

A Mechanical Heart-Lung Apparatus

Abstract: An apparatus is described for taking over the functions of the human heart and lungs for short periods of time to permit a surgeon to perform certain open-heart surgical procedures in a blood-free field. This equipment is capable of receiving venous blood from the patient, removing excess carbon dioxide and restoring the proper oxygen content, and finally of pumping the blood back into the patient's arterial system. The heart-lung apparatus is provided with controls that automatically maintain the pH of the blood at its correct value, maintain proper blood temperature and safeguard the patient against unwanted changes in blood volume and against excessive blood pressure during the course of the operation. The machine requires the attention of only two persons during normal surgical procedures.

Introduction

One of the difficult problems that has confronted the medical profession over a period of many years is the surgical repair of certain heart imperfections, such as abnormal openings between the right and left sides of the heart. These are serious enough to impair the patient's ability to carry on a normal level of physical activity, or, in some cases, even to jeopardize his chances of survival. Such defects allow a portion of the patient's blood to flow directly from one side of the heart to the other, in effect bypassing the normal path of the blood through the system of arteries and veins and depriving the tissues of the body of their proper amount of nourishment and oxygen.

The repair of these defects in the heart requires that the surgeon close up the openings, either by sewing together their edges or, for larger openings, by sewing in "patches" of some inert material. To do this job, the surgeon must have access to the inside of the heart itself for periods that can be as long as one hour.

Since the heart is essentially an hydraulic pump, if its pumping chambers are opened up and thus temporarily rendered inactive, a substitute pump must be employed to maintain a normal supply of blood to the organs and tissues of the body.

An additional complication exists, however. If the heart alone were bypassed by some mechanical means, the surgeon would be faced with the necessity of establishing about eight rather complicated and difficult connections with the patient's vascular system to maintain the normal flow of blood throughout the body, including the heart muscle itself. If, however, it were possible to construct a device to take the place of the lungs as well as of the heart, then the surgical problem would be much simplified, because only three rather simple connections

need be established with the patient's blood system, as shown in the diagrams of Figs. 1 and 2. Surgeons strongly favor the latter procedure because it not only reduces the amount of surgery required, but also the length of the operation itself, an important consideration in all surgical procedures.

The solution of the problem, therefore, requires not only that a substitute be provided to accomplish the pumping action of the heart, but also that the functions of the lungs be cared for as well, since breathing is essential to life in adding oxygen to and removing carbon dioxide from the blue venous blood.

In 1947, the late Thomas J. Watson, Sr., and Dr. John H. Gibbon, Jr., now Head of the Department of Surgery at the Jefferson Medical College, Philadelphia, met to discuss the need of the medical profession for apparatus to achieve the foregoing objectives and possible ways in which this task might be accomplished. Because of his previous work in this field, dating back to 1931 when he was engaged in surgical research at Harvard University, Dr. Gibbon was able to present a plan of attack which appeared feasible from the surgical point of view provided the necessary engineering help could be obtained to carry out the research and development required to design and construct the device itself.

Doctor Gibbon and his associates have pioneered the use of cardiopulmonary (heart-lung) machines to enable the performance of open-heart operations which today are becoming "commonplace," according to a recent survey reported in the popular press.*

*Engel, L.; "Heart Surgery: A New Attack on Our No. 1 Killer," *Harper's Magazine*, Vol. 214, No. 1283, April 1957, p. 41. For additional description of the use of heart-lung machines see "Surgery's New Frontier," *Time*, Vol. LXIX, No. 12, Mar. 25, 1957, pp. 66-77.

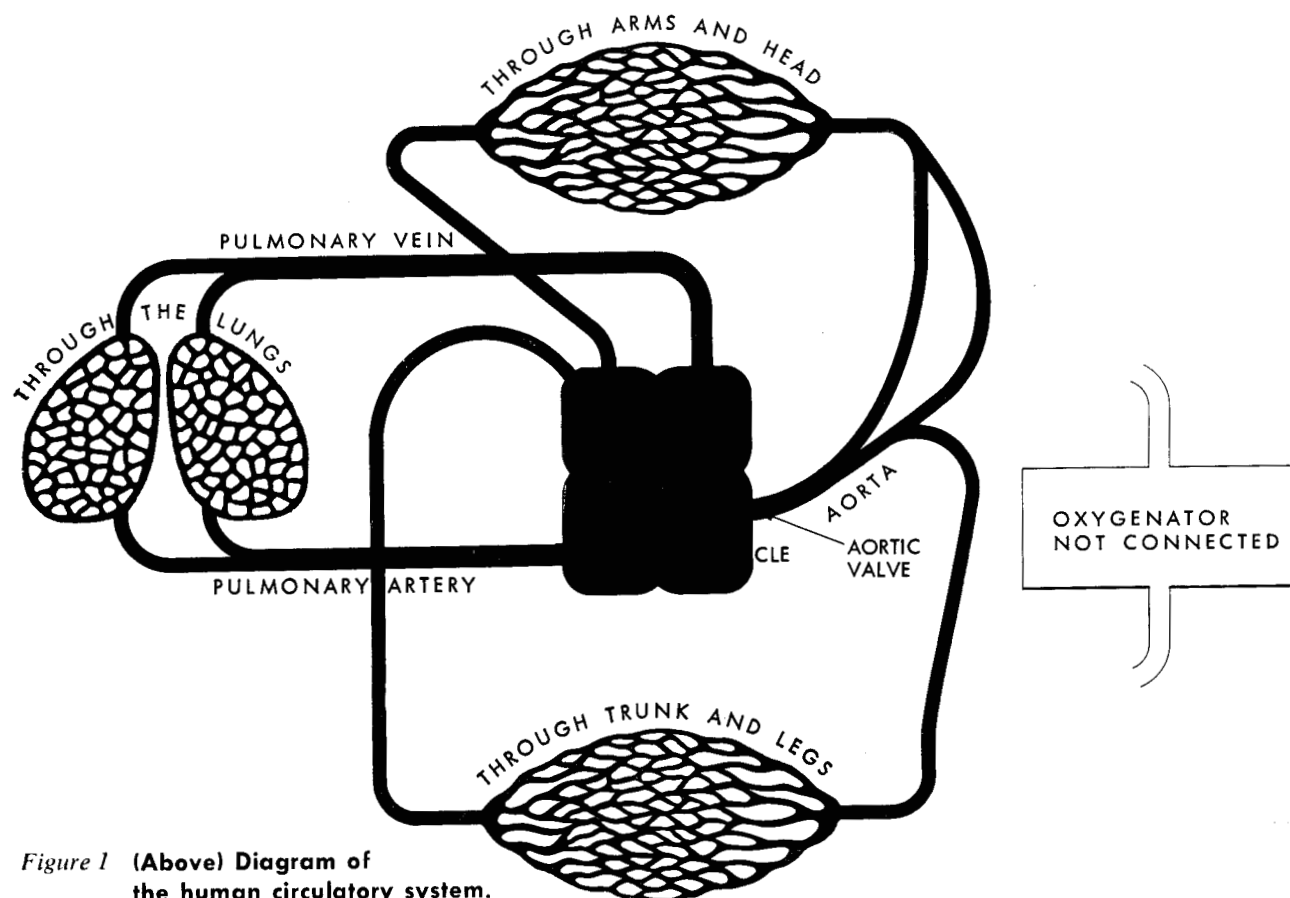
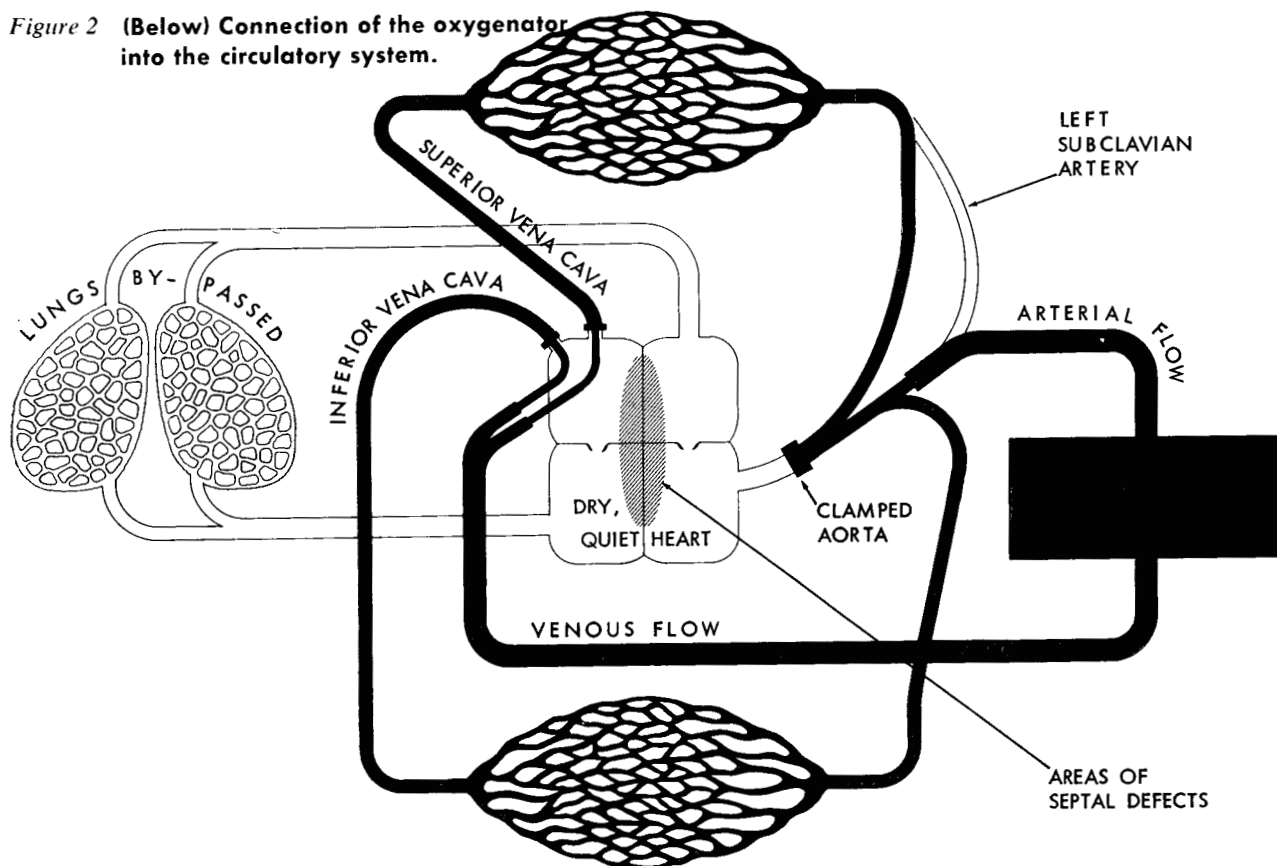


Figure 1 (Above) Diagram of the human circulatory system.

Figure 2 (Below) Connection of the oxygenator into the circulatory system.



Summary of accomplishments

IBM agreed to participate in this undertaking and has built, in close collaboration with the surgical staff at Jefferson, three models of a machine which is known both as a Mechanical Heart-Lung Apparatus and as an Oxygenator. The three models, while adhering to the same basic principles of operation, differ considerably in their capabilities and details of construction, as will be noted later. The first machine, Model I, had a blood-handling capacity of only a few hundred cubic centimeters of blood per minute and was used for experimental purposes only. Since total flow rates approaching 4000 cc/min may be encountered in humans, it was necessary to build the later models with the required capacity.

Model II, embodying many improvements in design and construction over the first apparatus, had a capacity of 2000 cc/min and was, therefore, large enough to meet the requirements of some patients. On May 16, 1953, using this model, Dr. Gibbon and his associates performed the first successful open-heart operation in which all the functions of the patient's heart and lungs were temporarily carried on by the machine.

The Model III heart-lung apparatus was delivered to Jefferson Medical College in late 1954 and, following extensive tests to prove its safety and effectiveness, has now been placed in regular use in the operating room under the direction of Dr. Gibbon and Dr. John Y. Templeton, III, Associate Professor of Surgery at Jefferson. This latest design, shown in Fig. 3, is smaller in over-all size than Model II, while having over twice the latter's blood-handling capacity. It also features many simplifications in construction and operation over its predecessors.

Design requirements

The basic tasks to be performed by the heart-lung apparatus are to ensure the proper flow of the patient's blood through his veins and arteries, the removal of excess carbon dioxide from his blood stream, and the addition of the proper amount of oxygen to it. A more general, but nonetheless important requirement, is that all factors pertaining to the patient's physiology be maintained as close to normal as the conditions of the operation will permit. This means that the rate of flow of blood, its temperature, its oxygen and carbon dioxide content, its degree of alkalinity or pH value, and its water content be kept as near their normal values as possible. The use of a minimum amount of drugs is also indicated under this heading. The blood must be handled with extreme care to avoid damage, as will be described in detail later, and, of course, strict adherence must be maintained at all times to the requirements for surgical sterility and to other factors which might affect the success of the operation and the safety and life of the patient.

The design of the heart-lung machine involves the solution to four major problems: the artificial lung to accomplish the required gas transfer; the mechanical pumps to replace the heart action in moving the blood

from the patient's low-pressure venous system through the heart-lung machine and back into the patient's higher-pressure arterial system; the handling of the blood itself, which raises questions of chemistry, materials of construction, and surgical cleanliness; and, finally, a system of control to provide for as much automatic performance as possible during the actual operation.

Of these problems, the design of the lung proved to be the most challenging. But, before we consider this work, let us first review very briefly some of the characteristics of human blood that concern us here.

Blood properties

Human blood is one of the most active of all chemicals and, at the same time, a most fragile substance easily damaged by rough treatment. It causes severe corrosion with most metals; it will penetrate the pin-holes in chromium plating to attack the base material and thereby cause peeling and flaking of the plating. Metallic portions of our machine that come in contact with the blood are made of either stainless steel or Monel metal. On the other hand, the blood is most susceptible to damage through hemolysis, a breaking down of the red corpuscles because of violent mechanical action or because of contact with substances exhibiting certain surface electric-potential characteristics.

Another characteristic of blood that must not be overlooked is its ability to clot readily when in contact with air or other gas. While this ability is needed to prevent excessive bleeding from any cuts and scratches, it presents a hazard to the operation of a mechanical lung which must of necessity expose the blood to gases if a gas exchange is to be accomplished. During operations calling for the use of the oxygenator, a drug is administered to the patient to inhibit the tendency of his blood to clot; at the close of the operation, a second, counteracting drug must be given to restore the blood to normal.

The primary function of the blood as it circulates throughout the body is to carry food and oxygen to the organs and tissues and to remove waste material and carbon dioxide. The transport of oxygen and carbon dioxide is the matter of importance here. The red corpuscles of the blood contain an iron compound, hemoglobin, which can form unstable chemical combinations with oxygen and with carbon dioxide. It is this characteristic of hemoglobin that allows it to discharge carbon dioxide and pick up oxygen in the lungs, and then perform the reverse process when the blood stream has carried the hemoglobin to other portions of the body. The control for this rather delicate balance in the chemistry of the hemoglobin resides primarily in the pH value of the environment in which the red cells find themselves. The maximum efficiency of this gas interchange occurs when the average pH value is 7.38 and the blood temperature is 98.6°F; hence, an effort is made to maintain these two conditions in the oxygenator. Human arterial blood normally is bright red and has an oxygen saturation of 95% of the theoretical maximum; venous blood is dark maroon and has a saturation of about 65% oxygen.

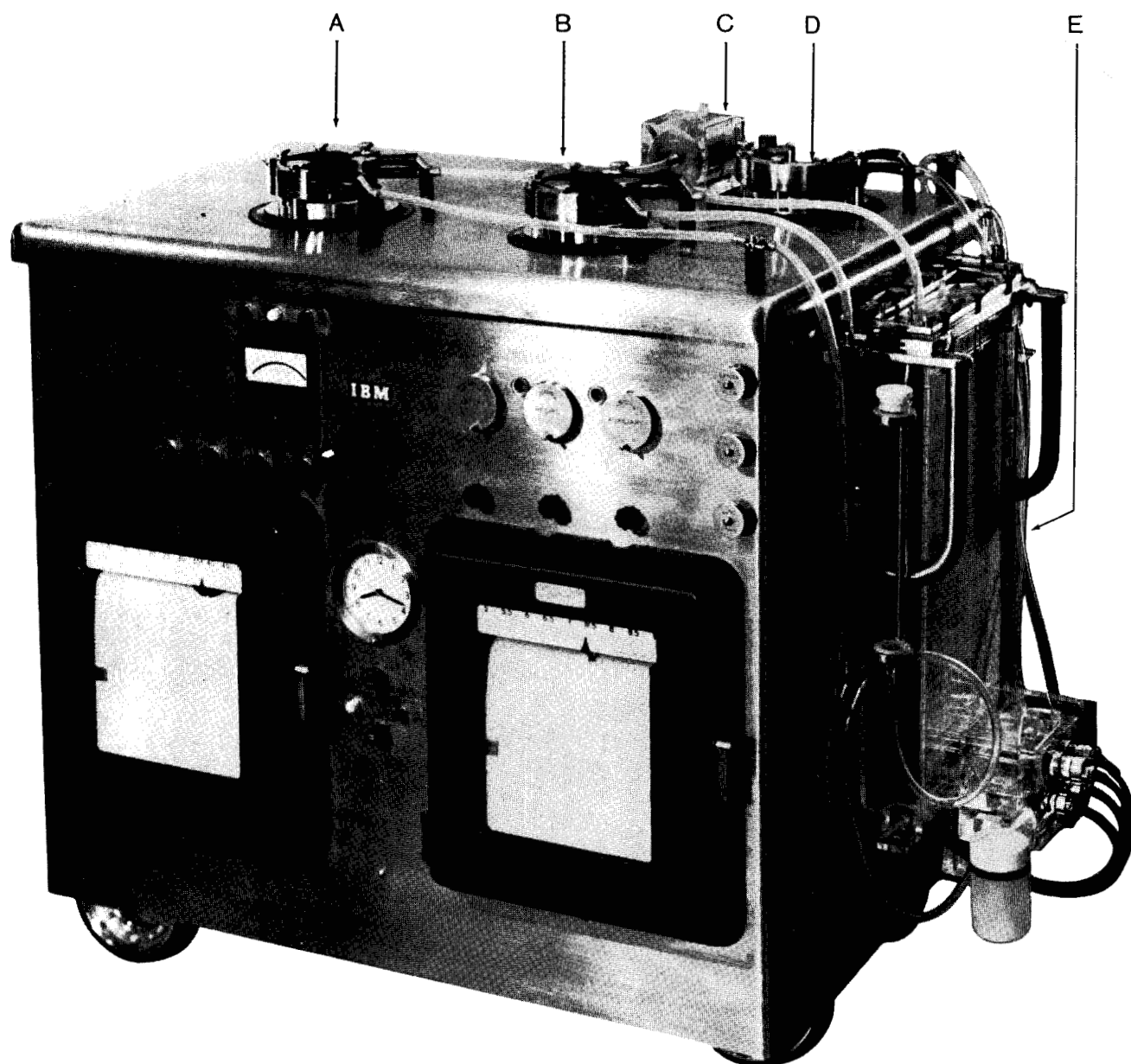


Figure 3 Model III Heart-Lung Apparatus.

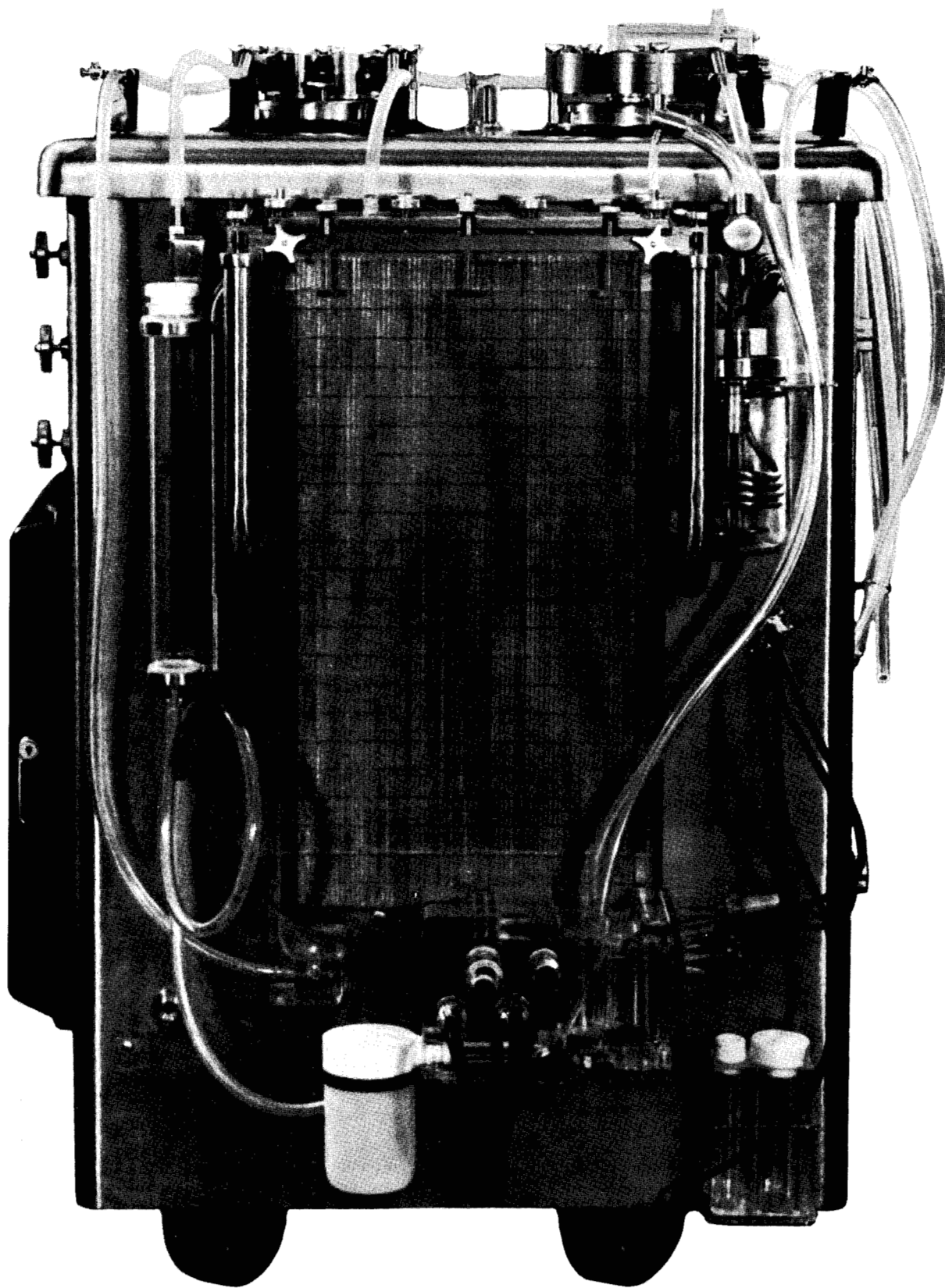
A. Arterial pump; B. Auxiliary pump (removes remaining blood from heart); C. Filter; D. Recirculation pump; E. Mechanical lung.

Mechanical lung design

With these blood characteristics and a few other requirements in mind, the designer is in a position to try to design a mechanical lung. These *other requirements*, however, also call for considerable thought. The oxygen-carbon dioxide transfer should not be accompanied by evaporation of water from the blood nor condensation of water into the blood; the design of the lung should not be such that large quantities of blood are needed for priming; the lung must be easy to take apart for cleaning and must have no inaccessible cracks or crevices where blood can stagnate and spoil; the materials of construction must be immune to the attacks of normal sterilizing

solutions; the lung must not weigh too much and thereby become hazardous to handle; and it must have a transparent case so that its operation can be viewed at all times by the surgical staff. Photographs of the mechanical lung attached to the right side of the Model III Heart-Lung Apparatus are shown in Figs. 3 and 4.

To achieve a rapid exchange of oxygen and carbon dioxide with the blood, it is desirable to spread the blood out in a thin sheet so that a maximum liquid surface is exposed to the gas. The first lung made use of a revolving cylinder to accomplish the formation of this film. The cylinder revolved on a vertical axis, and the blood



334 *Figure 4* **Mechanical lung used with Model III machine.**

was poured on its inner surface at the top and collected at the base. Although this system worked moderately well for the experimental Model I apparatus, its many shortcomings made it apparent that a better method would have to be devised if a practical, working oxygenator were to be built.

It was found that an efficient lung could be built if thin sheets of blood were allowed to flow vertically over stainless-steel wire-mesh screens. After trying various screens having many different shapes and sizes of openings, one was selected having a high degree of efficiency, relatively small priming requirement, and also considerable industrial usage so that its continued availability would be better assured.

The basic idea of the wire-screen lung adopted for use on the Model II machine was also used in the later Model III. So far as we know, no more acceptable means for accomplishing the desired result has yet been found. Figure 5 shows the essential elements of this lung. Figure 6 shows a nomograph that proved helpful in reducing the amount of work required to select the most suitable combination of number of screens, and height and width of screen to secure maximum lung efficiency together with the minimum blood-priming requirement.*

The wire screens of this lung are of stainless steel, as are the bars at the top which form the slits which, in turn, allow the blood to flow over the screens in thin sheets, or films (see Fig. 5).

The configuration of the openings in the screens is such as to produce gentle turbulence in the blood stream as it flows over the screens. This action increases the efficiency of operation of the lung considerably since it causes all particles of the blood to come to the surface, that is to the gas interface, as the whole volume of blood flows from the top to the bottom of the screens.

The rated blood-handling capacity of the lung is 4000 cc/min. At this rate of blood flow, the blood can enter the lung having an oxygen saturation of 65% and leave at a saturation of 95%. These saturations correspond, respectively, to normal venous and arterial saturations. To achieve this oxygen up-take in the blood, oxygen gas is passed through the lung case at the rate of 15 liters per minute. A controllable amount of carbon dioxide is mixed with the entering oxygen stream to keep the carbon-dioxide content of the blood at the proper level, as described below for the Model III machine. The amount of carbon dioxide mixed with the oxygen flows in at a rate of from zero to 1.5 liters per minute. This mixture of the two gases is heated to blood temperature and saturated with water vapor prior to entering the lung case, which itself is provided with an electric heater to prevent condensation of water. These precautions are taken to avoid the possibility of changing the water content of the blood as it passes through the mechanical lung.

*A good deal of credit should be given to Dr. Caddell and his associates at the E. I. duPont de Nemours Company for their help and cooperation in determining the oxygen transfer coefficients for blood under the conditions prevailing in our mechanical lung.

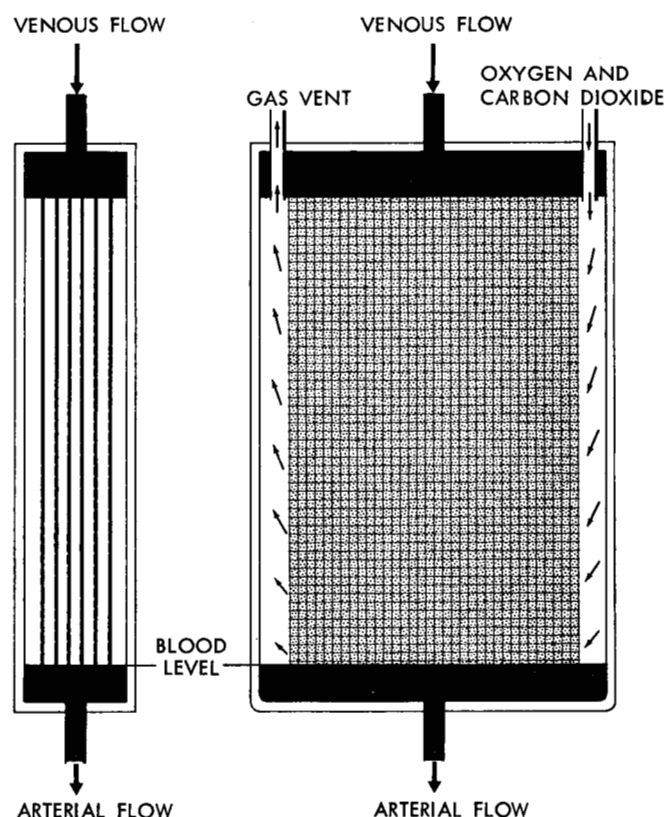


Figure 5 Diagram of mechanical wire-screen lung showing method of operation.

Mechanical blood pumps

The blood is pumped by means of DeBakey pumps.† The particular feature of these devices that makes them useful for this service is the fact that they have no valves nor other similar moving parts in contact with the blood stream. The operating principle of the DeBakey blood pumps is illustrated in Fig. 7.

These pumps are capable of circulating large volumes of blood with a minimum of damage because they produce little turbulence in the stream and contain no parts that might prove injurious in contact with any elements of the blood. The rubber tubing used is chemically inert with respect to the blood and presents a smooth, easily-cleaned interior surface.

DeBakey pumps are generally superior to the more common industrial pumps which make use of control valves. The latter pumps are difficult to clean, may present a hemolysis hazard to the blood because of the materials of construction, and almost always involve violent turbulent action which is destructive of the red blood cells. The pumps used in Model III have a maximum capacity of 5000 cc/min. (Fig. 3). They are electric-motor-driven through right-angle variable-speed transmissions.

†Invented by Dr. Michael DeBakey, now Professor of Surgery at Baylor University, Houston, Texas.

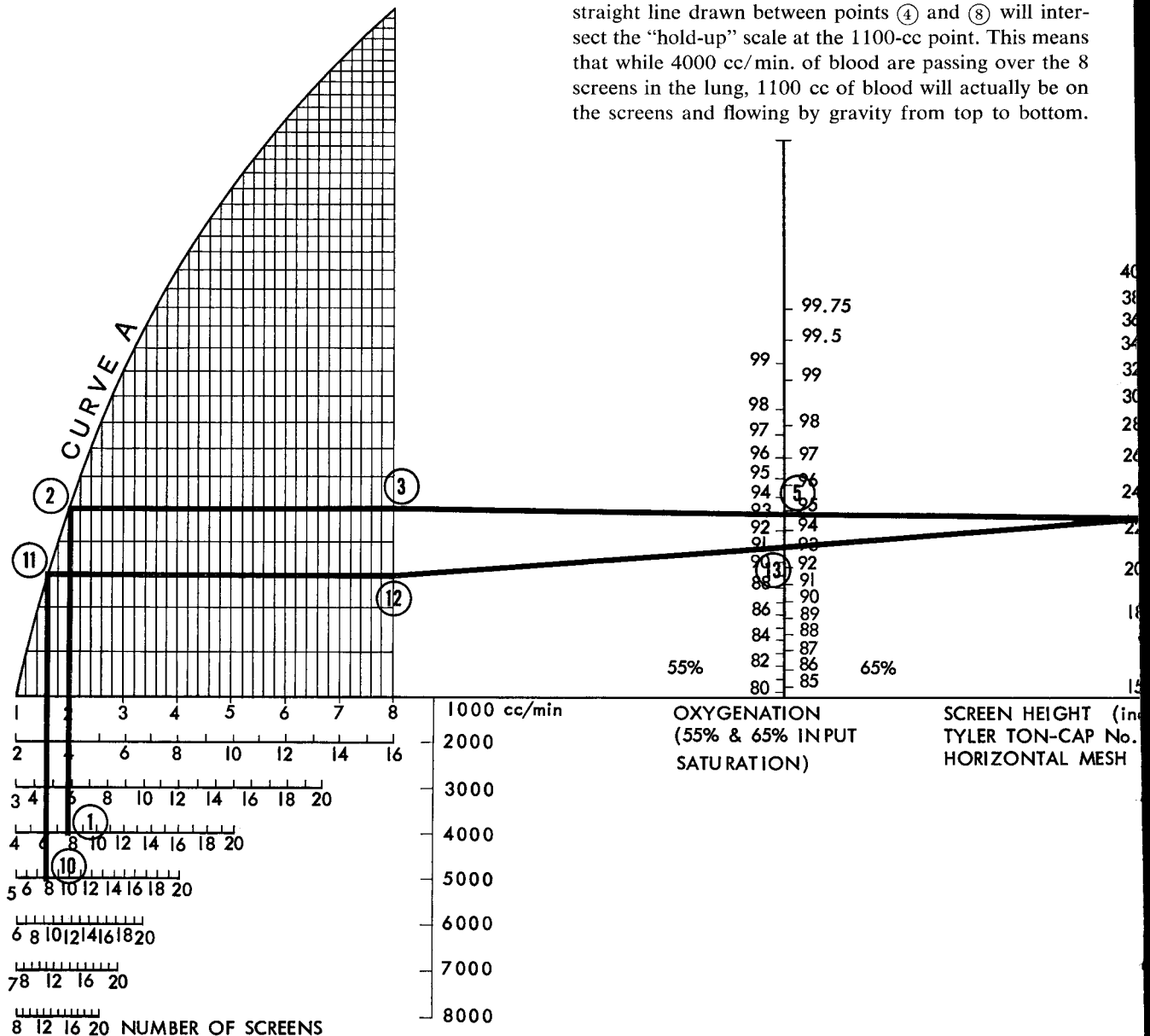
Figure 6 **Design nomograph for mechanical lung wire-screen assembly.**

The data on the nomograph apply to a particular type of screen (Tyler Ton-Cap No. 538 horizontal mesh); the nomograph is direct-reading when the width of the screens is 12 inches. The following two examples describe how the nomograph is used.

• Example I

The design objective of the lung is to increase the oxygen content of the blood from 65 to 95% when the blood flow is 4000 cc/min. The lung has 8 screens 12 inches wide and an effective height of 23 inches. Start on the abscissae of Curve A at the point for 4000 cc/min. and 8 screens (point ①) and proceed vertically upward until Curve A is reached (point ②). Then proceed horizontally to the right until point ③ is reached. A straight line passed through this point ③ and point ④ (the 23-inch screen height) will intersect the "oxygenation" scale at 95%.

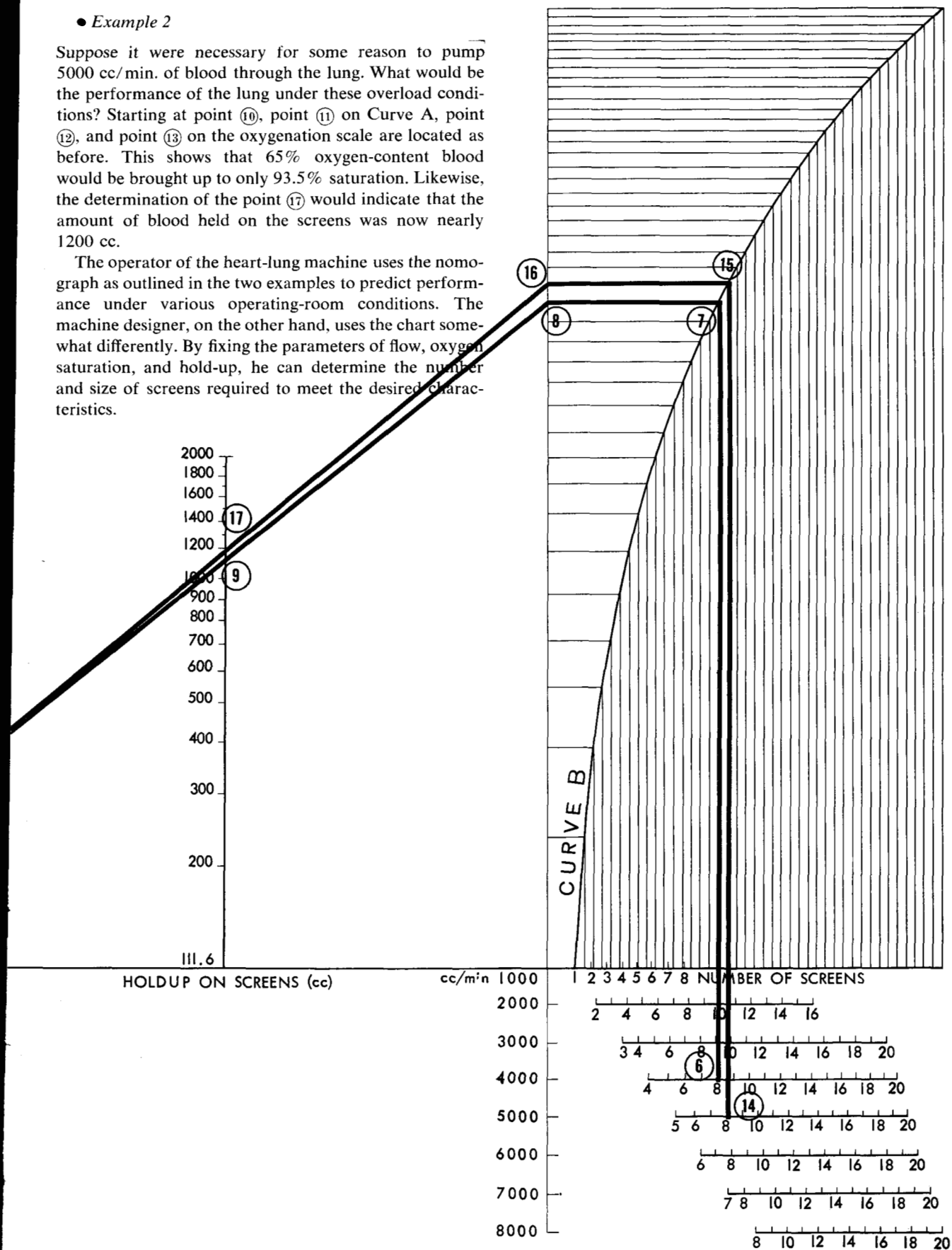
If the blood should enter the lung with only 55% oxygen content instead of 65%, it will leave the lung at about 93.3% saturation rather than 95%. In a similar fashion, the lung blood-priming requirement may be determined by the use of Curve B on the right side of the nomograph. Start at point ⑥ and proceed to points ⑦ and ⑧. A straight line drawn between points ④ and ⑧ will intersect the "hold-up" scale at the 1100-cc point. This means that while 4000 cc/min. of blood are passing over the 8 screens in the lung, 1100 cc of blood will actually be on the screens and flowing by gravity from top to bottom.



• Example 2

Suppose it were necessary for some reason to pump 5000 cc/min. of blood through the lung. What would be the performance of the lung under these overload conditions? Starting at point ⑩, point ⑪ on Curve A, point ⑫, and point ⑬ on the oxygenation scale are located as before. This shows that 65% oxygen-content blood would be brought up to only 93.5% saturation. Likewise, the determination of the point ⑰ would indicate that the amount of blood held on the screens was now nearly 1200 cc.

The operator of the heart-lung machine uses the nomograph as outlined in the two examples to predict performance under various operating-room conditions. The machine designer, on the other hand, uses the chart somewhat differently. By fixing the parameters of flow, oxygen saturation, and hold-up, he can determine the number and size of screens required to meet the desired characteristics.



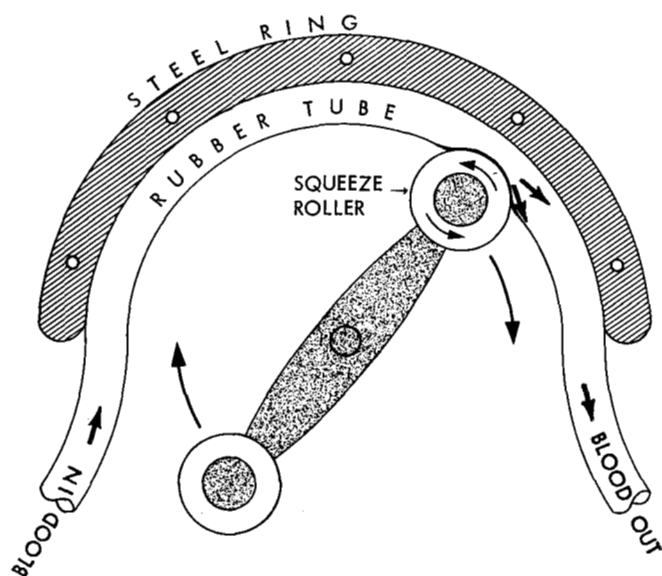


Figure 7 Operating principle of DeBakey blood pump.

A set of two rollers revolve in such a way that the pliable tubing is partially closed first by one roller, then by the other, to urge the liquid contained in the tubing to flow in the desired direction.

Operation of Model III oxygenator

The job of the heart-lung apparatus is essentially one of withdrawing blood from a patient's veins, removing the carbon dioxide and replenishing the oxygen content, and finally pumping the blood back to the patient's arterial system with as little disturbance to other physiological conditions as possible. Figure 2 shows in schematic form the relation of the machine to the patient's blood system, and Fig. 8 depicts, also somewhat schematically with many details omitted, what happens to the blood as it passes through the oxygenator.

To place one of these machines in readiness for an operation, it must first be primed with blood of the correct type to match the patient's own blood. The priming blood is carefully fed into the apparatus in such a way as to prevent the formation of air bubbles which might later find their way into the patient's body. All tubing and vessels are filled to the proper extent, and finally the recirculation pump (see Fig. 8) is started to cause a film of blood to form over the screens of the mechanical lung. The flow of blood is now just from the blood-receiving chamber, through the recirculation pump, over the screens of the lung, and back to the receiving chamber. The patient has yet to be connected to the machine.

The speed of the recirculation pump is set at this time so that the rate of blood flow around the recirculation loop will exceed the maximum amount that the patient

himself can provide. Once this pumping rate has been set, it is unnecessary to change or adjust it during the operation. The apparatus is constructed in such a way that, once the recirculation rate has been established and the tubing and other parts have been fully primed with blood, no change in the volume of blood contained within the machine can take place. This constant-volume feature has an important bearing on the proper functioning of the apparatus with respect to the patient in that it allows the blood flow to and from the patient to vary over a wide range without causing a change in the volume of blood within the patient himself. The quantity of blood required for priming purposes is approximately 2600 cc.

Following the priming procedure, the patient is connected to the apparatus as indicated in Fig. 2. As the patient's venous blood flows by gravity into the receiving chamber, the level there will start to rise and thereby cause the arterial pump to pump blood back into the patient's arteries. The level-control system operates in such a way as to insure that as much blood is pumped back into the patient's arteries as is withdrawn from his veins.

Meanwhile, other controls are at work to maintain blood temperature and alkalinity or pH value, at their proper levels. Blood temperature is controlled by a thermostat and electric heater in the recirculation loop as shown in Fig. 8. The pH controller measures the pH value of the blood and adjusts the admission of carbon dioxide to the mechanical lung so as to maintain the pH near the correct value of 7.38. Increasing the amount of carbon dioxide that is mixed with the oxygen causes the blood to retain more of its own carbon dioxide which in turn lowers the pH of the blood. Decreasing the amount of carbon dioxide supplied to the lung produces the opposite effect on pH. The maintenance of the correct value of pH is essential if the blood is to perform its proper function of transporting oxygen and carbon dioxide to and from the tissues of the body, since the ability of the hemoglobin in the red cells to pick up and release oxygen and carbon dioxide depends critically on this pH value.

There are other features of the Model III machine which were omitted from the sketch of Fig. 8 for the sake of clarity. A means for administering transfusions to the patient is provided by the connection of a burette to the blood-receiving chamber. Any blood allowed to flow into this chamber from an external source, such as a burette, will be pumped into the patient since the control of the apparatus maintains a constant blood level in this chamber and, hence, a constant volume of blood within the machine itself.

A third pump is also available, but not shown in the diagram, to withdraw, from the opened chambers of the heart, blood that enters the heart through the coronary arteries or coronary sinuses. The volume of this flow may be as great as twenty percent of the total flow and is, therefore, much too large an amount to discard; blood from this source is pumped back to the receiving cham-

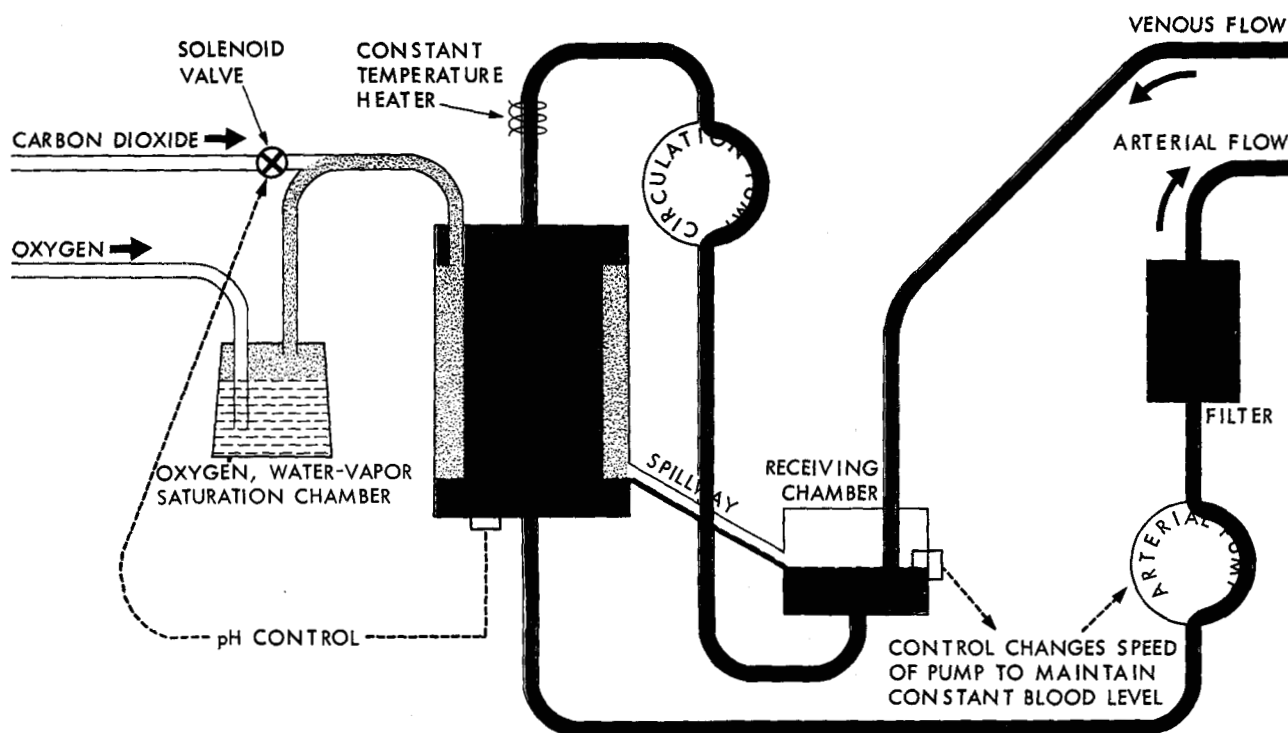


Figure 8 Schematic diagram of Model III Heart-Lung Apparatus.

ber by the third pump and there mixes with the blood entering the chamber from the two vena cavae.

Machine controls

Provision has been made for the measurement and control of the temperature of the blood within the machine. This temperature and the patient's rectal temperature are both recorded automatically at frequent intervals. Blood flow through the arterial circuit and through the recirculation loop is indicated by means of tachometers associated with the respective blood pumps. The machine also maintains the pH of the blood at a value near 7.38, as has been mentioned previously; a continuous strip-chart record of this quantity is also obtained. Blood tests of small samples of the patient's blood, his blood pressure, the degree of anesthesia, and various other vital factors are among the items requiring the attention of doctors and attendants during an operation, but the machine itself is not directly concerned with the making of these measurements or determinations.

Included in the equipment are many safety features to insure that unusual and unforeseen happenings have the least possible chance of upsetting the operating procedure or of causing injury to the patient. Among these features are devices to detect abnormally high or low blood level in the apparatus, or abnormally high arterial blood pressure at the outlet of the arterial blood pump. In case of failure of the automatic controls, manual controls may be employed so that the operation can continue.

A battery-powered motor-generator set was provided (as a separate unit) for use in the event the normal hospital electric service should fail, but this feature has never been needed.

A good deal of thought has been given to the design of the heart-lung apparatus to make its operation simple and reliable so that only a minimum of attention is required while an operation is in progress. Two persons are needed to attend its functioning, and one of these is present for purely supervisory purposes.

The main body of the apparatus is a Monel metal cabinet about 49 in. long, 30 in. wide, and 44 in. high which houses the electric motors for the pumps, various electrical controls including the electronic blood-level controls, and valves to control the flow of oxygen and carbon dioxide. Most of the electrical circuitry and components are built on a plug-in, modular basis for ease of maintenance. The mechanical lung, the hydraulic blood pumps, and all the plastic tubing through which the blood flows are attached to the outer Monel surfaces of the cabinet (Fig. 3). The design of the cabinet is such that it is not damaged in any way by contact with blood, nor with any of the common cleaning solutions; it may be washed down with a hose, if desired, at the end of an operation, without harm to the equipment within.

Other heart-lung machines

Shortly after the Model II apparatus was constructed, surgeons at the Mayo Clinic in Rochester, Minnesota,

started building their own equipment, following an extensive survey in which they determined that the IBM-Gibbon-type apparatus was best suited to their needs. The Mayo machine, while patterned to some extent after the IBM drawings of Model II, is larger in blood-handling capacity and contains some novel features not incorporated in Model II. It is understood that the Clinic has built a second machine and that both of these units are in regular service in Rochester.

Funds have been secured by public subscription in St. Louis for the construction of an apparatus to be used in surgery at the Barnes Hospital in that city, but little is known at this writing of the details of design of this new machine. Public announcement of its completion has not yet appeared.

Plans and drawings of the Model III apparatus have been sent by IBM to nearly a dozen medical institutions at their own request and with the concurrence and approval of Dr. Gibbon and the Trustees of the Jefferson Medical College. IBM has made all three models of the heart-lung apparatus as gifts to Jefferson and has placed

all patent rights and other control for these machines in the hands of the Jefferson Trustees, who in turn have since turned them over to the Research Corporation, New York City.

IBM personnel engaged in this project

The early experimental work on the heart-lung apparatus and the building of Models I and II was carried on under the direction of Mr. A. V. Malmros, who was then in charge of the IBM Endicott Physics Laboratory. The design and construction of Model III was accomplished by IBM's Department of Medical Equipment Engineering under the direction of the writer. Endicott engineers D. K. Rex, L. E. Farr, E. A. Barber, H. C. Kuntzleman, C. Coulter, S. E. Abramson, G. Neilsen, E. Clavez, J. Engstrom, and B. Marks, contributed greatly to the design of one or several of the three units and were ably assisted in the construction by W. Wingate, R. L. Avery, B. Kamp, J. Piechowski, and E. Brock.

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