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The Development and Use of a Mechanical Heart

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THE DEVELOPMENT AND USE
OF A MECHANICAL HEART

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by

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AN ABSTRACT

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This report deals with the problems involved in the development and use of a mechanical heart. An artificial lung is often used in conjunction with a mechanical heart so artificial oxygenation was also included.

The material for this report was taken from medical journals, scientific journals, and textbooks of anatomy and physiology.

Problems encountered in the development of a mechanical heart that were solved included the blotting of blood, hemolysis, air entering the blood, oxygenation of the blood, and the attachment of blood vessels to a mechanical heart.

The clotting of blood was prevented by the use of heparin. Removal of the heparin effect was accomplished by transfusion of whole blood or, in some cases, protamine sulfate was successful.

Hemolysis was reduced by making the functioning parts of the mechanical heart of smooth inert material. The pumping mechanisms of the later models move blood in a fashion similar to a living heart, thereby preventing trauma to the blood.

Air was prevented from entering the blood by the use of a cellophane dialysis-tubing obturator and by removal of canulae while they were under a saline solution.

The oxygenation of blood was accomplished through the use of dialysis, bubbling, or filming.

Blood vessels were handled with care to prevent permanent injury. They were carefully selected for the return of the blood to the body. Short catheters were used whenever possible to prevent excessive pumping pressure. Catheters were pointed in the right direction to prevent excessive fluid accumulation in parts of the body.

The mechanical heart is now a useful device and its use is increasing in many hospitals.

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CHAPTER I

INTRODUCTION

This report deals with the problems involved in the development and use of a mechanical heart. An artificial lung is often used in conjunction with a mechanical heart, so artificial oxygenation was also included in this report.

Much of the material for this report was taken from medical journals. Other scientific journals also proved very useful. Pertinent chapters in textbooks of anatomy and physiology were reviewed to gain accurate information on these phases of the mechanical heart problem.

The prevalence of heart disease is well known to almost everyone; however, the fact that surgery can cure many kinds of heart disease is not common knowledge. In fact, until recently, any invasion of the heart was considered a tragedy. Today heart surgery in many forms is commonplace. However, successful surgery was limited to repair of stenosis of valves until some safe method of stopping the heartbeat could be developed. The first attempt at surgery with a stopped heart involved the use of hypothermia. This method was limited by the short amount of time it permitted a surgeon to work. Thus it was imperative that some method of artificial pumping be developed before all types of heart surgery could be successful.

Artificial by-pass of only the left side would be very useful in aiding heart surgery. Dodrill, _et al._ (1952) stated that complete by-pass of the left ventricle by the blood would be helpful in several conditions in humans. Foreign bodies could be removed from the wall of the heart without danger of hemorrhage. It would be theoretically possible that such pathological processes as aneurysms of the left ventricle, severely infarcted areas, and neoplasms involving the heart wall could be resected while the systemic circulation was maintained. Since both the mitral valve and the aortic valve are not functioning while the left ventricle is being by-passed, pathological conditions involving these valves would be more amenable to surgical procedures. In fact, almost any kind of surgery could be performed on the heart if it could be stopped.

There are many anatomical and physiological factors relevant to the development and use of a mechanical heart so a chapter on circulation was included to make it easier to understand the mechanical heart problem.

CHAPTER II

THE CIRCULATORY SYSTEM

This chapter on the circulatory system is divided into four parts: (1) the heart, (2) blood vessels, (3) blood, and (4) blood pressure. Material for this chapter was chosen for its relevance to the mechanical heart problem.

The heart. The heart is a living pump that furnishes the power to maintain the circulation of the blood. At rest it must force 40 to 60 cc. of blood per stroke through the vascular circuit. Part of the energy of the heartbeat is used in moving the blood through the vessels, part is used in overcoming the friction offered by the blood vessels, and part as filtration pressure in the formation of tissue fluids of the body and of the glomerular filtrate in the process of urine secretion.

The heart, which is a hollow muscular organ, weighs about 300 gm. in the male. In a female the weight is about 250 gm. The heart is about 12 by eight cm. in size. It is completely divided by a partition into right and left halves, and functions as a double pump. The right side pumps blood through the lungs while the left side pumps blood through the rest of the body. The upper chambers of the heart are called atria and the lower are called ventricles.

The walls of all the chambers consist of three layers; an inner, the endocardium, a middle, the myocardium, and an outer, the epicardium. The endocardium is a smooth layer of endothelium in contact with the blood. The myocardium consists of layers of muscle. These layers are relatively thin in the atria but thicker in the ventricles. The wall of the left ventricle is three times as thick as that of the right ventricle.

The entire heart contains 10 openings. The right atrium has three, two for the venae cavae which return the blood from the systemic circulation to the heart, and the atrioventricular orifice. The superior vena cava drains the head, thorax, and upper extremities and enters the right atrium from above. The inferior vena cava drains the abdomen and lower extremities and enters the right atrium from below. These openings do not need valves since the atrial pressure is rather low. The atrioventricular opening leading to the right ventricle is guarded by the tricuspid valve. The right ventricle has a second opening, the pulmonary opening, leading into the pulmonary artery. This opening is guarded by the pulmonary semilunar valves.

The left atrium has four openings for the pulmonary veins, which return oxygenated blood from the lungs. The mitral valve guards the opening between the left atrium and left ventricle. The left ventricle also has an aortic opening, which is guarded by semilunar valves (Millard and King, 1945).

Blood vessels. Three kinds of blood vessels make up the blood-carrying organs of the body. These are the arteries, veins, and capillaries. The veins connect with the capillaries and carry the blood back to the heart.

The walls of arteries contain three distinct layers: the tunica intima, the tunica media, and the external coat or tunica adventitia.

The tunica intima is composed of endothelial cells and elastic tissue. The tunica media consists mainly of smooth muscle and elastic tissue. The tunica adventitia is made up of collagenous and elastic fibers in loose arrangement.

The lumen of the largest arteries, the aorta and the pulmonary, is about 25 mm. in diameter. The diameter of the lumen of the smallest arteries is about 3 mm. The diameter of the arteries is increased as blood is forced through them.

The walls of veins also have three layers but are thinner than arteries and are less elastic. The middle layer is poorly developed. Some veins contain valves which permit the blood to go in only one direction.

The capillaries are very fine thin tubes approximately eight microns in diameter. Their walls consist of a single layer of endothelial cells. The capillaries are the functional parts of the circulatory system. Through their walls, materials must pass into and out of the blood.

Several blood vessels, especially related to the use of a mechanical heart, deserve special mention. The aorta, a large artery arising from the left ventricle, supplies blood to all parts of the body. The innominate artery is a large short artery which arises as the first branch of the aorta and divides into the right subclavian and right common carotid arteries. The left common carotid artery and left subclavian artery are the other two arteries branching directly from the arch of the aorta. The two subclavian arteries arch in the neck above the clavicle and pass out to the axillae, where they branch into other arteries. The iliac arteries branch from the aorta into the legs and lead into the femoral arteries.

Several veins are used during the operation of a mechanical heart. The venae cavae have already been described. The head and neck regions are drained by the external and internal jugular veins. The external jugular vein flows into the subclavian just before the latter unites with the internal jugular to form the innominate. The innominate leads into the superior vena cava. The cephalic is a superficial vein on the lower arm. The femoral vein is located in the upper leg. It leads to the iliac vein which drains into the inferior vena cava (Millard and King, 1945).

Blood. There are properties of blood that need to be considered because of their relationship to the use of a mechanical heart. The primary function of the blood is to mai tain the constancy of the internal environment. This homeostasis is achieved, at least in part, by the movement of blood through the vascular circuit. Immunological substances must also be moved throughout the body.

The clotting of blood consists of two phases. The first phase is the conversion of prothrombin into active thrombin. In the second phase, fibrinogen is converted into fibrin. There are favorable and unfavorable factors influencing the clotting of blood. Contact with foreign materials and injured tissues tend to accelerate blood clotting. The inside surfaces of the vessels through which blood passes must be very smooth and hydrophobic or clotting will begin.

One of the problems encountered when using the mechanical heart is the prevention of blood clotting. This is usually accomplished by the use of heparin. Heparin acts by delaying or inhibiting the clotting reaction.

Blood pressure. Blood pressure is another aspect of the circulatory system closely related to the mechanical heart problem. Blood pressure is the result of the pumping action of the heart against arterial resistance and viscosity. During rest the heart pumps approximately four l. of blood per min. During strenuous exercise the output increases to 30 or 40 l. per min. The heart adapts itself to such wide variation by changes in venous return, in force of the heartbeat, and in frequency of the heartbeat.

Other factors of blood pressure need to be considered. First, the resistance offered by the peripheral blood vessels is due mainly to the degree of constriction of the arterioles. When they are constricted the blood pressure increases. Dilation of the vessels increases the vascular capacity and lowers blood pressure. The more fluid the vascular bed contains, the greater will be the pressure. The lymphatic system and the kidneys tend to keep the volume at the same level. The blood is about five times as viscous as water. This aids in the maintenance of blood pressure. The elasticity of the arterial system aids in keeping the blood pressure at the proper level. As the ventricular systole ends, the arterial walls press upon the blood to help force it through the vessels. As a result the pressure is continuous rather than pulsatile (Fulton, 1949).

CHAPTER III

DEVELOPMENT OF THE MECHANICAL HEART

Pumping devices were being made and tested before 1928 (Dale and Schuster, 1928). The devices were improved and the first successful experiments with animals were performed in 1950. Brull (1950) reported on the use of a mechanical heart with coagulable blood. This device was made from an aorta in which blood was propelled by a roller pulley. Peripheral resistance was provided by a perfused organ and by a shunt that was coated inside by a carotid. Air pressure exerted on this vessel regulated the arterial pressure. The iliac division of the aorta was included. All the branches were carefully ligatured. The aorta was cut five cm. below the left subclavian. The central end of the peripheral part was turned inside out over a Payr's canula 10 to 12 mm. in diameter and 80 mm. in length. The distal part of the vessel emerged from a rubber tube. The superior mesenteric branch was connected with a shunt which was a pressure regulator. One of the renal arteries was connected with a monometer. One of the iliac arteries led to a perfused organ or organs (i.e., kidneys). The other iliac artery, clamped, was used for rinsing the air out of the preparation. The canulae were coated on the inside with arteries. The output of the device was from 700 to 1000 ml. per min. against pressures from normal level up to 300 mm. of Hg. The blood was sent back to the right atrium through the jugular vein.

Helmsworth, et al. (1952) gave a complete account of artificial oxygenation and circulation during complete by-pass of the heart. The machine described depended upon dispersion for the introduction of oxygen into the blood and for the elimination of carbon dioxide. It provided for the removal of carbon dioxide and excess oxygen, in the form of bubbles, before the blood was pumped back to the animal. The pumping effect of this machine was obtained without the use of rollers, diaphragm, or piston systems. No moving parts were in contact with the blood.

The inferior and superior venae cavae were drained through a canula. The blood flowed upward in an inner sintered glass channel of a double-walled pyrex chamber. Oxygen was delivered at a pressure of five to ten lb. per sq. in. into a glass jar surrounding a central porous walled cylinder. It then passed through microscopic openings and entered the blood in the form of tiny bubbles. The sizes of the bubbles were determined by the diameter of the pores (four to five microns) in the wall of the central cylinder and possibly by the surface tension of the blood. The surface of the sintered glass had to be wettable by blood. If the porous surface was hydrophobic, the bubbles would have been too large for efficient gas exchange.

The blood had to be freed from bubbles (excess oxygen and carbon dioxide) before being returned to the animal. In a pyrex coalescence chamber tiny bubbles coalesced to form large bubbles which were withdrawn. Blood was passed over a broad surface coated with polymethylsiloxane defoaming compound. The coalescence chamber was packed with fine polyethylene fiber which was coated with two gm. of antifoam A evaporated from an ether solution.

During the third step bubbles were removed through a suction chamber. Electrodes, dipped in the chamber, controlled the suction. A small current passed when the electrodes were in contact with the blood. This automatically turned on a suction device. It was shut off, automatically, when the blood was below the electrodes. The blood was now ready to be pumped back to the animal.

The materials used had to be chemically inert. Valves were made of silastic in the shape of flat tubing. The adjustable electrodes were stainless steel rods in lucite holders. Except for the porous unit for oxygen dispersion all the glass parts and the plastic tubing (Surgical Koroseal or Tygon S-22-1) used for making connections were coated with silicone. The coating was reapplied after 20 experiments or when the surfaces no longer appeared hydrophobic.

There are several machines that could be used as sources for suction or pressure. In the pump described in the previous paragraph, a whirlwind machine was the source of suction and an oxygen tank the source of pressure. The pumping rate was controlled by regulating the clamp on the suction-pressure line, or the line leading from the machine to the animal.

Cleaning of the parts was thorough; however, no attempt was made to adhere to aseptic surgical procedures. The parts were cleaned with saline, then water, then with water containing chlorine. The polyethylene fiber in the coalescence chamber was rinsed with water, then 95 per cent alcohol and finally with ether in order to remove the antifoam compound. The polyethylene fiber was then recoated. Sulphuric acid was used to clean the porous glass wall. The coalescence chamber was sterilized by soaking it in a germicidal solution.

Helmsworth, _et al_. (1952) reported on the procedures used in experiments on dogs using the suction device previously described. All tissue was clamped before being separated. The right pleural cavity was entered through the fourth intercostal space. The femoral arteries and veins and the right common carotid were dissected free for a distance long enough to permit canulation. When the chest was opened, controlled pressure was applied to a breathing bag attached to an endotracheal tube. Rib margins were separated with a self-retaining retractor and the right lung was moved so as to expose the superior vena cava. A rubber ribbon was passed around the superior and inferior venae cavae at their entrance into the right atrium. Venous return in the coronary sinus was drawn off by a simple suction device and measured.

Heparin was given to render the blood incoagulable. Ten mgs. per kg. of body weight had to be given before the coaguability of the blood was sufficiently reduced. Reversal of the heparin effect was a problem. Protamine sulfate was used but this caused severe hypotension. Transfusion of fresh whole blood proved successful.

The tendency of the walls of the venae cavae to collapse presented another problem. This condition was corrected by the use of a femoral vein canula. Danger of air embolism during insertion of the canula was eliminated by the use of a cellophane dialysis-tubing obturator in the lumen of the canula.

At the termination of total by-pass, closure of the heart and removal of the right heart canula were accompanied by the danger of air embolism. Possibility of trapping air in the heart was reduced by allowing the heart to fill completely, before closure, with blood from the coronary sinus, or by pouring in saline to fill the atrium. The danger of air embolism during the removal of an L canula was minimized by filling the pleural space with saline, withdrawing the instrument, and clamping the vein under the level of the solution.

In early experiments oxygenated blood was returned through both femoral arteries in a retrograde fashion by the use of polyethylene catheters passed into the arch of the aorta. Arterial return by this method was adequate, but high pumping pressures were necessary in order to overcome the resistance in long catheters. Return through one femoral and one common carotid artery caused orbital edema. Most successful was return through a catheter pointed centrally in the right femoral artery, and the other pointed toward the heart in the right common carotid. These catheters were four mm. in diameter and were inserted for only short distances.

Two additional canulations completed the pickup and return. A catheter was placed in the right femoral vein and this served for vein to vein pumping. The left femoral artery was canulated to obtain blood pressure and for oximetry. Partial by-pass was used until mechanical adjustments were made.

The mean blood pressure remained within a normal range in most of the animals during total by-pass. Animals continued normal respiratory movements. Ventricular contractions remained strong and tended to slow down. Formation of urine was not interrupted. Oxygen saturation before by-pass was between 93 and 98 per cent. During by-pass it was between 90 and 95 per cent.

Before the pumping began, the plasma pH gradually fell. This change was probably due to retention of carbon dioxide, resulting from the method of anesthetization and inflation of the lungs. During the by-pass period, the tendency toward acidosis was somewhat aggravated. In the post-pumping period the pH fell further.

Liberal doses of antibiotics were administered but long-term survivors were few. Fifty-two remained alive until by-pass circulation was completed. Fifty-seven dogs were used but only seven lived for several months. Causes of deaths were the following: (1) pleural adhesions, (2) pericardial effusion, (3) subcutaneous abscesses in the chest wall, (4) chylothorax and compression atelectasis, (5) pulmonary consolidation, (6) thrombosis of the superior vena cava, (7) pulmonary edema, (8) purulent pericarditis. Transfusion of incompatible blood caused deaths in the first 29 experiments. Filters caught some erythrocytes and fibrin masses. Filters were not used in most of the surviving dogs.

Causes of thrombosis of the superior vena cava were: (1) trauma to the intima of the superior vena cava during canulation and while the walls of the venae cavae were pressed to the canula in the period of total by-pass; (2) the intravenous administration of protamine sulfate into the cephalic vein, relatively close to the site of caval trauma and the stump of the azygos vein; (3) local infection in animals with septicemia; and (4) abrasions of the intima of the superior vena cava.

With some practice, the canula could be inserted without intimal trauma. Narrow rubber bands have been employed as ligatures to compress the caval walls around the canula. This caused less damage than the use of cords for this purpose.

Dodrill, et al., (1952) described a pump that was used in many successful experiments. This pump worked by creating a volume change in a latex rubber finger cot that was enclosed in a cylinder. The finger cot also separated the actuating air from the fluid being pumped. Volume change of the finger cot was achieved by collapsing it with negative air pressure and then expanding it with positive air pressure. Collapse of the finger cot resulted in liquid being drawn into the cylinder through the inlet valve. Expansion of the finger cot forced the liquid out of the cylinder through the outlet valve. The inlet and outlet valves were closed by pressure to provide unidirectional flow of the blood. Positive and negative air pressures were admitted alternately to the finger cot by an air valve which could be operated at different speeds. There were six individual units on each side. The machine was tested with water to determine its operating characteristics. Tests were also run to determine the amount of hemolysis. No significant hemolysis occurred during short periods of operation.

As less pressure is required to pump blood to the lungs than to the rest of the body, a continuous flow pump was designed for the right side. This constant flow on the right side was obtained by valving the admittance of air pressure to the inside of the finger cots in such a manner than one of the six individual pumps discharged every 60 degrees of camshaft rotation. Use of 12 mm. tubing with six units gives the pump a capacity of approximately five l. per min.

Pump parts were made of stainless steel, glass, and rubber. Standard Pyrex brand glass was used for the glass parts while the finger cots were made out of surgical latex rubber. Individual units were very easy to disassemble for cleaning and autoclaving. All surfaces that came in direct contact with the blood stream were coated with Cow Corning DC-1107 Silicone dissolved in carbon tetrachloride. After coating, the metal and glass parts were baked for one hr. at 300 deg. F. This made the surface practically non-wettable, thereby preventing the formation of fibrin.

This pump was selected for further analysis and testing because it was a variable displacement pump; that is, each stroke of the pump was accompanied by discharge of a quantity of fluid governed by the actuating pressure and resistance to fluid flow in the circulatory system. The pump had three camshaft speeds: 65, 75, and 85 rpm. Separate controls for positive and negative air pressures were provided for each side.

A flow meter assembly served three purposes: flow-rate indication, filtration of the blood, and collection of any air that may enter the system. When the flow meter was used on the delivery side of either pump, a considerable pulse dampening took place because of the large volume of air or oxygen trapped in it. Pressure and vacuum were supplied by two air pumps at a distance from the pump.

Sixty-five experiments, in which this pump was used, were performed on dogs. No deaths occurred due to infection but other problems were encountered. Uncontrollable oozing took place if more than five mgs. of heparin per kg. of body weight was used. The Bainbridge reflex in the right heart of dogs caused the blood pressure to be lowered. Atropine was used to diminish this condition (such a severe reflex is not present in man). The experimenters had to administer blood and use vasoconstrictor drugs to maintain systemic pressure. The mitral valve was clamped to prevent blood from entering the left ventricle.

A pulmonary arterial pressure pattern was used to determine if all right-sided blood completely by-passed the ventricle. The pressure represented by the right ventricle disappeared. Pressure patterns of the aorta showed partial and complete substitution for the left ventricle.

The devices developed during the past three years are much smaller and more efficient than the older devices. The Selas Corporation of America developed an oxygenation chamber which was used in conjunction with a pump. The apparatus works when oxygen, which is pumped into the cylinder at a pressure of approximately 20 lb. per sq. in. diffuses through a microporous filter disk made of porcelain and having 800,000,000 holes per sq. in. At the same time, blood from the veins is pumped above the filter and mixes with the diffused oxygen. The blood then passes through plastic fibers coated with a substance to prevent foaming, which removes the free oxygen by filtration. The blood is pumped back into the arteries (Jordan, 1955).

Du Shane, et al. (1956) stressed the importance of the mechanical heart. Operations were performed on 20 patients with congenital ventricular septal defects. Such defects may result in death in early infancy or handicapping disability in childhood.

Nineteen of the patients were children under 12 years of age. One was a 29-year-old man. All of the children but two were underweight. All of the children were handicapped in regard to exercise tolerance. Cardiac enlargement was present in all patients.

Repair of defect in each patient was achieved under direct vision during open cardiotomy. The circulation was maintained by a mechanical pump. The time for the operation varied from 10 to 45 min. Canulae within the superior and inferior venae cavae diverted the venous blood from the patient to the mechanical heart. Blood was returned through a canula inserted into the aorta through the previously divided subclavian artery. Blood was collected from the open chambers of the heart by means of a specially designed sucker; this blood was returned to the mechanical heart.

The abnormal opening in the septum was exposed by incision into the wall of the right ventricle. Repair was accomplished by direct suture in the first three patients. In the other 17 a nonabsorbable polyvinyl (Ivalon) sponge was inserted into the opening and sutured to the heart wall.

During the time of extracorporeal circulation, the average flow of blood to the patient was 70 cc. per km. of body weight per min. The oxygen content of the blood leaving patient was between 65 and 85 per cent of saturation. The returning blood was saturated. A dye solution technique was used to determine the effects of the closure. This technique tests the oxygen content of the blood in different parts of the body. Electrocardiograms and electroencephalograms were made continuously throughout the operation in all patients.

Sixteen patients survived the operation and have shown pronounced improvement in general well-being. Only one death occurred in the last 13 operations.

Felipozzi (1956) gave an account of successful operations on two human patients with pulmonary stenosis. These operations were performed under direct vision. A sigma pump took over the work of the heart. The patients' own lungs continued their work of oxygenation. By-pass of the right side of the heart was accomplished by pumping the blood from both venae cavae into one of the branches of the left pulmonary artery. The left heart was by-passed by pumping blood from the left atrium into the right subclavian artery. This procedure makes it possible to correct ventricular septal defects as well as other abnormalities of the ventricles.

Kay, et al. (1956) reported on the use of a pump-oxygenator. According to this article the requirements of a pump-oxygenator are that it must: (1) provide the needs of the body for oxygen without the dangers of emboli or foaming; (2) not be overly traumatic to the components of the blood; (3) not interfere with the clotting mechanism of the blood; (4) maintain the body metabolites; and (5) not significantly alter the acid-base balance.

In the experiments described, a rotating disk reservoir oxygenator with a sigma-motor pump was used experimentally and clinically. Trauma to blood, hemolysis, clotting, and bleeding tendency was not a problem.

Some of the success of the experiments can be attributed to the use of a pump by which hydraulic compression was employed through a fluid medium. This pump was less traumatic than most other pumps. The capacity of the device was increased to more than 4,000 cc. per min. This is sufficient for use in adults. The flow rate of the pump can be varied from 40 to 80 cc. of blood per kg. of body weight per min. The flow rate was determined by the venous return and the level of the mean arterial pressure, which ranged from 40 to 80 mm.

A minimum of 800 cc. of blood is required to prime the machine. An optimum of 1,4000 cc. was used for these experiments. Heparin sodium in the amount of 0.75 mg. per lb. of body weight was used to lessen the danger of clotting.

The average increase in hemolysis during operations on 17 patients was 33.4 mg. per 100 cc. Increase in hemolysis was associated with an increase in flow rates and increase in duration of cardiac by-pass. When teflon-coated disks were used, hemolysis was less than when siliconized disks were used.

Oxygen saturation of the arterial blood in all cases ranged from 97 to 103 per cent while that of the venous blood ranged from 35 to 53 per cent. The greater blood flows per km. were associated with higher percentages of venous oxygen saturation. This may be beneficial but perhaps is not because of the increased trauma to the blood as evidenced by the greater degree of hemolysis.

Acidosis or alkalosis was not a problem. The pH, carbon dioxide content and carbon dioxide combining power of the arterial and venous blood were determined before, during, and after the cardiac by-pass. Hyperventilation prior to the perfusion tends to cause a lowering of the carbon dioxide content in the range of 30 to 45 vol. per cent. However a metabolic acidosis was observed during the by-pass. This corrected itself with restoration of normal circulation. One to two per cent carbon dioxide added to the oxygenator regulated the carbon dioxide content.

Potassium levels were determined before and after the perfusion as an index of the red blood cell destruction and as an indication of whether toxic levels might be reached during the by-pass. The average potassium concentration prior to the perfusion was 3.82 m Eq. per l. as compared to 4.08 afterward. This degree of concentration is not harmful to the blood.

Trauma to the red blood cells and white blood cells did not appear to be significant and no consistent changes were produced by the pump perfusion system. There was platelet destruction in every instance; however, this did not occur to the extent of interfering with the clotting mechanism of the blood. Plasma fibrinogen level in each instance fell only slightly. There were three deaths among 17 patients. This was not necessarily due to the use of the pump but was closely related to the severity of risk and complexity of congenital deformity.

CHAPTER IV

SUMMARY

The mechanical heart has become a useful machine only to the extent that its design has approached that of the human heart. Earlier devices were much too traumatic to the delicate components of the blood. All the functioning parts of the mechanical heart had to be made of smooth, inert material that would not interfere with the blood. The present pumping mechanisms all move blood by alternately squeezing and releasing a flexible tube. No metallic parts touch the blood. A minimum amount of shock is transferred from the motor to the blood. All sharp corners had to be left out of the devices to prevent platelet destruction and hymolysis.

Other problems that had to be solved include the technique of attaching the mechanical heart to the various blood vessels. Blood vessels must be handled with care or permanent injury will result. Also blood vessels must be carefully selected for return of blood to the body. Short catheters should be used whenever possible to prevent excessive pumping pressure. The catheters should be pointed in the right direction to prevent excessive fluid accumulation in parts of the body.

The possibility of air entering the blood stream presented a problem that had to be overcome. Air may enter during insertion of a canula. Helmsworth, et al. (1952) stated that the problem was overcome by the use of a cellophane dialysis-tubing obturator in the lumen of the canula. During removal of a canula, air would enter the blood stream if certain precautions were not taken. The most successful technique was to remove the canula while it was under a saline solution.

The clotting of blood was prevented in most cases by the use of heparin. Removal of the heparin effect was by transfusion of whole blood or, in some cases, protamine sulphate was successful.

The oxygenation of blood was accomplished through the use of one of three methods. They are dialysis, bubbling, or filming. In dialysis, oxygen is made to pass through an artificial membrane much like the lung. Cellophane-like plastic tubing is enclosed in an air-tight drum through which pure oxygen is pumped. In bubbling, pure oxygen is passed up through a reservoir of used venous blood. The mixture is defoamed and the freshly oxygenated blood is returned to the body. In filming, the blood is spread out into a fine surface film which is surrounded by oxygen.

The use of a mechanical heart has increased during the past five years. The Mayo Clinic of Rochester, Minnesota has successfully used a mechanical heart on 175 seriously ill patients (Anonymous, 1957). This is only one of the many places that successfully use the mechanical heart.

Kings County Hospital in Brooklyn, New York plans to use a mechanical heart as standard procedure on patients with a previous heart attack. The mechanical heart would pump only about one-third of the total amount of blood to relieve the burden of the patient's heart. This pumping would continue for about eight hours or until the patient's own heart would be able to handle the full load (Anonymous, 1957).

Other future applications include immediate revival after apparent death, major repair of worn-out circulatory systems, and healing rest for tired hearts (Anonymous, 1957).

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