 5 liters per minute. A resting heart rate is about 72, and systolic, mean, and diastolic pressures are approximately 140, 100, and 80 respectively.

The distribution of blood in the model is approximately correct; however, it should be calculated more accurately if very close comparison to a particular human subject is desirable. This fixed model responds to G loading and lower body negative pressure in much the same way as a human would for short periods of time. Longer range changes may be simulated by a change of compliance, especially in the legs and vena cava. The exact parameters for this model are given in the user's guide.

9. AN EXPERIMENT

Although a very large number of experiments have been run with this program, only a single experiment is included with this paper.

The experiment involves applying lower body negative pressure to the prone fixed computer model of section 8. Sixteen seconds were allowed for the model to stabilize with zero negative lower body pressure (LBNP). Then - 30, - 40, - 50 mm of mercury were applied for 8 seconds each, followed by a 16 second run at zero LBNP. The deck setup as well as the graphical output is included with the User's Guide.

10. EXAMPLES OF PARAMETER CHANGES *

The user's guide included with this report contains a listing of parameter cards used for the fixed computer model. In this section we illustrate by example various changes in the model.

A. More Conditioned Legs

With better conditioning, the legs are less compliant and will accept less blood upon standing or sitting under gravity stress. The slope of the compliance curve must, therefore, be made smaller as per the following example:

```
OLD CARD
 6      0.     -5.    800.     40.  1000.     80.  1200.    140.  2000.    190.

NEW CARD
 6      0.     -5.    900.     40.  1000.     80.  1100.    140.  1400.    190.
```

*Additional information is available in Appendix VI.

Note that since a nominal pressure in the prone legs of 80 mm of mercury is to be maintained, the curve must pass through the initial leg volume of 80 mm of mercury.

B. Change in Volume of Kidney

Compliance changes must always accompany volume changes unless fluid loss or gain is to be simulated. Suppose we wish to keep the model basically the same, but reduce kidney volume by 50%. The following changes will accomplish the desired result:

```
OLD CARDS
 4     0.    -5.    450.    40.    500.    80.    650.    140.   1000.    190.
24   500.

NEW CARDS
 4     0.    -5.    225.    40.    250.    80.    325.    140.    500.    190.
24   250.
```

C. Fluid Loss in System

The simplest way to simulate fluid loss is to reduce initial volume without changing compliance. While the blood can be removed from any organ, or by taking part of the blood out of all organs, a simple way is to remove the total amount to be depleted from the vena cava. The following illustrates a 150mℓ blood loss:

```
ØLD CARD
27   350.

NEW CARD
27   200.
```

It should be remarked here that since the model does not consider intravascular or extravascular fluid shifts, removal of 100 to 150 mℓ of blood from the model is about equivalent to removal of ½ liter of blood from a human.

D. Increase Flow to Legs to Simulate Exercise

Since $F = \frac{P_1 - P_2}{R}$, we can double flow by halving resistance. The following change will double the flow through the legs. There will, however, be a corresponding rise in cardiovascular output and an increase in heart rate automatically to accomplish the desired change.

```
ØLD CARD
76   6.00.0014

NEW CARD
76   3.00.0014
```

E. Change in Cardiovascular Output without Heart Rate Change or vice versa

These changes require a considerable fine tuning of all organs from the vena cava through the last section of the aorta. Resistances and compliances must be changed together throughout the system, accompanied by inertial changes to maintain realistic flows and especially to maintain the correct amount of back flow in the aorta. No attempt will be given here to explain these changes. They are best accomplished by the trial and error method and had best be made in small amounts. Often a 10% change in value of compliance can be easily seen on a plot, and often a 50% change will cause a mis-balanced system that will no longer operate.

Consulting any good medical physiology textbook will yield considerable insight into the behavior of this model, both in normal and "pathological" modes of operation.

APPENDIX I

DERIVATION OF AORTIC PRESSURE-VOLUME EQUATION

APPENDIX I

DERIVATION OF AORTIC PRESSURE-VOLUME EQUATION

1) $$T = E\frac{\Delta r}{r_o} + \frac{Re}{r_o}\frac{d\Delta r}{dt} = \frac{Pr}{\delta}$$

$$\Delta r = r - r_o$$

2) $$(\frac{E}{r_o})r - E + (\frac{Re}{r_o})\frac{dr}{dt} = \frac{Pr}{\delta}$$

3) $$(\frac{E\delta}{r_o}) - (E\delta)\frac{1}{r} + (\frac{\delta Re}{r_o})\frac{1}{r}\frac{dr}{dt} = P$$

$$A = \pi r^2$$

$$\frac{dr}{dt} = \frac{1}{2\pi r}\frac{dA}{dt}$$

4) $$(\frac{E\delta}{r_o}) - (E\delta)\frac{\pi^{1/2}}{A^{1/2}} + (\frac{\delta Re}{r_o})\frac{1}{2\pi r^2}\frac{dA}{dt} = P$$

5) $$(\frac{E\delta}{r_o})(1-(\frac{Ao}{A})^{1/2}) + (\frac{\delta Re}{2r_o})\frac{1}{A}\frac{dA}{dt} = P$$

By Taylor Series Expansion

6) $$1-(\frac{Ao}{A})^{1/2} = \frac{5}{4}(\frac{A}{A_o} - 1)$$

$$7)\quad \left(\frac{5}{4}\,\frac{E\,\delta}{r_o A_o}\right)(A-A_o) + \left(\frac{\delta Re}{2r_o}\right)\frac{1}{A}\,\frac{dA}{dt} = P$$

or

$$E_s = \frac{5}{4}\,\frac{E\,\delta}{r_o A_o}$$

$$E_d = \frac{\delta Re}{2r_o}$$

$$8)\quad E_s(A-A_o) + E_d\,\frac{1}{A}\,\frac{dA}{dt} = P$$

But, V = A*X where X is length of each section of the aorta. Thus,

$$9)\quad E_s\frac{(V-V_o)}{X} + E_d\,\frac{1}{V}\,\frac{dV}{dt} = P$$

By adding the same gravity term as in basic pressure, equation 4) yields:

$$10)\quad P = E_s * \frac{(V-V_o)}{X} + G + \frac{E_d}{V} * \frac{dV}{dt}$$

APPENDIX II

DESCRIPTION OF VARIABLES USED IN COMPUTER PROGRAM

APPENDIX II
DESCRIPTION OF VARIABLES USED IN COMPUTER PROGRAM

VARIABLE/	UNITS/	NORMAL RANGE/	DESCRIPTION
ADDF	CM**3/SEC	-100 TO 2000	FLOW TEMP STORAGE
AFLO	CM**3/SEC	50 TO 400	HEART FLOW (CARDIAC OUTPUT) TEMP STORAGE
AII	INTEGERS	1 TO 1200	REAL REPRESENTATION OF II
ANGLE	DEGREES	0 TO 90	BODY ANGLE WITH CONVENTION 0 = HORIZONTAL
AOLD	CM**2	10 TO 1000	SURFACE AREA OF BODY NODES
APRS	MM HG	90 TO 110	MEAN BLOOD PRESSURE TEMP STORAGE
ARAD	RADIANS	0 TO 6.28	BODY ANGLE WITH CONVENTION 0 = HORIZONTAL
COMP	VARIOUS	-100 TO 2000	COMPLIANCE TABLE (SEE TEXT FOR DETAILS)
CTIME	SECONDS	0 TO 36000	CURRENT TIME
DADT	CM**2/SEC	-100 TO 100	DERIVATIVE OF AREA WITH RESPECT TO TIME
DELT	SECONDS	0.001 TO 0.01	TIME FOR ONE COMPUTE CYCLE
DHRATE	BEATS/MIN	-20 TO 20	DELTA HEART RATE FOR CONTROL OF HEART
DIAS	MM HG	50 TO 100	DIASTOLIC BLOOD PRESSURE TEMP STORAGE
DIST	CM	-200 TO 200	BODY NODE DISTANCE FROM HEART
DOTO	SECONDS	.0005 TO .005	ONE HALF TIME FOR ONE COMPUTE CYCLE
DTIME	MILLISECONDS	0 TO 1200	TIME WITHIN BEAT
DVDT	CM**3/SEC	-1000 TO 1000	DERIVATIVE OF VOLUME WITH RESPECT TO TIME
EDP	MMHG*SEC**2/CM**3	.4 TO 4	INERTIAL VALUE FOR AORTIC WALLS
ERTIA	MMHG*SEC**2/CM**3	.0005-.002	INERTIAL VALUE FOR BLOOD
ESP	NOT USED IN THIS FORM		STATIC INERTIAL VALUE OF AORTIC WALLS
F	CM**3/SEC	-100TO2000	OUTPUT BUFFER OF VALUES OF FOLD
FI	INTEGERS	10 TO 240	COMPUTE STEPS PER HEART BEAT
FOLD	CM**3/SEC	-100 TO 2000	FLOW BETWEEN BODY NODES
FPRV	CM**3/SEC	-100 TO 2000	PREVIOUS FLOW BETWEEN BODY NODES
FTIME	SECONDS	0 TO 36000	CURRENT TIME TEMP STORAGE
GRAV	G	0 TO 5	GRAVITY FIELD
G(1)	MM HG	-50 TO 50	LOWER BODY PRESSURE, OUTPUT VECTOR
G(2)	MM HG	100 TO 200	SYSTOLIC BLOOD PRESSURE OUTPUT VECTOR
G(3)	MM HG	50 TO 100	DIASTOLIC BLOOD PRESSURE OUTPUT VECTOR
G(4)	MM HG	90 TO 110	MEAN BLOOD PRESSURE OUTPUT VECTOR
G(5)	BEATS/MIN	0 TO 180	HEART RATE OUTPUT VECTOR
G(6)	DEGREES	0 TO 90	BODY ANGLE OUTPUT VECTOR
G(7)	CM**3/SEC	50 TO 400	HEART FLOW (CARDIAC OUTPUT) OUTPUT VECTOR
G(8)	G	0 TO 5	GRAVITY FIELD OUTPUT VECTOR
HAFLO	CM**3/SEC	50 TO 400	HEART FLOW (CARDIAC OUTPUT)
HAPRS	MM HG	90 TO 110	MEAN BLOOD PRESSURE
HDIAS	MM HG	50 TO 100	DIASTOLIC BLOOD PRESSURE
HIGH	CM	-200 TO 200	BODY NODE HEIGHT FROM HEART
HMAX	BEATS/MIN	0 TO 180	MAXIMUM HEART RATE
HMIN	BEATS/MIN	0 TO 180	MINIMUM HEART RATE
HOLD	REAL	ANY	INPUT VECTOR FOR ALL INPUT CONSTANTS
HRATE	BEATS/MIN	0 TO 180	HEART RATE
HSYST	MM HG	100 TO 200	SYSTOLIC BLOOD PRESSURE
HTIME	SECONDS	0.3 TO 1.2	TIME FOR ONE HEART BEAT
I	INTEGER	ANY	LOOP COUNTER
ICOMP	1/SEC	100 TO 1600	COMPUTE FREQUENCY INTEGER
IEC	MILLISECONDS	0 TO 1200	TIME WITHIN BEAT
IETMS	MILLISECONDS	0 TO 1200	BEAT TIME
IFIRST	INTEGERS	1 TO 10000	BUFFER COUNTER
IHOLD	INTEGER	ANY	NUMBER OF PHYSICAL UNIT OF STORAGE TAPE
II	INTEGERS	1 TO 1200	COUNTER FOR COMPUTE LOOP
IN	INTEGER	ANY	NUMBER OF PHYSICAL UNIT OF CARD READER
INDEX	UNITLESS	NONE	NOT CURRENTLY USED
INDX	INTEGER	ANY	INTERMEDIATE VARIABLE

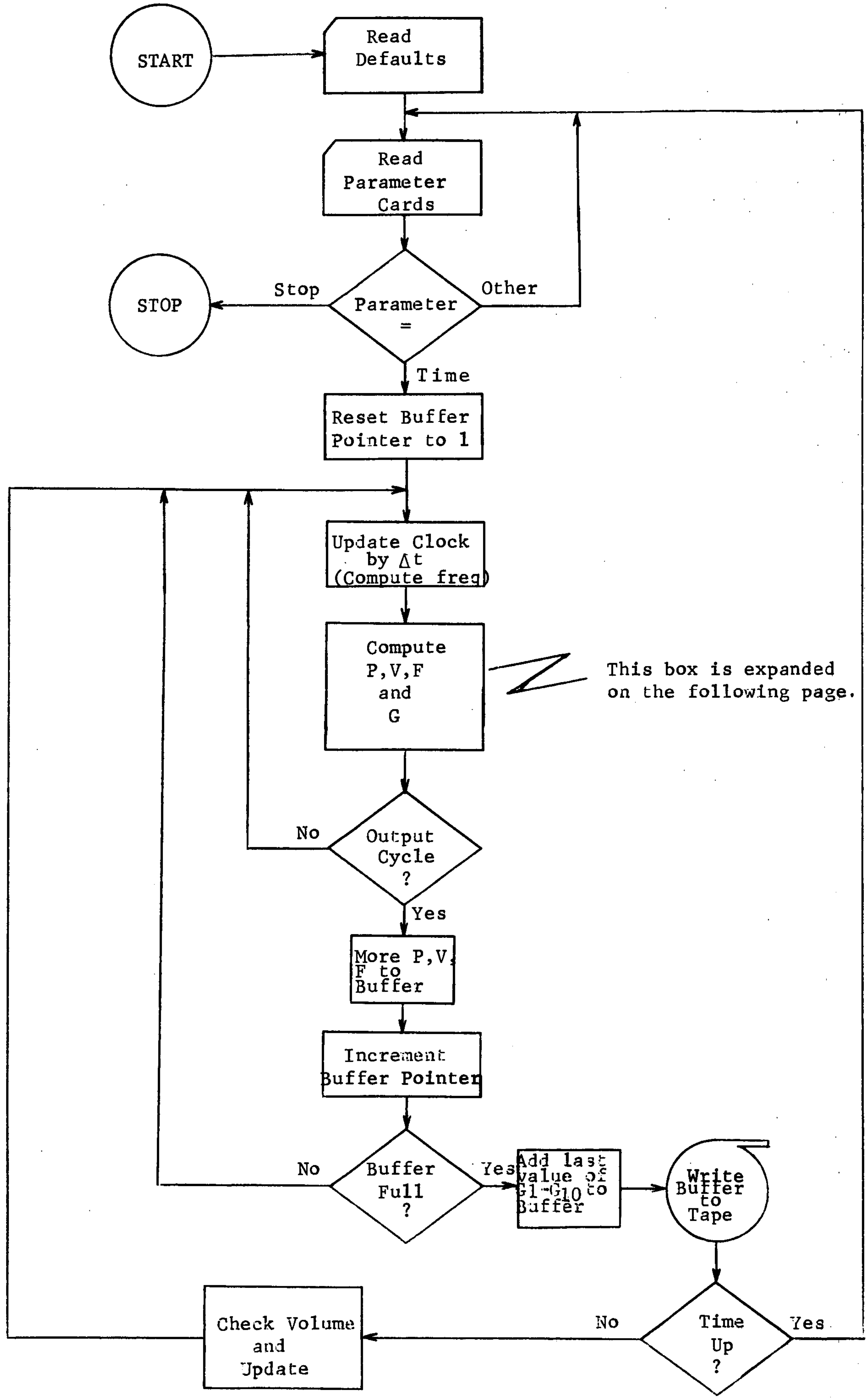
DESCRIPTION OF VARIABLES USED IN COMPUTER PROGRAM(CONTINUED)

VARIABLE/	UNITS/	NORMAL RANGE/	DESCRIPTION
IOTEST	INTEGER	ANY	INTERMEDIATE VARIABLE
IOUT	INTEGER	ANY	NUMBER OF PHYSICAL UNIT OF PRINTER
IOUTF	1/SEC	50 TO 200	OUTPUT FREQUENCY INTEGER
IPRINT	INTEGERS	0 OR 1	PRINT OPTION SWITCH, 0 FOR NO PRINT
IRUN	INTEGERS	ANY	NUMBER OF CURRENT RUN
ISKIP	INTEGERS	1 TO 16	ICOMP/IOUTF
ISTEP	INTEGERS	10 TO 240	COMPUTE STEPS PER HEART BEAT
ITEST	INTEGER	0 TO 99	INTERMEDIATE STORAGE OF INPUT CARD NUMBER
ITIME	MILLISECONDS	300 TO 1200	INTEGER TIME FOR ONE HEART BEAT TEMP
J	INTEGER	ANY	LOOP COUNTER
K	INTEGER	ANY	LOOP COUNTER
LIEC	MILLISECONDS	0 TO 1200	TIME OF END OF BEAT
LOOP	INTEGERS	200 TO 800	COMPUTE STEPS PER OUTPUT BUFFER
N	INTEGER	ANY	TEMP STORAGE FOR INPUT
NTIME	MILLISECONDS	300 TO 1200	INTEGER TIME FOR ONE HEART BEAT
P	MM HG	-5 TO 200	PRESSURE AT NODES, OUTPUT BUFFER
PADJ	MM HG	-5 TO 200	PRESSURE ADJUSTMENT FOR ORGAN HEIGHTS
PLBNP	MM HG	-50 TO 50	LOWER BODY PRESSURE, NEG VALUES HAVE -SIGN
POLD	MM HG	-5 TO 200	PRESSURE AT NODES
PSUBR	MM HG	-5	PRESSURE OF COLLAPSED WALL
RE	MMHG*SEC/CM**3	.0001 TO 10	RESISTANCE TO FLOW BETWEEN NODES
SANG	UNITLESS	-1.0 TO 1.0	SINE OF BODY ANGLE
SINC	1/SEC	100 TO 1600	COMPUTE FREQUENCY
SYST	MM HG	100 TO 200	SYSTOLIC BLOOD PRESSURE TEMP STORAGE
TACC	SECONDS	1 TO 36000	LENGTH OF CURRENT RUN
TEMP	1/SEC	50 TO 200	OUTPUT FREQUENCY
TIME	SECONDS	1 TO 6000	LENGTH OF CURRENT TIME SEGMENT
TINC	SEC	0.1 TO 10	TIME FOR FILLING ONE OUTPUT BUFFER
TNOW	SECONDS	1 TO 36000	CURRENT TIME WITHIN SEGMENT
TOUT	SECONDS	1 TO 36000	OUTPUT VALUE OF CURRENT TIME
TVOL	CM**3	4000 TO 6000	TOTAL VOLUME OF BLOOD
UPDATE	CM**3	-2. TO 2.	ERROR IN BLOOD VOLUME BEFORE UPDATE
V	CM**3	10 TO 2000	OUTPUT BUFFER OF VALUES OF VOLD
VC	CM**3	10 TO 2000	VARIABLE USED FOR VOLUME CHECK
VOLD	CM**3	10 TO 2000	VOLUME OF BODY NODES
VPRV	CM**3	10 TO 2000	VOLUME OF BODY NODES AT LAST STEP

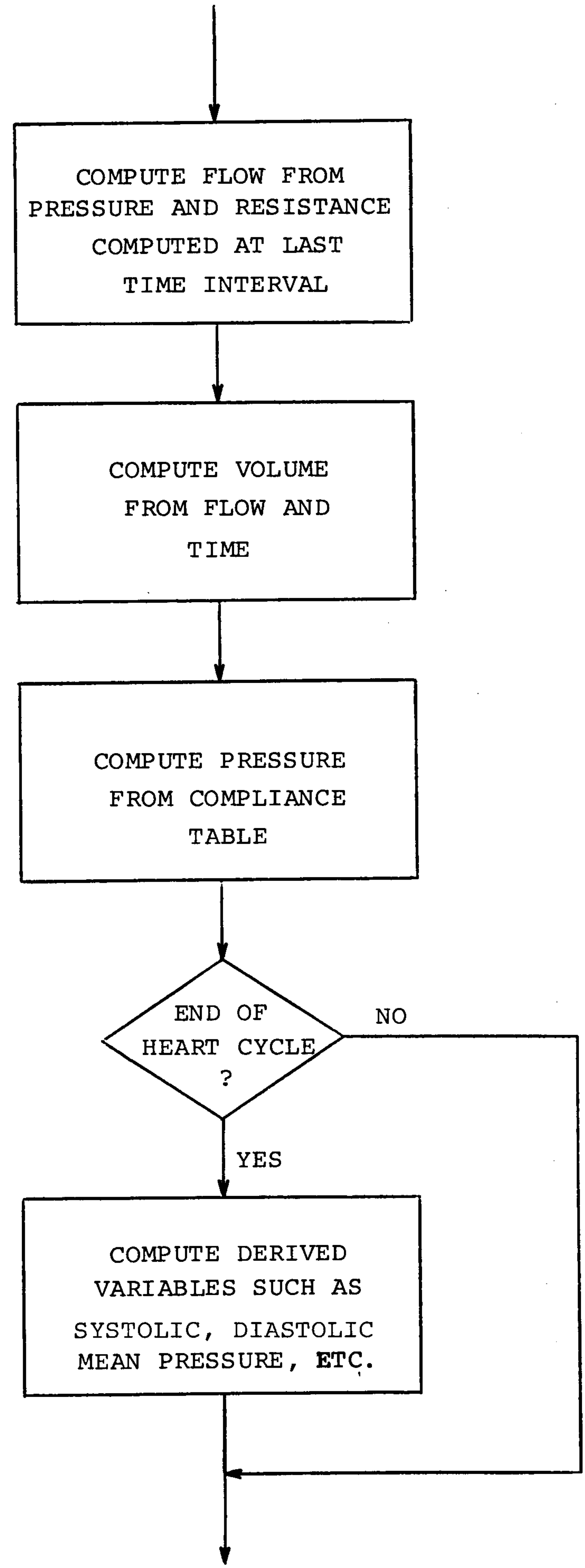
APPENDIX III

FLOWCHARTS

GENERAL PROGRAM FLOWCHART



INNER COMPUTATION LOOP FLOWCHART



APPENDIX IV

COMPLIANCE CARDS

APPENDIX IV

COMPLIANCE CARDS

The compliance cards 1-16 are read with a format of I2,10F7.2. The I2 field is the same two digit indicator field as other control cards. Numbers 1-15 are compliance for the 15 organs. Number 16 is a heart rate control table.

The other 10 fields should be considered as five pairs of values. The first of each pair (odd values) is in all cases the independent variable. The second of each pair (even values) is the dependent variable. The table is always entered with an independent variable. The dependent variable is computed by linear interpolation and returned to the program for computation.

The units for these variables are in three classes:

Indicator Field	Independent Variable	Dependent Variable
16	Pressure in mm Hg at baroreceptor	Beats per minute to be added to heart rate
8,11,12	Time in milliseconds within a heart beat	Compliance C in $\frac{\text{CM}}{\text{mm Hg}}$
All other fields	Volume V of organ in cm^3	Pressure P in mm Hg

Note that for the heart chambers 8, 11, and 12, since P is a function of both volume and time, a more complicated computation is necessary. In the other chambers, since P is a function of volume only, we save considerable time at no loss of generality by returning P instead of C.

An example of use follows. The following is the image of the compliance card for the legs:

6	0.	-5.	800.	40.	1000.	80.	1200.	140.	2000.	190.

For a value of 1000 cm^3, the pressure returned will be 80 mm Hg. For 1200 cm^3, the returned pressure will be 140 mm Hg. If the input volume were 1020 cm^3, then by linear interpolation the pressure returns will be 86 mm Hg.

The current compliance table is given below for reference.

1	0.	-5.	450.	40.	500.	80.	650.	140.	1000.	190.
2	0.	-5.	450.	40.	500.	80.	650.	140.	1000.	190.
3	0.	-5.	450.	40.	500.	80.	650.	140.	1000.	190.
4	0.	-5.	450.	40.	500.	80.	650.	140.	1000.	190.
5	0.	-5.	450.	40.	500.	80.	650.	140.	1000.	190.
6	0.	-5.	800.	40.	1000.	80.	1200.	140.	2000.	190.
7	0.	-5.	200.	5.	475.	10.	750.	15.	2000.	90.
8	0.	20.	50.	2.7	170.	2.2	220.	100.	500.	20.
9	0.	-5.	450.	0.	500.	40.	650.	100.	1000.	150.
10	0.	-5.	450.	0.	500.	40.	650.	100.	1000.	150.
11	0.	4.5	60.	3.5	90.	500.	130.	13.	1200.	8.
12	100.	24.	150.	1.4	250.	1.1	330.	48.	700.	24.
13	0.	-5.	20.	65.	30.	100.	50.	180.	200.	200.
14	0.	-5.	20.	65.	30.	100.	50.	180.	200.	200.
15	0.	-5.	20.	65.	30.	100.	50.	180.	200.	200.
16	85.	25.	97.	1.	99.	.01	101.	-.01	121.	-20.

APPENDIX V

DESCRIPTION OF VARIABLES USED IN TEXT

APPENDIX V

DESCRIPTION OF VARIABLES USED IN TEXT

SYMBOL	DESCRIPTION
P	pressure
P_r	pressure for collapsed wall
P_n	pressure at organ n
V	volume
V_o	volume at time o
F	flow rate
$\overset{n}{F}$	flow rate at step n
C	compliance
t	time
R'	resistance/unit length
R	resistance
X	length
A	area
A_o	area at time o
r	radius
E_s	static elasticity
E_d	dynamic elasticity
L'	density • length
L	inertial constant for blood
ρ	density
η	viscosity
δ	wall thickness
T	wall tension
E	Young's Modulus
R_e	wall drag coefficient
G	gravity
t	time

DESCRIPTION OF VARIABLES USED IN TEXT (CONTINUED)

Assumed Relationships

$$R' = \frac{\delta\eta}{\pi r^4}$$

$$L' = \frac{o}{\pi r^2}$$

$$P\frac{\delta}{r} = T = E\frac{\Delta r}{r} + R_e \frac{d\frac{\Delta r}{r}}{dt}$$

APPENDIX VI

USER'S GUIDE

for

LBNP PROGRAM AND THE ASSOCIATED DISPLAY PROGRAM

APPENDIX VI

The University of Texas
M. D. ANDERSON HOSPITAL AND TUMOR INSTITUTE AT HOUSTON
Department of Biomathematics
Section of Bioengineering

USER'S GUIDE

for

LBNP PROGRAM AND THE ASSOCIATED DISPLAY PROGRAM

Prepared under Contract NAS 9-11119

by

Robert P. Giese

for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

August 1971

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USER'S GUIDE
for
LBNP PROGRAM AND THE ASSOCIATED DISPLAY PROGRAM

GENERAL

This program is a model of the human cardiovascular system. The model consists of 15 body compartments or organs and the 21 associated flow paths between these organs (Figure 1). The body parameters in the sample deck supplied with the program are for a "typical" male human. That is to say it functions as a male of average height and weight. These parameters have been tested under various conditions such as positive and negative lower body pressure, various G loading between -2 and +10 G's, and various postures such as lying, standing, and sitting. In all cases, parameters such as heart rate, flow, cardiovascular output, pressures, and volumes are about what one would expect with a conditioned man.

The basic formulae for the model are:

1) $$V = V_o + \int (F_{in} - F_{out})\,dt$$

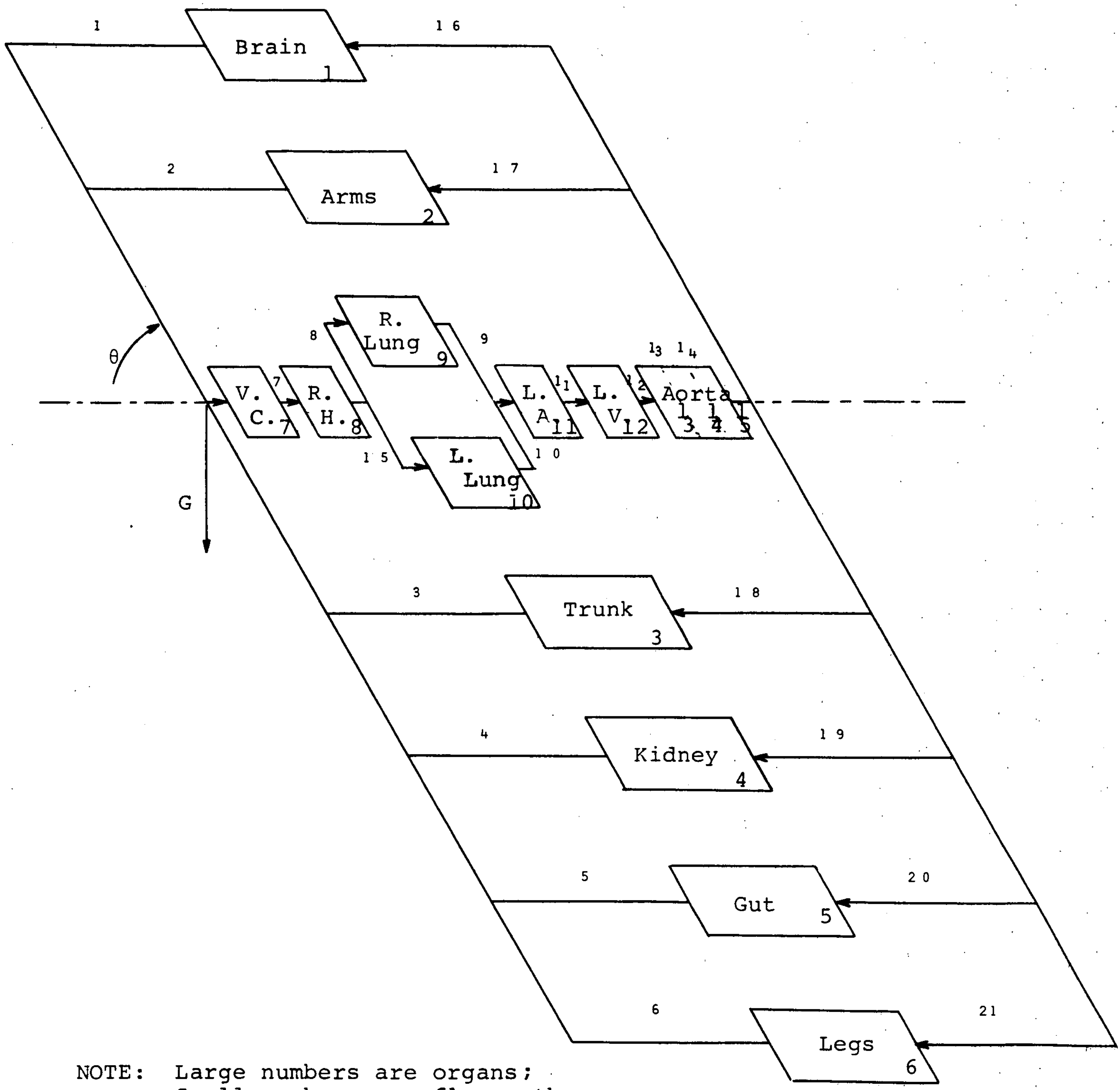
2) $$P = \frac{V}{C} - P_r + G$$

3) $$F = \frac{P_m - P_n - G - L\,\frac{dF}{dG}}{R_{m,n}}$$

where V is volume, P is pressure, F is flow, R is resistance, C is compliance, G is gravity, and L is inertia.

Figure 1

MODEL CONFIGURATION



NOTE: Large numbers are organs;
Small numbers are flow paths.

Flow to any organ may be altered by changes in resistance between the organs with a smaller resistance yielding a larger flow. In this way exercise may be simulated. If we reduce the resistance to the arms to one-half we will get approximately double the normal flow to the arms along with the associated increase of both heart rate and cardiovascular output.

Equation 2) is expedited by use of a volume pressure function where for a given volume, a value of P is returned. The function for the legs of a man with good conditioning and 1000mℓ blood volume in the legs may look like Table Ia.

<u>Conditioned</u>

Volume	Pressure
0	-5
800	40
1000	80
1200	140
2000	190

Table Ia

<u>Unconditioned</u>

Volume	Pressure
0	-5
600	40
1000	80
1400	140
2000	190

Table Ib

Thus, for the unconditioned man a larger volume change is necessary to obtain a given pressure. Thus, if the unconditioned man is subjected to standing under any G forces, more blood will tend to flow to his legs before the model stabilizes. In most cases the model will stabilize in 20 seconds after minor changes, but may take 60 or more seconds if large changes are made.

The input of physiologically unreasonable data constants will, in general, create conditions that will cause the program to fail. In general, these same conditions if applied to the human body will also cause it to fail. Examples of this are given, but this list is not meant to be exhaustive, namely:

a) Changes in initial volume of an organ must be accompanied by changes of the compliance table.

b) Changes of resistance and inertia affect flow rates and volume changes. Thus, changes should be relatively small; and in many cases, they should be accompanied by changes in compliances.

c) Rapid discrete changes in body angle will result in immediate changes of pressure, and thus sharp changes in flow will occur.

d) There are no default options for volumes, pressures, compliances and resistances. Failure to input these constants leads to failure of the model.

e) Because the computation is in discrete space instead of a continuum, the compute frequency is critical. Generally, at least 200 steps per second should be considered the minimum compute frequency. One should bear in mind that running time is proportional to compute frequency.

The general input and output for the program is very flexible. For example:

a) Parameter cards may be read in any order.

b) Parameter cards can be duplicated. Only the last card read will be used.

c) A parameter, once read, will remain unchanged until another parameter of the same type is read.

d) Any of the computed parameters may be output graphically, with from 1 to 20 of these parameters displayed in a single run. (Up to 40 parameters are allowed if a 22 inch plotter is used)

e) The display program is separate from the compute program so that any number of display runs may be made from a single compute run.

f) Both time and value scaling of the graphical output is flexible and independent of the output frequency.

g) Output parameters may be displayed in any order.

DECK SETUP FOR LBNP PROGRAM

Input cards are as follows: (Format (I2, 10F7.2))

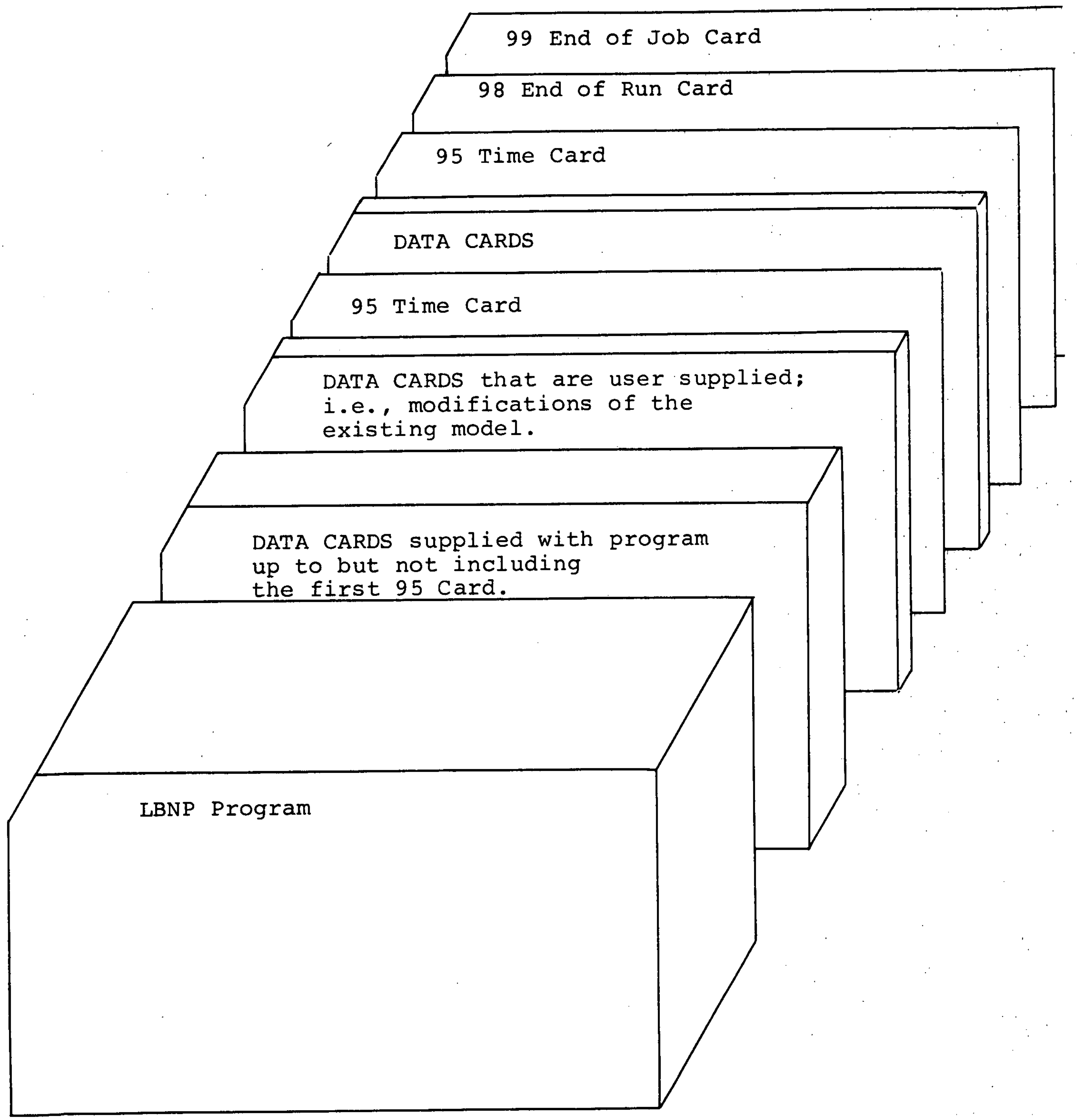
TABLE II

```
COMPARTMENTS
           1  BRAIN         7  VENA CAVA                      13  AORTA
           2  ARMS          8  RIGHT HEART                    14  AORTA
           3  TRUNK         9  RIGHT LUNG                     15  AORTA
           4  KIDNEY       10  LEFT  LUNG
           5  GUT          11  LEFT  ATRIUM
           6  LEGS         12  LEFT  VENTRICLE

FLOW RELATIONSHIP BETWEEN COMPARTMENTS.  V DENOTES VALVE.
           1   1 -> 7       V  8   8 -> 9        V 15   8 ->10
           2   2 -> 7       V  9   9 ->11          16  15 -> 1
           3   3 -> 7       V 10  10 ->11          17  15 -> 2
           4   4 -> 7       V 11  11 ->12          18  15 -> 3
           5   5 -> 7       V 12  12 ->13          19  15 -> 4
       V   6   6 -> 7         13  13 ->14          20  15 -> 5
       V   7   7 -> 8         14  14 ->15          21  15 -> 6

INPUT CARDS
           1 - 15    COMPLIANCE CARDS
          16         MEAN PRESSURE-DELTA HEARTRATE TABLE.
          21 - 35    INITIAL VOLUME CARDS
          41 - 55    INITIAL PRESSURE CARDS
          60         GRAVITY IN G'S.
          61 - 66    DISTANCE FROM HEART TO ORGANS 1 - 6 IN CM.
          70         INERTIA CONSTANT FOR AORTA.
          71 - 91    RESISTANCE AND INERTIA BETWEEN NODES
          92         INITIAL HEART RATE IN BEATS PER MINUTE.
          93         LOWER BODY NEGATIVE PRESSURE IN MM HG.
          94         ANGLE IN DEGREES.  0 LYING, 90 STANDING.
          95         TIME IN SECONDS FOR RUN WITH ABOVE PAR.
          96         COMPUTE AND OUTPUT FREQUENCY.
          97         PRINT OPTION.  0 NOPRINT, 1 PRINT FIRST BUF
          98         END OF RUN.
          99         END OF JOB.
```

The program will read cards until a 95 card (Time), a 98 card (End of Run) or 99 card (End of Job) is read. A convenient way of using the program is as follows:

Figure 2

DECK SETUP FOR LBNP PROGRAM



Multiple or stacked runs may be run by inserting more Data cards and Time cards beyond the first 98 End of Run card. Each run must be ended with a 98 End of Run card.

If used in this way, no parameter cards will be missing. If a change to the model is considered permanent then it can be put in the place of its counterpart in the Data cards supplied with the program.

The program will compute and produce output for the number of seconds specified on the Time card. This time should be whole seconds if an output frequency of 200 or more is used, even seconds if an output frequency of 100 or more is used, 4 times an integer number of seconds if 50 is used, etc. After the specified number of seconds, the program will read new parameter cards until a new Time card is read. Only changes need be added, since all unchanged parameters will remain fixed. The LBNP will create a data tape to be read by the DISPLAY Program. Compute frequency should be a non-negative integer power of 2 multiple of the specified output frequency; i.e., if output frequency is 100, then compute frequency should be 100, 200, 400, 800, etc.

DECK SETUP FOR DISPLAY PROGRAM (Figure 3)

Item

1. DISPLAY Program

2. Scale Cards supplied with Display Program in order received.

3a. One card specifying number of output graphs, maximum graph height, and seconds per display inch in FORMAT (I4,2F4.0).

NOTE:

Number of graphs must be between 1 and 20. (up to 40 are allowed for 22 inch plotter)

Height must be ½, 1 or 2 inches. (up to 4" allowable with 22 inch plotter)

Seconds per inch can be any real number.

3b. One card specifying which parameters are to be displayed, FORMAT (20I4); the parameter codes are listed in Table II.

For 22 inch plotters, if more than 20 parameters are to be displayed, then two of the above cards must follow each card specifying the number of graphs.

TABLE III

DISPLAY CODES FOR PARAMETERS

101-121	FLOWS 1-21
201-215	VOLUMES 1-15
301-315	PRESSURES 1-15
401	LBNP (LOWER BODY PRESSURE)
402	SYSTOLIC PRESSURE
403	DIASTOLIC PRESSURE
404	MEAN BLOOD PRESSURE
405	HEART RATE
406	BODY ANGLE
407	CARDIOVASCULAR OUTPUT
408	GRAVITY
411	SYSTOLIC, MEAN AND DIASTOLIC PRESSURE

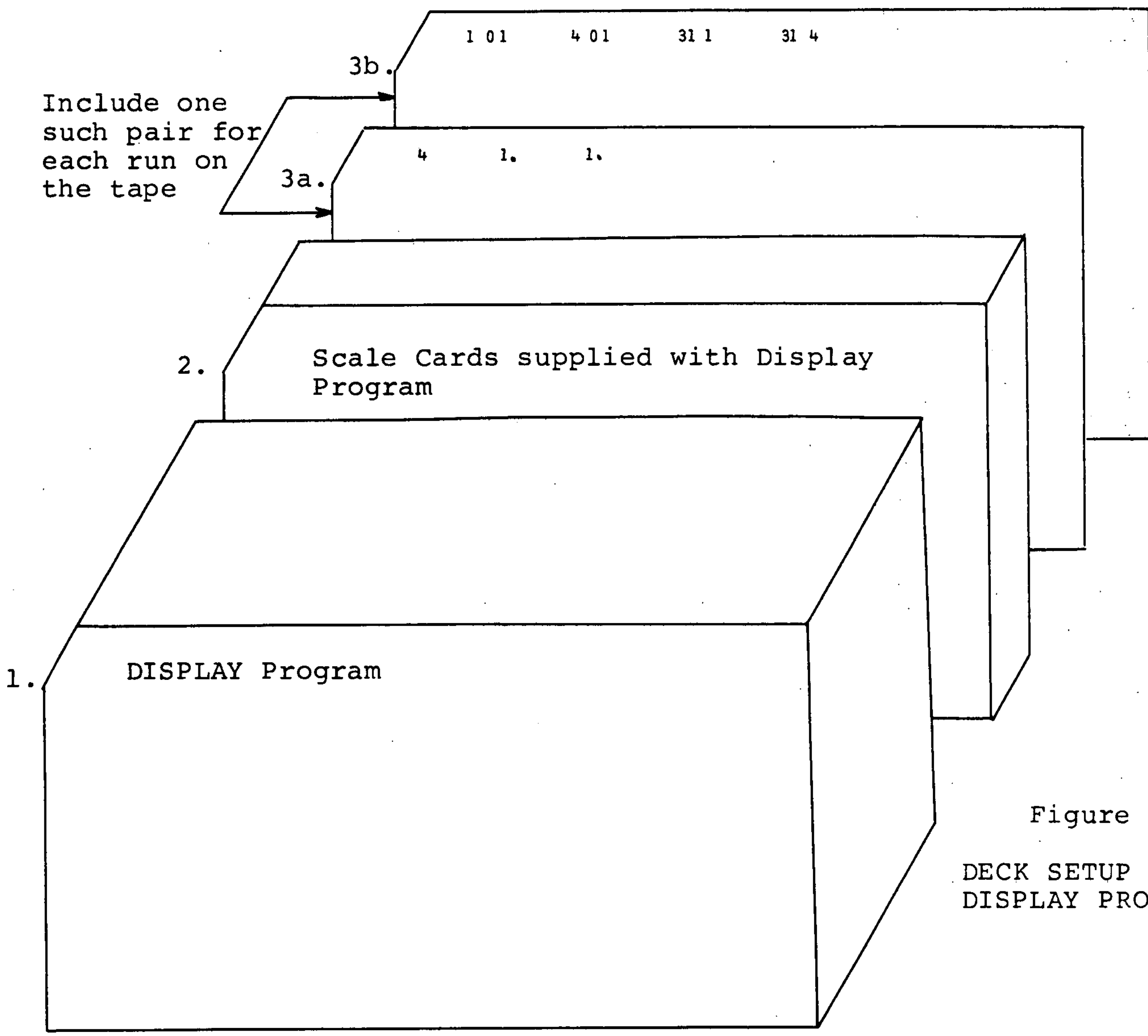


Figure 3

DECK SETUP FOR DISPLAY PROGRAM

RUNNING TIME

On the XDS Sigma 5 computer with a compute frequency of 200 steps/second and an output frequency of 50 steps/second, the execution time of the LBNP Program is 3.373 minutes for the enclosed experiment which lasted 56 seconds. This amounts to about 3½ times as much computer time as the desired model time. The execution time of the Display Program to generate the enclosed plot is 1.280 minutes, or nearly real-time. The digital plotter required 4.565 minutes to plot this display. The same display at ½ inch per second would require about twice this amount of compute and plot time. (See Appendix)

Remark on Stepsize: As seen in the previous section, the Basic Flow equation (5) becomes a first order, first degree differential equation (7) when inertia is added. In the descrete approximation to (7) the corresponding difference equation

$$F = \frac{P_m - P_n - G - L\,\frac{\Delta F}{\Delta t}}{R_{m,n}}$$

is sensitive to stepsize changes. Larger than real life inertial values and greater than real life flow rate changes create an unstable situation for large stepsizes. In general, a high-frequency ringing of flow, especially in the aorta, can be stopped only by using a smaller stepsize (higher compute frequency) or by reducing the blood inertial values. A compute frequency of 200 is usually sufficient for a stable condition with any realistic inertial values or flow rates.

The DISPLAY Program reads the tape created by the LBNP Program and produces the specified graphs. There is no provision for multi-runs from the same data tape; however, the program may be run any number of times using different plot parameters with the same data tape.

For information concerning this model that is not in this user's guide, see "A Cardiovascular System Model for Lower-Body Negative Pressure Response" by Mitchell, B.A. and Giese, R.P., included with the Quarterly Report No. 5, NASA Contract No. NAS 9-11119.

APPENDIX

UNIVAC 1108 DECK SETUP

for

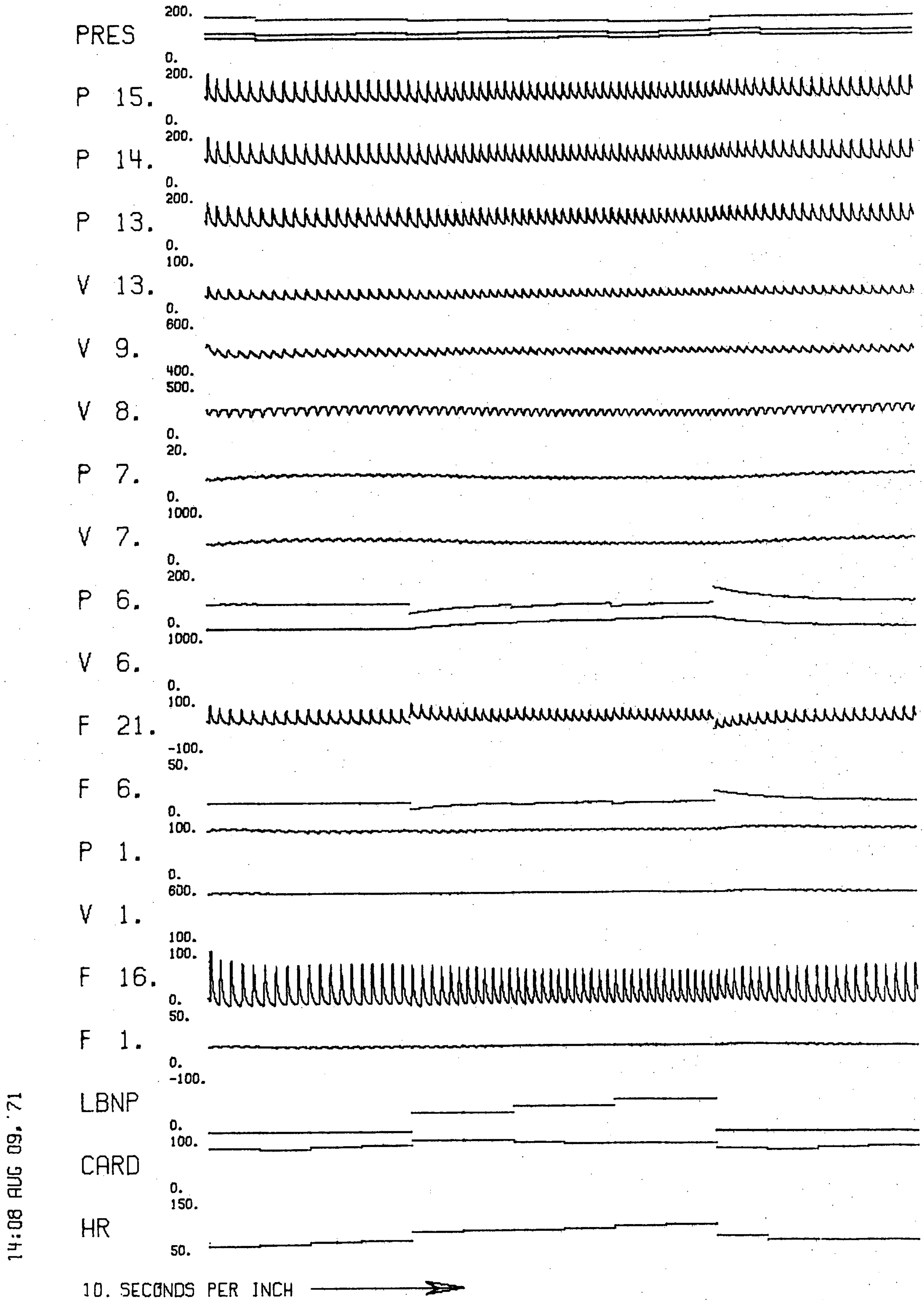
RUNNING BOTH PROGRAMS TOGETHER

UNIVAC 1108 Deck Setup for Running both Programs Together

```
Z RUN B02380,DB6,243,8636N,Q509,C,10,5                              MAULDIN        4 I
N MSG       FILE REQD    TAPE 3    FH432   O    FSTRAN   1
S ASG A=58500
SR   ASG  C=63402
 ASG F=CALPLT
 XQT CUR
  TRW A,C,F
  IN C
  TRI C
 FOR A1,A1

(LBNP PROGRAM)

 FOR AH,AH

(DISPLAY PROGRAM)

 XQT A1
 1      0.     -5.    450.    40.    500.    80.    650.   140.   1000.   190.
 2      0.     -5.    450.    40.    500.    80.    650.   140.   1000.   190.
 3      0.     -5.    450.    40.    500.    80.    650.   140.   1000.   190.
 4      0.     -5.    450.    40.    500.    80.    650.   140.   1000.   190.
 5      0.     -5.    450.    40.    500.    80.    650.   140.   1000.   190.
 6      0.     -5.    800.    40.   1000.    80.   1200.   140.   2000.   190.
 7      0.     -5.    200.     5.    475.    10.    750.    15.   2000.    90.
 8      0.     20.     50.    2.7    170.    2.2    220.   100.    500.    20.
 9      0.     -5.    450.     0.    500.    40.    650.   100.   1000.   150.
10      0.     -5.    450.     0.    500.    40.    650.   100.   1000.   150.
11      0.     4.5     60.    3.5     90.   500.    130.    13.   1200.     8.
12    100.     24.    150.    1.4    250.    1.1    330.    48.    700.    24.
13      0.     -5.     20.    65.     30.   100.     50.   180.    200.   200.
14      0.     -5.     20.    65.     30.   100.     50.   180.    200.   200.
15      0.     -5.     20.    65.     30.   100.     50.   180.    200.   200.
16     85.     25.     97.     1.     99.    .01    101.   -.01    121.   -20.
21    500.
22    500.
23    500.
24    500.
25    500.
26   1000.
27    350.
28    250.
29    500.
30    500.
31    120.
32    120.
33    30.
34    30.
35    30.
41     80.
42     80.
43     80.
44     80.
45     80.
46     80.
47      5.
48    100.
49     50.
```

```
50    50.
51   100.
52   100.
53   100.
54   100.
55   100.
61   35.
62   20.
63  -15.
64  -22.5
65  -30.
66  -70.
70 2.5
71    4.00.0014
72    6.00.0014
73    6.00.0014
74    6.00.0014
75    6.00.0014
76    6.00.0014
77    0.02.0014
78    0.30.0014
79    0.45.0014
80    0.45.0014
81  0.003.0007
82  0.005.0014
83  0.007.0014
84  0.010.0014
85    0.30.0014
86    1.00.0014
87    1.50.0014
88    1.50.0014
89    1.50.0014
90    1.50.0014
91    1.50.0014
92  80.
93      0.
94      0.
96  200.   50.
95 16.
93   -30.
95  8.
93   -40.
95  8.
93   -50.
95  8.
93      0.
95 16.
98
99
  XQT AH
 101    0 .02
 102    0 .05
 103    0 .05
 104    0 .05
 105    0 .05
 106    0 .02
 107    0.002
 108    0.002
 109    0 .01
 110    0 .01
```

```
111    0•002
112    0•001
113    0•001
114    0•001
115    0•001
116    0 •01
117    0 •01
118    0 •01
119    0 •01
120    0 •01
121-100•005
201 100•002
202 100•002
203 100•002
204 100•002
205 100•002
206    0•001
207    0•001
208    0•002
209 400•005
210 400•005
211    0•005
212    0•002
213    0 •01
214    0 •01
215    0 •01
301    0 •01
302    0 •01
303    0 •01
304    0 •01
305    0 •01
306    0•005
307    0 •05
308    0•005
309    0 •01
310    0 •01
311    0 •02
312    0•005
313    0•005
314    0•005
315    0•005
401    0-•01
402    0•005
403    0•005
404   90 •05
405   50 •01
406    0 •01
407    0 •01
408    0 •10
409    0 •01
410    0 •01
411    0•005
 20 0•5   10
405 407 401 101 116 201 301 106 121 206 306 207 307 208 209 213 313 314 315 41
 XQT CUR
  TRI A,J
E PMD
 EOF
```


PRES
200.
0.
P 15.
200.
0.
P 14.
200.
0.
P 13.
200.
0.
V 13.
100.
0.
V 9.
600.
400.
V 8.
500.
0.
P 7.
20.
0.
V 7.
1000.
0.
P 6.
200.
0.
V 6.
1000.
0.
F 21.
100.
-100.
F 6.
50.
0.
P 1.
100.
0.
V 1.
600.
100.
F 16.
100.
0.
F 1.
50.
0.
LBNP
-100.
0.
CARD
100.
0.
HR
150.
50.
14:08 AUG 09, '71
10. SECONDS PER INCH