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Bioengineering Study on the Nature and Function of the Human Cardiovascular System

by

W.H. Hoppmann II

under

U.S. Army Contract DAAD05-68-C-0406

with

College of Engineering
University of South Carolina
Columbia, S. C. 29208

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21

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Forward

Technical support and guidance for work under the contract were supplied by Dr. Joseph Sperrazza, Mr. William Kokinakis, and Mr. Larry Sturdivan, all of Aberdeen Proving Ground. Also, stimulating and critical discussion of the problem and the models was held at the University of South Carolina during April 1969. At that time the author represented the University and Mr. Larry Sturdivan, B.R.L., Dr. Fred Stemler, Edgewood Arsenal, and Dr. Joe Amato, Edgewood Arsenal, represented the Government. The discussion was subsequently followed up by a review of related work being conducted at the Edgewood Arsenal.

Messrs. D. R. Hayes, W. W. Swink, and James Liu, graduate students in Engineering at the University aided substantially in designing, constructing, and operating the models.

The extensive and necessary implementation of the project with respect to experimental apparatus and machine shop construction on the models was greatly facilitated by the efforts of Dr. R. G. Fellers, Dean of Engineering, and Mr. Harry Mullinax, shop supervisor.

Abstract

Mechanical models have been constructed and operated for the purpose of studying the nature and function of a human cardiovascular system.

Three types of models are described and the appropriateness of each as a mechanical analogue is evaluated.

It is demonstrated that the models have been developed to a point at which serious research on flow of fluid in such recirculatory elastic systems can be conducted.

Table of Contents

I. Introduction

The cardiovascular system has been studied extensively both in vivo and in vitro [1, 2, 3, 4, 5][1]. The in vitro approach is essentially that of model experimentation. The present author has discussed elsewhere, in [6] some detail, the basic nature of experiments with models, especially as related to biological systems.

The present report is concerned mainly with providing information on the design, construction, and operation of models of the cardiovascular system for use in developing precise and reliable knowledge of the mechanical aspects of the functioning of the prototype. A further purpose is to discuss the possibility of using the models to determine the effect of abnormalities, such as bleeding, on the performance of the system.

II. Design and Construction of the Models

Three types of experimental models were built. They are the Simon Rodbard model[3] shown in Figs. 1 and 2, the model for experiments on actual mammalian hearts, shown in Fig. 3, and the simplified model of the left ventricular subsystem shown in Fig. 4. Also see Fig. 5.

The Rodbard model was built and operated but it becomes immediately apparent, as it did to Dr. Rodbard, that real progress in study of the prototype requires simpler models.

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[1] Numbers in brackets refer to references at end of report.

A second model, of somewhat simpler type, using actual beef hearts was built in our laboratory. Incidental to the designing and building of this model, careful dissection and examination of several beef hearts, as suggested by Dr. H. Melvin Kinsely of the Charleston Medical College were made in order to obtain first hand knowledge of some of the important working parts of a mammalian heart. Anyone who performs such a study will never forget the complexity and marvelous structure of the organ, especially the valve system. It is obvious that no human being could construct a detailed working model of the left ventricle and its valve. However, it is considered that such a feat is not necessary for our purpose and a simpler model should provide useful knowledge of the over-all mechanical aspects of the functioning prototype. In particular, it is considered that reliable information concerning the systemic effect of bleeding on the performance of the complete recirculatory system can be best obtained with the use of a much simpler model. Consequently, a third type model was designed and built. It is clear that this model is limited to the left ventricular system, bypassing the lungs. In using such a model for studies of bleeding some questions may arise. For example, the most obvious effects of bleeding within the left ventricular loop is an immediate drop of pressure in that loop and a dropoff in the flow into the right ventricular loop, thus limiting the flow into the left ventricular loop a half-cycle later. The two phenomena, the decrease in pressure and volume, are out of phase by half a cycle. The answer would be, of course, that the total bleedout time is very long compared to the cycle time. Therefore the half cycle time may be neglected and the left ventricular loop may be considered to be dumping fluid back into itself without its passing through the right half. This model is shown in

Fig. 4. As shown, the ventricle is represented by a rubber urinal bag inside a rigid walled air chamber. The controlled flow of compressed air is provided by the machine shown in Fig. 2. Very recently a more suitable model of the ventricle was built. It consists of two rubber hemi-spheroids held together as a unit by means of an aluminum ring. Flap valves are used with this model as well as with the one using a urinal bag. The driving mechanism, a reciprocating machine which provides predetermined amplitudes of motion and frequency, has been previously described [7]. It was developed at Rensselaer Polytechnic Institute by the author in connection with rheological research sponsored by the U. S. Navy.

The rest of the system used with this model of the ventricle is shown in Fig. 4. A single latex tube represents the aorta and arterial system; another single tube represents the venous return. These tubes are connected at a controlled reservoir which represents a capillary bed. Analogues for vasomotor tone of the cardiovascular system consist of variable resistances and compliances incorporated in the working model.

The bleeder unit, which will probably be an important part of future experiments, can be installed at various positions along the line of flow. Obviously it can be cut in and out of the system with ease and the effect of bleeding on the general performance studied.

III. Operation of the Models

The Rodbard model was operated using the compressed air machine shown in Fig. 2. A pulsatile flow with a frequency in the neighborhood of 70 beats per minute was used. In this model ball check valves are employed for the purpose of producing unicursal flow. They perform very well. Continuous circulation can be maintained at controlled rates for any desired length of time. It was after observing the complexities of the Rodbard model that a decision was made to examine the possibilities of experimenting with real mammalian hearts. The apparatus shown in Fig. 3 was built but never operated because it became apparent that an extensive research program on the compliances of the actual heart would be required to make meaningful over-all flow studies. To obtain a sustained unicursal flow with this model would not be too difficult if its use is considered desirable.

The improved variation of the model shown in Fig. 4 has been put in operation and it holds the best promise of providing immediately useful results. Using it, the rheological problem of flow in a system and the effects caused by bleeding can now be studied in accord with the best standards of theoretical and applied mechanics now available.

IV. Apparatus for Measuring and Recording Experimental Data

High quality electronic equipment for measuring and recording physical variables in the problem has been provided by the University of South Carolina. At present suitable diaphragm type pressure gages are available. Several of these have been calibrated and used in exploratory studies for the investigation. Also, sufficiently sensitive displacement and strain measuring and recording equipment have been calibrated and put into use. Plans are underway to add to these basic tools of research so that quick, accurate measurements can be made of pressure and total flow at any point in the system.

Clip gages employing resistance wire strain gages as the sensing elements have been designed, calibrated, and put into use. They are quite successful in performance and promise to be valuable in determining the change of section of the tubes through which the liquid is flowing. An important aspect of the gages for the present purpose is that they reliably determine the required changes without responding to over-all incidental motions. This they can do.

Also, some implementation will be necessary to obtain velocity traverses across various sections.

V. Measurement of Compliances

As the most cursory investigation shows, the cardiovascular system is at least elasto-dynamic, not only as influenced by the heart itself, but equally as influenced by the arteries, veins, and capillaries. Undoubtedly it represents an even more complicated rheological problem. However, to initiate meaningful studies of the system it is considered that one might well start with the simplest assumptions concerning the elastostatics associated with the problem. Such being the case it is necessary to determine the elastic compliances of the various parts of the model. So far, some exploratory statical load-displacement experiments have been performed on the model of the ventricle. In addition, an initial investigation has been begun to determine the compliance of the tubing or arterial analogue. An ancillary doctoral level investigation by a graduate student at the University under the supervision of the author is revealing some important non-linear elastic characteristics of tubes. At present one of the findings is that, with rational analysis based on advanced theories of large elastic deformation, understanding can be obtained for at least the statical deformation of the aorta. Our theoretical findings have been compared with the experimental results from experiments on aortae of forty rabbits. These data obtained by Glagov and Wolinsky were recently published in Nature [8]. The study that we are making has revealed some important characteristics of large deformation response in such tubes. The initial results of this investigation reveal the importance of knowledge of the role of compliance in determining the performance of the complete circulatory system. It is planned to press the research on compliances as a necessary activity for really understanding the biological flow processes. It is considered that the necessary knowledge to be derived will be available in essence within the next three months.

VI. Discussion and Recommendations

It is considered that the work of developing the models has been successful and that satisfactory models are now available, with the required measuring and recording equipment, to proceed with a meaningful study of the flow in the circulatory system. It is understood at the present time that the U. S. Army will provide some contractural support to the author for this proposed effort. As with the contract, which covered work described in the present report, technical supervision will be supplied by personnel of the Ballistic Research Laboratory, Aberdeen Proving Ground.

It is planned in the further study to investigate the effect on the circulation of any bleeding that may be imposed, by wounds for example, on the system. The importance of the influence of loss of blood on the operation of the system is stressed in a very recent paper [9]. In that paper it is stated that, "Decreases in cardiac filling, due to depletion of the effective circulating blood volume, can thus produce marked changes in the performance of the heart."

In any research program concerning the flow in the cardiovascular system, different kinds of liquids simulating blood should be used. Effects on the heart action should be noticeable as the type of liquid is changed in the experiment. The radically different performance of non-Newtonian liquids as compared with that for Newtonian liquids has been demonstrated and reported in various places. The author has had the opportunity to investigate some of those and has published the results elsewhere[10]. He has also observed the amazing effects on drag resistance caused by the addition of minute quantities of high polymers to water flowing around objects[11]. This latter phenomenon may well be of great importance to the control of blood flow in man and other animals.

The models produce definite and controllable pulsatile flows. It is clear that flow in such elasto-dynamic systems is analyzable in terms of wave motions. The treatment of reflections from bifurcations in the the arterial branches have been notably presented by Campbell and Yang [12]. Future work in the field should be done with a complete awareness of their results. At the present time it would seem that the method of characteristics would be appropriate for studies of the flow which, to a first approximation, may be thought of as one-dimensional but non-linear. The non-linearity is introduced into the problem at least by the elasticity of the walls of the pump and of the tubes. Of course, non-linearities will be introduced to some extent for other reasons such as nature of fluid, turbulence, accelerations, etc.

Under a subsequent Government Contract DAAD05-69-C-0460, dated July 1, 1969, much of the additional research described in the present report will be conducted. It is considered that, among other things, useful information on the effect of bleeding on the cardiovascular system will be obtained.

LIST OF PARTS FOR CARDIOVASCULAR SYSTEM

(After Simon Rodbard)

A - Right Auricle
B - Check valve
C - Right Ventricle
D - Enclosure aroung Right Ventricle
E - Check valve
F - Lungs
G - Left Auricle
H - Check valve
I - Left Ventricle
J - Enclosure around Left Ventricle
K - Check valve
L - Spleen, Liver, etc.
M - Pathway without vasomotor tone
N - Pathway with active vasomotor tone, splanchnics, skin, muscles
O - Venous return
P - Valve
Q - Flow control
R - Valve
S - Pipeline from compressor system
A' - Compressor
B' - Pressure gage
C' - Valve
D' - 3-way connector
E' - Pressure reducer
F' - Gage
G' - Low pressure reducer
H' - Gage
I' - 3-way steam cock
J' - Crank
K' - Connecting rod
L' - Crank
M' - Motor from windshield wiper
S - Pipeline from compressor system to heart model

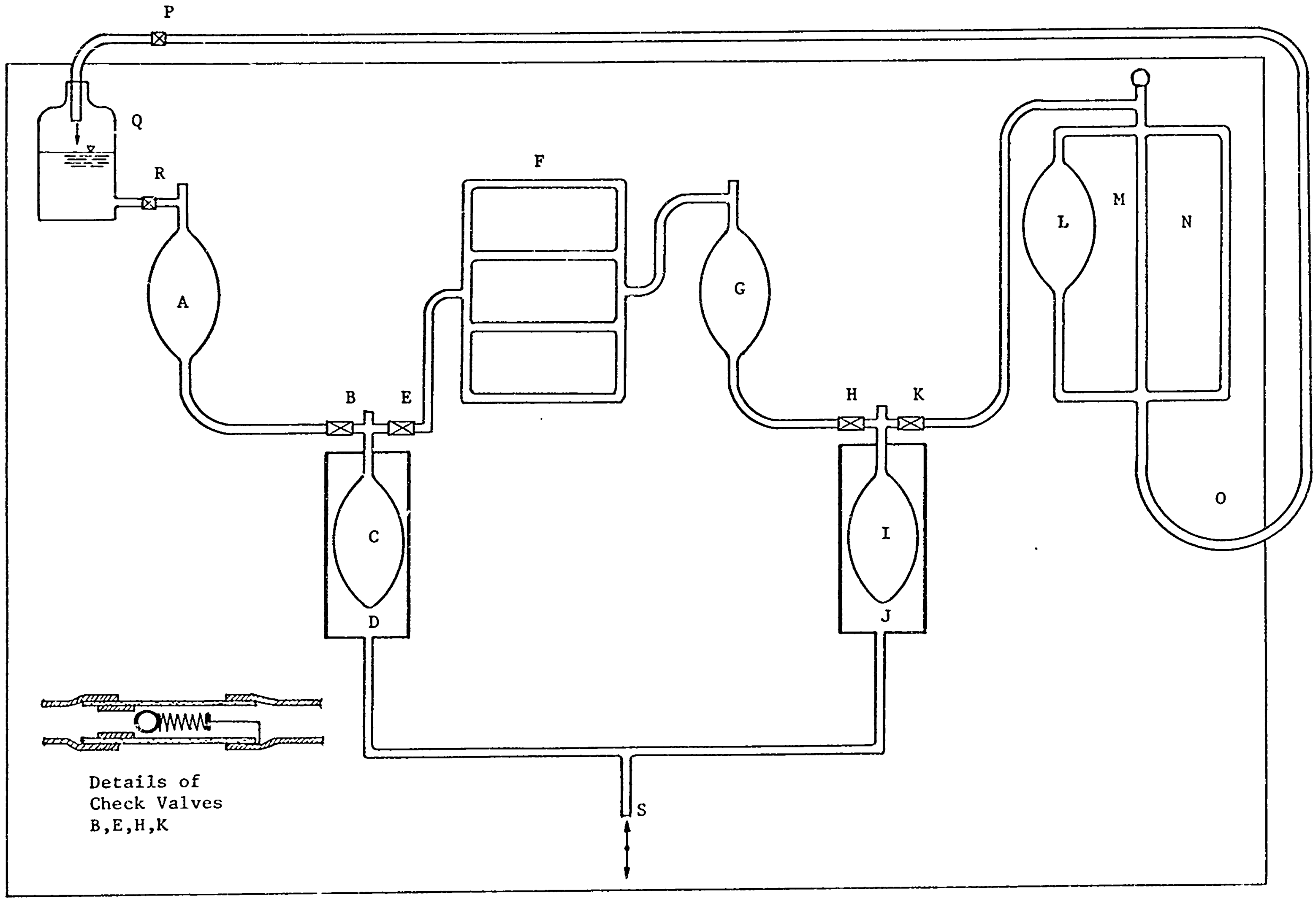

FIG. 1. Physical Model of Cardiovascular System (After Simon Rodbard)

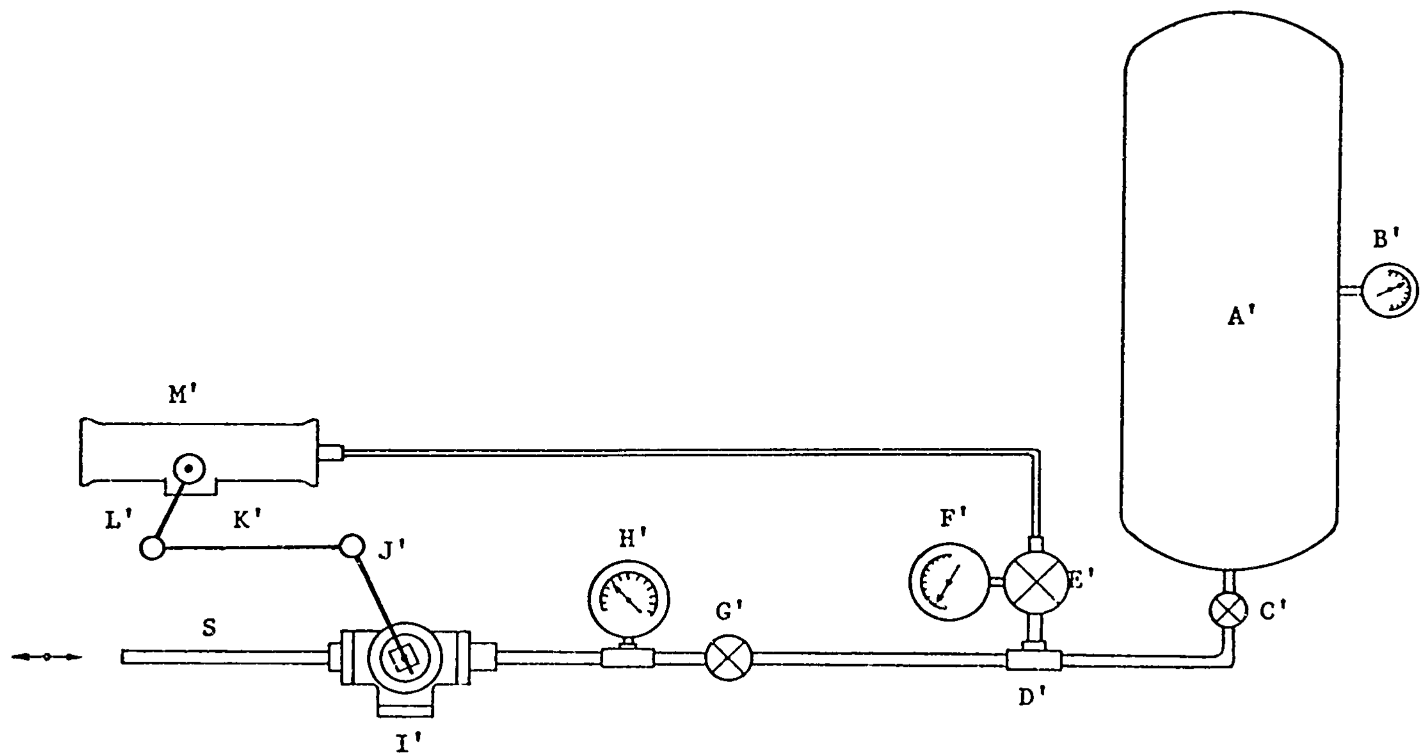

FIG. 2. Schematic Arrangement of Pulsatile System for Air Supply to Cardiovascular Model

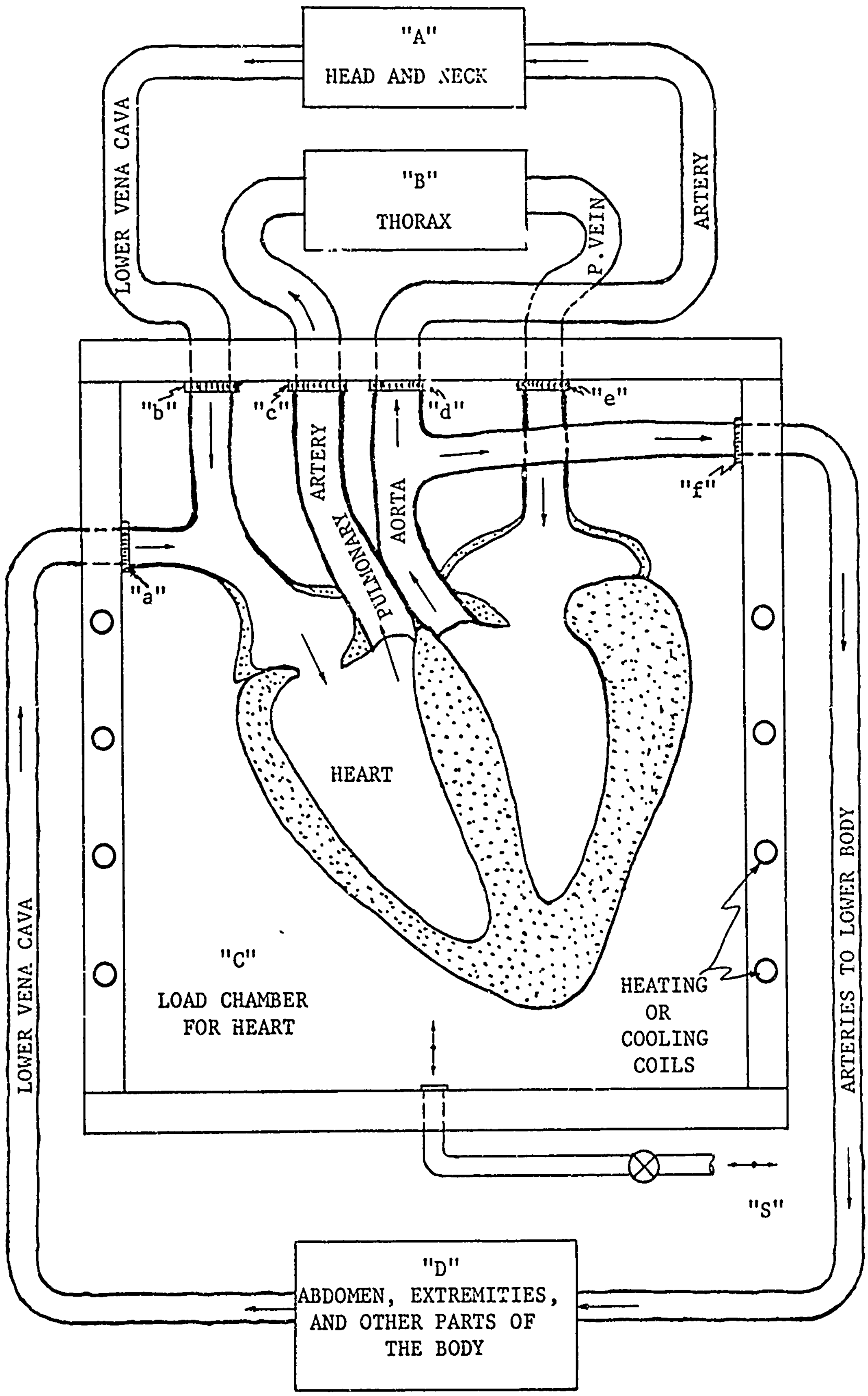

FIG. 3. Physical Model of Cardiovascular System with Mammalian Heart as Pump.

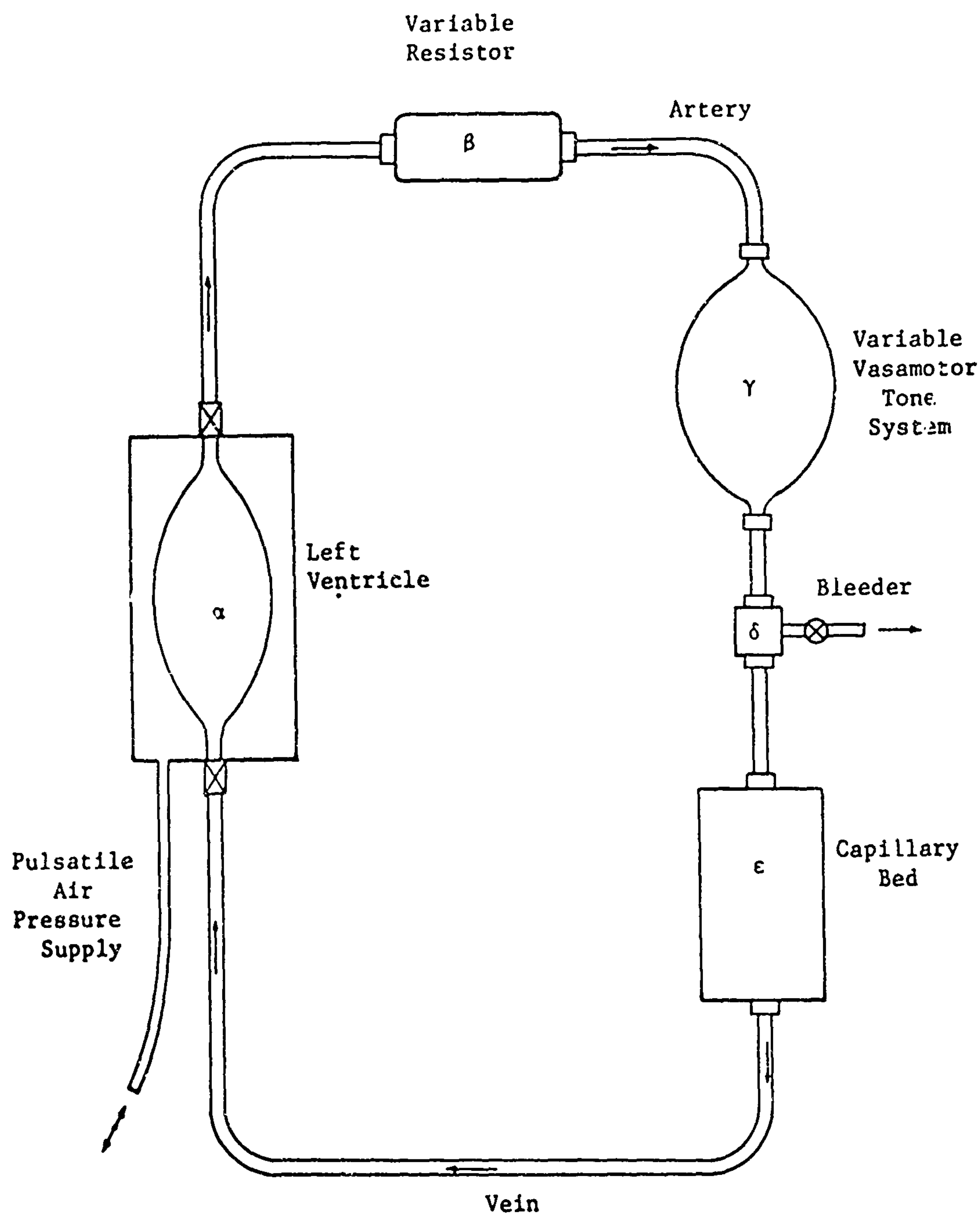

FIG. 4. Physical Model of Left Ventricular Branch of Cardiovascular System.

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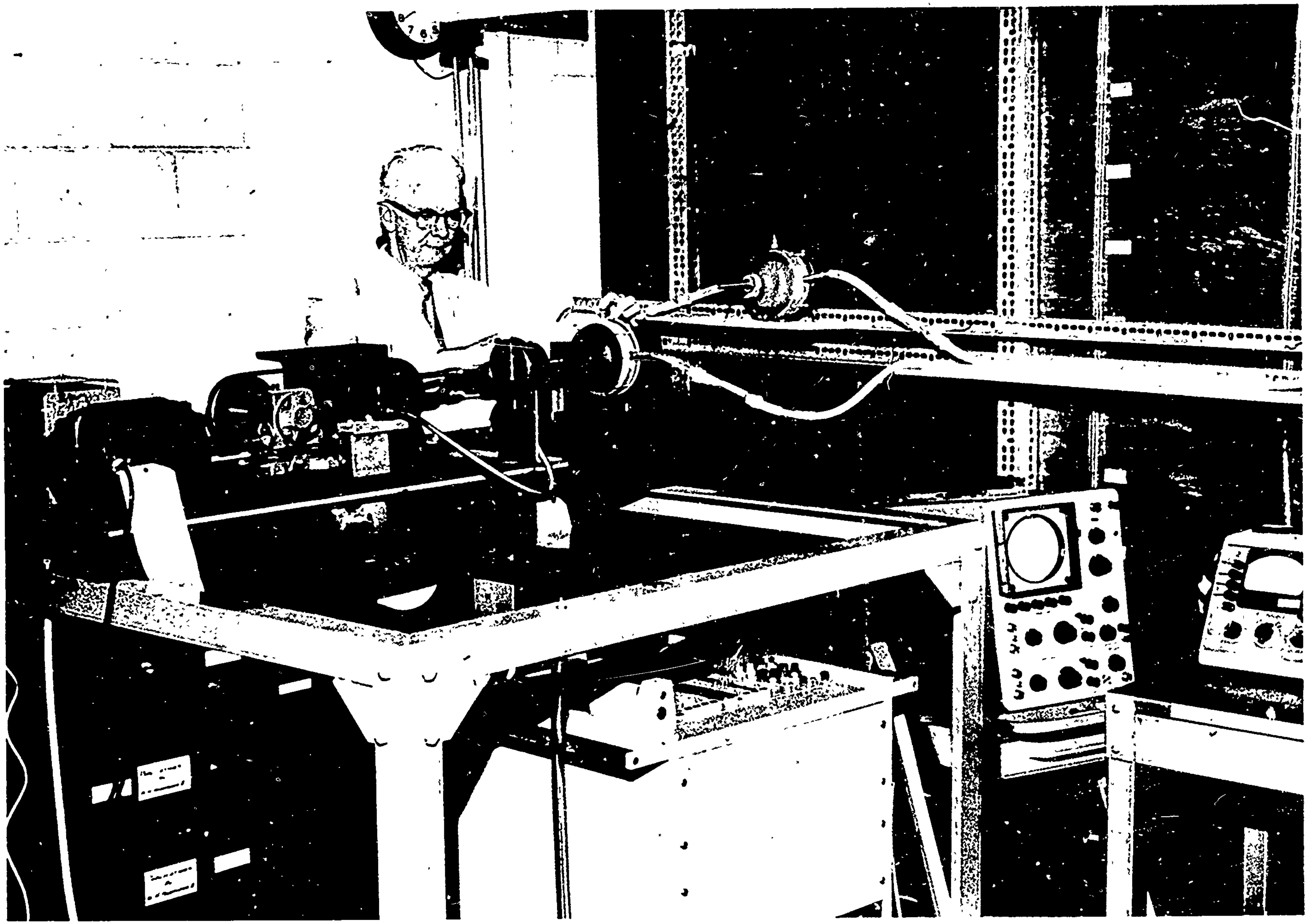

Fig. 5. View of model of left ventricular system.

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13. ABSTRACT

Mechanical models have been constructed and operated for the purpose of studying the nature and function of a human cardiovascular system.

Three types of models are described and the appropriateness of each as a mechanical analogue is evaluated. It is demonstrated that the models have been developed to a point at which serious research on flow of fluid in such recirculatory elastic systems can be conducted.

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