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Apical-Aortic Shunt : certain physiologic studies and an experimental technic for aortic arch resection

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CERTAIN PHYSIOLOGIC STUDIES
AND
AN EXPERIMENTAL TECHNIC FOR AORTIC ARCH RESECTION

by

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INTRODUCTION

The surgical approach to the problem of aortic aneurysms has proceeded historically along four lines: first, the production of clot within the aneurysm; second, the external reinforcement of the aneurysm using reactive cellophane; third, endo-aneurysmorrhaphy (i.e., obliteration of an aneurysm by suture within the sac), as described by Matas;[53] and finally, excision of the aneurysm with lateral aortorrhaphy for saccular aneurysm and resection and graft replacement for fusiform aneurysm.

In 1864, Moore and Murchison[55] attempted to produce intra-aneurysmal thrombosis by introducing a silver wire into the aneurysm. Since that time, many authors[8,9,13,51] have described similar procedures with varying degrees of palliative success.

Harrison and Chandy[42] were the first to describe cellophane wrapping as a treatment for aneurysms with the stimulation of periarterial fibrosis often acting as an effective reinforcement. However, the realm of curative therapy belongs exclusively to lateral aortorrhaphy when feasible, or to resection with graft replacement.

Tuffier[69] in 1902 recognized that excision and aortorrhaphy was the procedure of choice in the treatment of saccular aneurysms. In his first case of a saccular aneurysm of the ascending aorta, excision could not be accomplished and he was

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only able to ligate the neck of the sac which was left *in situ*. Postoperatively the sac became gangrenous and the patient died of a hemorrhage thirteen days later. Monod and Meyer[54] reported the first successful excision of a saccular aneurysm in 1950.

Resectional Surgery of the Distal Thoracic Aorta

The successful excision of a coarctation of the aorta by Gross and Hufnagel[37] and Craaford and Nylin[22] in 1945 marked the beginning of the era of resectional surgery in the treatment of diseases of the aorta.

Extensive technical problems have not been encountered in resectional surgery of the abdominal aorta below the renal arteries, but resection of the thoracic aorta, and expecially the arch and ascending portions, has posed a considerable challenge. While saccular aneurysms allow tangential excision by lateral aortorrhaphy without interruption of aortic flow, the treatment of fusiform aneurysms of the thoracic aorta requires interruption of the blood flow which introduces two special problems: first, ischemia to the tissues beyond the point of occlusion; and second, a sudden increased load on the left heart which would likely result in acute left ventricular failure if adjuvant measures were not taken. The closer to the root of the aorta that the occlusion must take place, the more difficult are the problems to solve.

Hypothermia, bypass shunting, and temporary maintenance

of the circulation by a pump-oxygenator are the three major methods that have evolved in the resectional treatment of thoracic aortic aneurysms. However, DeBakey and Cooley[26] reported in 1953 the successful resection of a luetic aortic aneurysm located distal to the origin of the left subclavian artery without using any special protective measures. The thoracic aorta was occluded for forty-five minutes and the patient recovered without neurologic or renal sequelae. A second patient reported by the same authors[17] suffered from bilateral lower extremity weakness after an identical period of occlusion without hypothermia or shunting.

<u>Hypothermia</u> Hardin *et al*[41] showed conclusively with dogs that hypothermia between 28 and 30°C. exerts a definite protective effect, both on the spinal cord and on other tissues distal to the point of aortic occlusion. Many other reports[7,17,25,28,41,47] have dealt with the application of hypothermia to patients undergoing resectional surgery of the descending portion of the thoracic aorta.

<u>Bypass Shunting</u> One of the earliest attempts to resect a fusiform thoracic aneurysm arising distal to the left subclavian artery was by Lam and Aram[50] in 1950. The aneurysm was dissected and excluded from the circulation, the defect being bridged by a length of lucite tubing around which a homograft had been placed. Before completion of the inferior suture line, the lucite was withdrawn, and the anastomosis completed. The aneurysm itself was left *in situ*. The patient

made a good early recovery but died three months later of sepsis originating in the old aneurysm sac. This technic of intraluminal shunt which was first described by Carrel[10] in 1910 has also been used by Johnson, Kirby, and Lehr[46] in the successful resection of a mid-thoracic aortic aneurysm.

External shunting as an adjuvant measure in the resection of the thoracic aorta has been accomplished in a variety of ways. Clatworthy and Varco[12] reported that the use of small bore polyethylene shunts in dogs, running from the left subclavian back into the aorta distally, essentially negated the neurologic deficit found when the thoracic aorta was cross-clamped without shunting. A similar study was carried out by Schafer and Hardin[64] who applied this principle successfully to several patients with thoracic aneurysms arising distal to the left subclavian. Other shunting technics have been described[1-3,11,43,45,52,58,61,66] for use in the resectional surgery of this segment of the aorta. However, left heart bypass[15,16,20,24,27,29,56] in which left heart return is shunted via a mechanical pump into the femoral artery, has largely replaced the earlier methods.

Resectional Surgery of the Aortic Arch

The basic problems of resecting the ascending aorta and aortic arch are identical with those encountered in the distal thoracic aorta, but are of much greater magnitude. In solving the problem of ischemia distal to the point of aortic occlusion,

the entire systemic circulation must be considered. Furthermore, cross-clamping of the ascending aorta without protective measures would leave the coronary arteries as the only avenue of escape for total cardiac output and would soon lead to left ventricular dilatation and myocardial collapse. The approach to these problems has proceeded along the same lines as those which have been mentioned for resection of the distal thoracic aorta, namely, hypothermia, shunting, and the use of the pump-oxygenator.

Hypothermia Takahashi[67,68] has reported using profound hypothermia as an isolated protective measure in the excision of the dog's aortic arch but there have been no human applications of this technic. Hypothermia in conjunction with shunting or extracorporeal circulation has been used by many authors and will be discussed subsequently.

Bypass Shunting The first reported attempt to resect a fusiform aortic arch aneurysm was by Schafer and Hardin[64] in 1951. Based on their experimental work in dogs, they placed four polyethylene shunts in the ascending aorta proximal to the aneurysm and ran them to the innominate artery, the left common carotid, the left subclavian, and the descending aorta, distal to the aneurysm in each case. Before the arch resection could be carried out, the patient suffered irreversible ventricular fibrillation.

The well known case of Stranahan, Alley, Sewell, and Kausel[66] in 1953 was the first in which the arch was actually

excised. The patient was a 53 year old white male with a luetic aneurysm involving all of the transverse arch. At operation, a three-cornered shunt was used, consisting of one centimeter bore Tygon tubing connected via siliconized glass joints to two heterologous arterial sleeves, the first of which was anastomosed to the ascending aorta end-to-side and the second to the distal aorta below the aneurysm. The host innominate artery was cannulated with the third arm of the shunt. Dissection of the aneurysm proceeded after the shunt was in place and functioning. The left common carotid was cross-clamped and the left subclavian was permanently occluded. After removal of the entire transverse arch, the defect was bridged with two reconstituted lyophilized heterologous grafts (calf) spliced together. The innominate and left common carotid arteries of the host were anastomosed end-to-side to this donor segment. It was also necessary to do a left pneumonectomy since the aneurysm had eroded the left mainstem bronchus and the left pulmonary artery. The patient responded immediately after this fifteen hour procedure but as he was being moved from the table to a stretcher his condition suddenly deteriorated. Emergency re-exploration revealed that the tie on the left pulmonary artery had cut through, resulting in an exsanguinating hemorrhage. All suture lines associated with the graft were shown at necropsy to be intact.

Schimert *et al.*[65] used a similar three-cornered Tygon shunt in a patient and devised a nut-screw mechanism to anchor the connections to the ascending and descending aorta. The sidearm was placed in the left common carotid. It was not necessary to resect the arch in this patient who had a large saccular aneurysm, but the shunt was allowed to function while the arch was occluded during tangential excision of the sac.

Resection of an aortic arch aneurysm by permanent Ivalon shunting was reported by Conklin, Grismer, and Aalpoel[14]. Two shunts were used, the first running from the side of the ascending aorta to the side of the descending aorta. The second shunt was placed between the base of the ascending aorta and the proximal divided end of the right subclavian; the innominate artery was oversewn at its origin and the distal subclavian was ligated. Thus, perfusion of the right common carotid was accomplished via retrograde flow through the right subclavian. The left common carotid and left subclavian arteries, being found occluded with thrombus and plaques, were merely ligated. The patient made a satisfactory early recovery but expired on the twelfth postoperative day from a rupture of the graft.

Another technic for permanent shunting was recently described by Muller, Warren, and Blanton[57]; they successfully resected an aortic arch aneurysm after placing a graft between

the ascending and descending aorta with sidearms to the innominate, left common carotid, and left subclavian arteries. All the anastomoses were performed end-to-side and the aneurysm was resected centrally. The authors point out, however, that had the ascending aorta not been free of disease, this method would have been impossible to accomplish.

A similar procedure had previously been described by Creech, DeBakey, and Mahaffey[23] with the patient surviving ten days postoperatively.

Ellison, Cope, and Moretz[33] reported placing a bypass shunt from the ascending to the descending aorta using Ivalon with a T-limb at its midpoint. A Y-adapter was placed in the T-limb and the carotids perfused with plastic catheters. The aneurysm was successfully resected and a graft was implanted, but the patient expired in the early postoperative period.

Hypothermia in Conjunction with Bypass Shunting The use of hypothermia in conjunction with shunting for aortic arch replacement has been described frequently. Cooley, Mahaffey, and DeBakey[21], reporting on the resection of an entire aortic arch, used moderate hypothermia and a four-limbed Ivalon shunt connecting the ascending and descending aorta with sidearms to the innominate and left common carotid arteries. After excision of the aneurysm, an Ivalon graft was sutured in place, but as this was being done it was noted that pulsations in the right common carotid had ceased. It was then eight minutes

before the anastomoses could be opened, at which time full pulsations returned. The patient never recovered consciousness and died six days later.

Creech, DeBakey, and Mahaffey[23] described using two shunts and moderate hypothermia in an aortic arch resection. The first of these was an Ivalon shunt connecting the ascending and descending aorta. The second was a homograft intercarotid shunt between the innominate and the left common carotid at points distal to the aneurysm so that either vessel could be occluded proximally without interrupting flow to the other. The four anastomoses of the two shunts were all end-to-side, and again this procedure could not have been accomplished had the ascending aorta been involved by the aneurysm. A total of eleven anastomoses was required in this patient who failed to survive the early postoperative period.

Another method of combining shunting with hypothermia was reported by Gwathmey and Pierpont[38]. In their patient only one shunt was used. A descending aorta homograft placed from the side of the ascending aorta to the side of the innominate artery, fulfilled the duties of both a shunt and a permanent graft. The left common carotid which was completely occluded by clot and plaques was ligated and divided. The aneurysm was excised and an arch homograft was used to bridge the gap between the ascending aorta and the descending aorta. The innominate and left common carotid vessels of the graft

were oversewn at their origin, and the host left subclavian was anastomosed to the donor arch via a thoracic homograft. Despite a total ascending aortic occlusion of only 23 minutes the patient remained oliguric until his demise 12 hours post-operatively. The same authors[39] subsequently reported three more cases of aortic arch resection; two were accomplished by combining shunting with hypothermia, and the third by employing a pump-oxygenator. None of the patients survived. Three other patients who underwent resection of the ascending aorta with the assist of shunts alone were also presented; the only patient to survive was done under normothermic conditions. The authors suggested that hypothermia in aortic arch surgery is extremely dangerous because of cardiac irregularities and that the procedures of choice would be either shunting with normothermia or mechanical bypass.

Muller _et al_.[57] also reported on the use of shunts in conjunction with hypothermia in a patient with an arch aneurysm. In this case the shunt was a tube of polyvinyl sponge with "many fingers", utilizing the ascending aorta as a take-off point and perfusing vessels to the head via polyethylene tips on the fingers of the shunt. Once the sunt was functioning, the aneurysm was excised and a homologous graft was sutured in place. Following this the shunt was removed. The patient failed to survive.

Extracorporeal Circulation As is the case with thoracic

aneurysms located distal to the left subclavian, recent work on left heart bypass or total cardiopulmonary bypass in the treatment of arch aneurysms has prompted a reevaluation of the earlier technics. The first successful resection of the ascending aorta was accomplished by Cooley and DeBakey[18] in 1956. The patient was a 50-year-old white male with a traumatic aneurysm of the ascending aorta. At operation, complete venous return was diverted into a pump-oxygenator with arterial return taking place through the femoral and right common carotid arteries. Occluding clamps were positioned just above the coronary ostia and between the innominate and left common carotid. The coronary arteries were not perfused separately, but rather the blood remaining in the cardiopulmonary circuit when total vena caval diversion commenced was relied upon to maintain myocardial viability. The aorta was cross-clamped for a total of 31 minutes. Cardiac arrest occurred ten minutes after the onset of occlusion but massage was not undertaken. Ventricular fibrillation followed the release of the aortic clamps, but the patient was defibrillated on the first shock and made an uncomplicated recovery.

DeBakey, Crawford, Cooley, and Morris[30] reported the first successful resection of an aortic arch aneurysm which involved the ascending aorta and the origins of the innominate and left common carotid arteries. Operation was performed in 1957 with the use of a pump-oxygenator. Cannulas were placed in the

venae cavae for venous return diversion and into the femoral, innominate, and left common carotid for arterial perfusion. The latter two cannulas did not completely occlude the vessels but were held in place by sutures in the arteriotomy incisions. Coronary blood flow was maintained on the basis of the blood volume trapped in the cardiopulmonary circuit. A lyophilized homograft was used to replace the diseased segment of aorta. The patient made an uneventful recovery and was completely well five months postoperatively.

Cooley, DeBakey, and Morris have subsequently[19,20,56] presented considerable data on the technic of aortic arch resection utilizing cardiopulmonary bypass. Their basic method has remained the same, i.e., total venous inflow diversion with arterial return via the femoral, innominate, and left common carotid arteries. For aneurysms arising distal to the left subclavian, left heart bypass alone has been found to be satisfactory.

DeBakey *et al.*[27] in 1958 reviewed 50 cases of aneurysm of the aortic arch treated surgically; 35 of these were of a luetic origin, arteriosclerosis accounted for ten, three were of a traumatic origin, and two were of unknown etiology. The majority of the patients were in their sixth or seventh decades, with males outnumbering females four to one. Associated with the 26 saccular aneurysms there was a mortality of 28 per cent, while with the 24 fusiform aneurysms there was a mortality

of 75 per cent. When the aneurysm involved the ascending aorta a pump-oxygenator was used but when only the transverse arch was to be resected, a permanent Dacron or Teflon fabric shunt was implanted as follows: a straight graft was placed between the side of the ascending aorta and the side of the descending aorta; sutured to its midpoint was the superior opening of a bifurcation graft whose iliac limbs were then anastomosed end-to-side to the innominate and left common carotid distal to the aneurysm; following this, the transverse arch could be excised, and the defect thus created was bridged by another straight fabric graft, anastomosing end-to-end the ascending and descending aorta; finally, the left subclavian was sutured end-to-side to this second straight graft.

Bahnson and Spencer[6] described the surgical treatment of four cases of aneurysms of the ascending aorta, all of which were resected with the aid of cardiopulmonary bypass and, when the aneurysm extended to the root of the aorta, coronary perfusion. If a clamp could be placed across the ascending aorta, some blood was allowed to bypass the right-sided cannulas to provide coronary flow. Three of the four histologic sections showed cystic medial necrosis while one revealed luetic changes. The one death in these four patients resulted from a pulmonary embolus two weeks postoperatively.

Experimental Resection of the Arch

Technics for experimental resection of the dog's aortic arch have been confined in general principle to those already discussed for human arch replacement. While the canine aorta presents certain technical operative difficulties due to its well known friability, resection of the dog's aortic arch is somewhat less complex than in the human since only two vessels take their origin from the transverse arch, namely, the brachiocephalic and the left subclavian. However, the basic problem remains the same, i.e., how best to protect the tissues distal to the point of occlusion from the effects of prolonged ischemia.

The experimental use of hypothermia as a lone protective measure in arch replacement by Takahashi[67,68] has already been mentioned. Recently, Sauvage, Rudolph, and Gross[63] reported on the use of hypothermia in resection of the dog's arch with the following sequence of grafting: a homograft was anastomosed end-to-side to the host descending aorta; the left subclavian anastomosis was then carried out end-to-end; following this, a clamp was placed on the graft between the origins of the brachiocephalic and the subclavian, thus opening the subclavian anastomosis so that the Circle of Willis was supplied by the left vertebral while the brachiocephalic suture line was accomplished, also end-to-end; both venae cavae were obstructed while the ascending end-to-end anastomosis was carried out, but the azygos vein was left open to

provide coronary flow; finally, the descending aorta suture line was taken down and remade end-to-end. Of six animals operated on by this method, two survived.

Numerous varieties of shunting procedures have been devised, many of which have been applied to human arch resection with only limited success. Alley and his co-workers[4] described in 1956 the use of bovine brachiocephalic as a temporary bypass shunt in dogs. The bovine brachiocephalic is the only vessel arising from the transverse arch and divides into the four major arteries of the head and upper extremities. By ligating the left subclavian of the parent vessel, a three limbed shunt remained, two limbs of which were anastomosed end-to-side to the ascending and descending canine aorta respectively. With the origin of the bovine brachiocephalic closed with sutures and the host brachiocephalic supplied by the third limb of the donor segment, a complete arch bypass was instituted. Five of 24 animals survived on a long term basis.

This same group[2] of investigators had earlier reported on the use of a three-limbed Tygon shunt in bypassing the dog's aortic arch while homografts were implanted. Only two of 20 animals survived the early postoperative period, and one of these died six weeks later of aneurysm and rupture of the graft.

Hardin and his group[40] investigated polyethylene shunts as a means of temporarily diverting the blood flow from the

arch. Three separate flanged catheters were placed in the ascending aorta and inserted distally into the brachiocephalic, the left subclavian, and the descending aorta. The isolated segment of the arch was excised and replaced with a homograft. Consistent with the nine-to-one cross-sectional ratio of ascending aorta to shunts was the nearly 90 per cent operative mortality, with death being due either to cardiac embarrassment in the form of a slowly progressive cardiac dilatation or to hemorrhage. A second group of animals was operated on by the identical shunting technic but the inferior vena cava was occluded in each case while the arch was resected. All four animals in this group survived.

The use of a bypass graft as a permanent shunt was studied by Neville and Clowes[58]. Both the ascending and descending suture lines were of the end-to-side variety, but the brachiocephalic and left subclavian were attached end-to-end, which allowed one anastomosis to function before the other had been begun. The operative mortality was greater than 50 per cent, and no animal survived longer than seven weeks.

Satinsky, Neptune, and Alai[62] described two alternate methods for experimental arch resection using homografts. One of these was performed under normothermic conditions by first completing the descending anastomosis in an end-to-side fashion. Then, after end-to-end suturing of the left sub-

clavian, the clamps were shifted to allow retrograde flow to this vessel while end-to-end anastomosis of the brachiocephalic was carried out. Before the ascending aorta was clamped, a polyethylene shunt was passed into the left ventricle via the left auricular appendage and when the aorta was divided, the free end of the shunt was ligated into the host distal ascending aorta while the ascending anastomosis was accomplished. The authors reported that "Despite a reduced cardiac output and since there are no valves in the tube, a free left ventricular regurgitation, one is able to complete the final anastomosis with impunity." Seven of 15 animals survived following the sacrifice of many animals to development of the technic. In the second method described, the procedure was performed under hypothermia without a shunt. The anastomoses were carried out in the same order and the time limit for accomplishing the ascending aortic suture line was reported as 15 to 20 minutes. All three dogs operated on by this method survived.

Still another experimental shunting technic for aortic arch resection bears mentioning. Di Matteo and Manfredi[31], reporting in the Italian literature, described the use of a polyvinyl T-tube between the apex of the left ventricle and the descending aorta, one arm of the T being directed cephalad and the other caudad. The ventricular arm of the shunt was placed via a purse-string suture in the apex. Once the shunt was in place and functioning, the ascending

aorta was cross-clamped and the three vital anastomoses accomplished end-to-end. The left subclavian was entrusted with supplying cerebral circulation while the brachiocephalic was occluded. After the arch had been replaced, the apical-aortic shunt was removed. Two of three animals undergoing this procedure survived. The authors make no mention of adverse effects resulting from a valveless shunt such as is described nor were any physiologic studies carried out. However, the procedure is similar in general principle to the one to be presented in the present report.

In order to resect the dog's arch without hypothermia or shunting, a rapid mechanical coupler was devised by Kelly and Wohlrabe[49]. In 26 operations carried out, the descending anastomosis was performed end-to-side and the venae cavae were occluded while the ascending aorta was coupled with the graft. The brachiocephalic anastomosis was also accomplished by use of the coupler. Eight of the animals survived longer than four weeks.

Finally, extracorporeal circulation has been utilized extensively in aortic arch replacement in the dog. Cross and his group[24] investigated left heart bypass for use in canine arch replacement. The systemic circulation was pump assisted from the left ventricle via the left auricular appendage into either the femoral artery alone or into the femoral plus the brachiocephalic via the right brachial artery. Actual resection of the arch was carried out in several

dogs by utilizing this technic. Austen and Shaw[5] also recently reported their work on left heart bypass in dogs, comparing active pumping and gravity flow from the left auricle.

The data compiled by other workers investigating extracorporeal circulation as a means of experimental arch resection will be mentioned subsequently.

The present study was undertaken with a twofold purpose. In view of the generally unsatisfactory results in resection of the aortic arch, the first of these aims was to investigate the apical-aortic shunt first described by Carrel[10] and later modified by Donovan, Sarnoff, and Case[32,60] as a temporary bypass in dogs during aortic arch resection. Secondly, an effort was made to determine the physiologic efficiency of the apical-aortic ball valve shunt in maintaining cardiovascular homeostasis.

MATERIALS AND METHODS

Studies were performed on a total of 21 mongrel dogs ranging in weight between 16 and 34 kilograms. In all cases, intravenous Nembutal (30 mg. per kg.) anesthesia was used and the animals were supported on a mechanical respirator delivering pure oxygen at a rate of 2 liters per minute per 10 kg. of body weight via an endotracheal tube. Whole blood transfusions and intravenous fluids were administered as necessary. The original left ventricular apex to thoracic aorta shunt* used in the present study is shown in Figure 1 and was patterned after that described by Donovan, Sarnoff, and Case[32,60]. Due to technical difficulties in placing the aortic end of the prosthesis in some of the early experiments, a revision was deemed necessary and while the basic principle of the apical-aortic shunt remained the same, the delivery end of the housing was markedly altered. The final version of the prosthesis is shown in Figure 9 and has the following structural statistics: the entire housing of the prosthesis is made of Lucite but the spoked wheel for fixation of the ventricular end to the myocardium is Nylon. The ball within the Hufnagel[44] valve segment is a silicon-latex compound (Silastica). In

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* Made by Mr. Carl Hewson, Brunswick Manufacturing Company, North Quincy, Massachusetts.

the longest straight-line dimension, the prosthesis measures 9.7 centimeters, with an outside diameter of 1.4 centimeters and an inside diameter of 1.2 centimeters at the ventricular end, and an outside diameter of 1.4 centimeters and an inside diameter of 1.1 centimeters at the aortic end. The side-arm for brachiocephalic perfusion which is located 6.5 millimeters from the termination of the valve housing has an outside diameter of 8 millimeters and an inside diameter of 5 millimeters. One millimeter walled Tygon tubing with a bore of 5 millimeters was attached to the sidearm and the delivery end of the tubing was cut on an angle so that the open portion of the bevel would face the origin of the left common carotid artery. The curve of the housing at the ventricular end makes an angle of 45° with the horizontal and the side-arm is placed slightly anterior to the superior-inferior plane so that the Tygon tubing could make a gentle sweep into the brachiocephalic without kinking, lying anterior to the hilus of the left lung. The technic of placing the prosthesis will be described subsequently.

Physiologic Studies

Pressures and Electrocardiogram Femoral artery, right brachial artery, and intracardiac pressures were all measured via a pressure transducer and recorded on either the Sanborn Twin-Viso recorder or on the multi-channel Offner Dynagraph Type R. Lead II of the electrocardiogram was ordinarily used

as an index of myocardial stability although in each acute experiment several complete records were taken. The same machines were used for recording the EKG as were used for the pressures but the multi-channeled Offner was more satisfactory since several pressures, the EKG, and the cardiac output could all be recorded simultaneously.

Oxygen Studies Blood samples for arterial and venous oxygen saturations drawn at intervals after implantation of the apical-aortic shunt were analyzed in the chemistry laboratory by the technic of Roughton and Scholander[59].

Cardiac Outputs Of the several methods available for cardiac output determinations, the technic chosen was that of thermal indicator-dilution curves, first applied by Fegler[34], in which a cold bolus of indicator injectate (saline) is sensed by an intravascular thermistor. Goodyer and his group[36] recently revised this method and using it have found a favorable comparison with both dye-dilution curves and the Fick principle.

In the present study, a 4-7 cc. bolus of room temperature saline was injected rapidly into the right ventricular outflow tract using an ordinary 10 cc. syringe and a #15 gauge needle. The sensing thermistor (Veco 32 A 75)* was placed via a femoral artery in the aorta at the level of the diaphragm. The thermistor coupler and amplifier were so

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* Victory Engineering Corporation, Union, New Jersey

arranged that a positive deflection of the galvanometer reflected a negative change in temperature. A satisfactory record was obtained with the recording paper running at a speed of 10 millimeters per second.

Sensitive thermometers were used to measure the rectal temperature of the dog and the temperature of the saline injectate. Notation of the volume of the bolus was also made in each determination.

Calculation of the cardiac output, in which blood flow is inversely proportional to the area under the curve, was made according to the following formula:

$$\text{Cardiac Output (ml./min.)} = 60 \frac{\Delta T \cdot V}{A \cdot St \cdot .84}$$

where ΔT equals the difference in temperature in degrees Centrigrade between the animal and the injectate, V is the volume of the injectate, A is the area under the curve in millimeter-seconds, St is the sensitivity of the thermistor-amplifier system in degrees Centrigrade per millimeter of galvanometer deflection (0.0054 $^{\circ}$C/mm. for the Sanborn and 0.0069 $^{\circ}$C/mm. for the Offner), and

$$.84 = \frac{0.87}{1.04} = \frac{\text{specific heat of blood}}{\text{specific gravity of blood}}$$

Cooling of the blood following the cold bolus by blood vessels previously cooled by this bolus accounted for the prolonged downslope of each curve (Figures 21 and 22). Accordingly, allowances for this artifact must be made in

the calculation of the total area. The first portion of the curve to a point just beyond the peak was measured by a planimeter. Determination of the second part of the curve was made according to the following formula:

$$A_2 = \frac{P_1 \cdot t}{\log_e P_1 - \log_e P_2}$$

where A_2 is the area of the second portion of the curve, P_1 and P_2 are arbitrary points on the semilogarithmic downslope in millimeters of galvanometer deflection (see Figures 21 and 22), and t is the time in seconds between P_1 and P_2. P_1 is also the arbitrary limit of the first portion of the curve. The sum of the areas measured by planimetry and by mathematical calculation was applied as A in the original formula.

Resection of the Aortic Arch

Resection of the arch was accomplished by the following technic. Under sterile conditions the chest was entered through the bed of the resected fifth left rib, excising a one centimeter segment of the sixth rib posteriorly to gain adequate exposure of the distal descending aorta and the left ventricular apex. The thoracic aorta at the level of the apex was dissected free of pleura and surrounded with an umbilical tape, ligating intercostal arteries four and five as necessary. An esophageal artery was also occasionally encountered and ligated. The entire aortic arch was then dissected from the level of the coronaries to approximately two centimeters dis-

tal to the origin of the left subclavian, taking care to identify and preserve the left phrenic, left vagus, and left recurrent laryngeal nerves. The ligamentum arteriosum was divided. The brachiocephalic artery was dissected from its origin to its trifurcation into right subclavian, right common carotid, and left common carotid arteries. Two small mediastinal arteries which originate anteriorly and posteriorly from the brachiocephalic segment were also ligated and divided. The left subclavian artery was freed from surrounding structures for a distance of several centimeters and the preaortic fat pad was trimmed from the ascending aorta, ligating small bleeders as necessary.

After the dissection had been completed, a short diverticulum was anastomosed end-to-side to the previously dissected thoracic aorta at the level of the apex, isolating a segment by means of a Beck vascular clamp. In the early experiments the material used was a latex-Nylon fabric diverticulum as described by Glenn and others[35] fashioned into a short curve to meet the aortic end of the prosthesis (Figure 3). In the later work when knitted Dacron was used as an arch replacement, the descending portion of the graft was made extra long and it was the open end of this that was anastomosed to the thoracic aorta at the level of the apex. In this way, the graft could be preclotted at this point in the procedure, and once the interstices were competent to withstand arterial pressure without leaking the fabric was divided at its base,

leaving a two to three centimeter diverticulum of 12 millimeter Dacron to accept the aortic end of the prosthesis. Before placement of the ventricular end of the prosthesis was carried out, the brachiocephalic sidearm was passed up the descending portion of the graft and out its brachiocephalic. This situation is shown in Figure 3.

Donovan, Sarnoff, and Case[32,60] have previously described the technic for implantation of the ventricular end of the prosthesis and it was by their method that this was accomplished in the present study. The special instruments needed are shown in Figure 11. In brief, the technic involves the following maneuvers. A purse-string suture of 2-0 silk was placed at the base of the left auricular appendage and a Rummel tourniquet affixed to it. The introducer (Figure 11) was passed down through the auricular appendage into the left atrium and then into the left ventricle, seeking out the apex. When the introducer tip was satisfactorily situated, the stylus plunger was depressed and the apex was thus perforated from within the ventricle. With the apical retraction ring (Figure 11) gently stretching the myocardium over the introducer tip, a hole was cut in the apex by means of the apical knife (Figure 11). The latter is actually nothing more than a dermatology punch biopsy knife with an outside diameter of 0.9 centimeters and a hole bored in its handle to accept the stylus of the introducer as a guide. The rubber introducer tip was gently delivered through the

hole in the apex and the stylus withdrawn into the shaft of the instrument. With the prosthesis completely filled with Heparin solution (10 mg. per 100 cc. of saline) the ventricular end was placed over the introducer tip and guided carefully up into the ventricle. Two 2-0 silk sutures were placed in the myocardium at the apex and tied around the Nylon spoked wheel to secure the housing. The introducer was then withdrawn from the heart and the left auricular appendage was ligated at its base. Since the apical knife measures 0.9 centimeters and the ventricular end of the prosthesis measures 1.4 centimeters in their outside diameters, the apical myocardium was actually stretched over the Lucite and a snug fit was afforded.

The next steps in the procedure were to cannulate the brachiocephalic with the Tygon sidearm and then to excise the arch, placing clamps across the ascending aorta, the descending aorta, and the left subclavian. Figures 4 and 5 demonstrate these steps. In this way, total cardiac output minus coronary flow was diverted out the apex with cerebral circulation being provided via the Tygon sidearm. The brachiocephalic anastomosis was performed end-to-end around the cannula (Figure 5). Next, the ascending anastomosis was accomplished, also end-to-end. With these first two suture lines completed, the Tygon tubing was occluded at its origin and the cannula withdrawn from the brachiocephalic. With the left subclavian cross-clamped and a second clamp placed

across the distal portion of the graft, the clamp on the ascending aorta was released, thus instituting the normal anatomical route of flow to the first segment of the graft (Figure 6). Meanwhile, the blood flow caudad was still supplied by the apical-aortic shunt. Reinforcing sutures were taken as necessary in the ascending and brachio-cephalic suture lines. After the descending anastomosis had been accomplished end-to-end, the shunt could be occluded at its aortic end (Figure 7) and the left subclavian anastomosed on an optional basis.

The ventricular end of the prosthesis was removed by first placing a purse-string suture in the apical myocardium around the Lucite housing and then dividing the retaining sutures to the spoked wheel. The purse-string was gradually tightened as the prosthesis was withdrawn. Interrupted sutures were employed as necessary. The incision in the aorta at the level of the apex was repaired in routine fashion with 4-0 arterial silk (Figure 8). The chest was closed in layers. A rubber catheter in the left thoracic cavity was brought out through a stab wound for postoperative aspiration.

The end result of this technic was that the aortic arch was resected under normothermic conditions, without heparinization, using all end-to-end anastomoses, and requiring only one extra anastomosis for the aortic end of the prosthesis.

Lyophilized or fresh frozen homologous grafts were used

in some of the experiments while in others knitted Dacron was implanted. A typical fabric graft is shown in Figure 10 and consists of a 12 millimeter diameter aortic segment with 8 millimeter brachiocephalic and 6 millimeter left subclavian segments. The latter two lengths were anastomosed end-to-side to the larger section before sterilization.

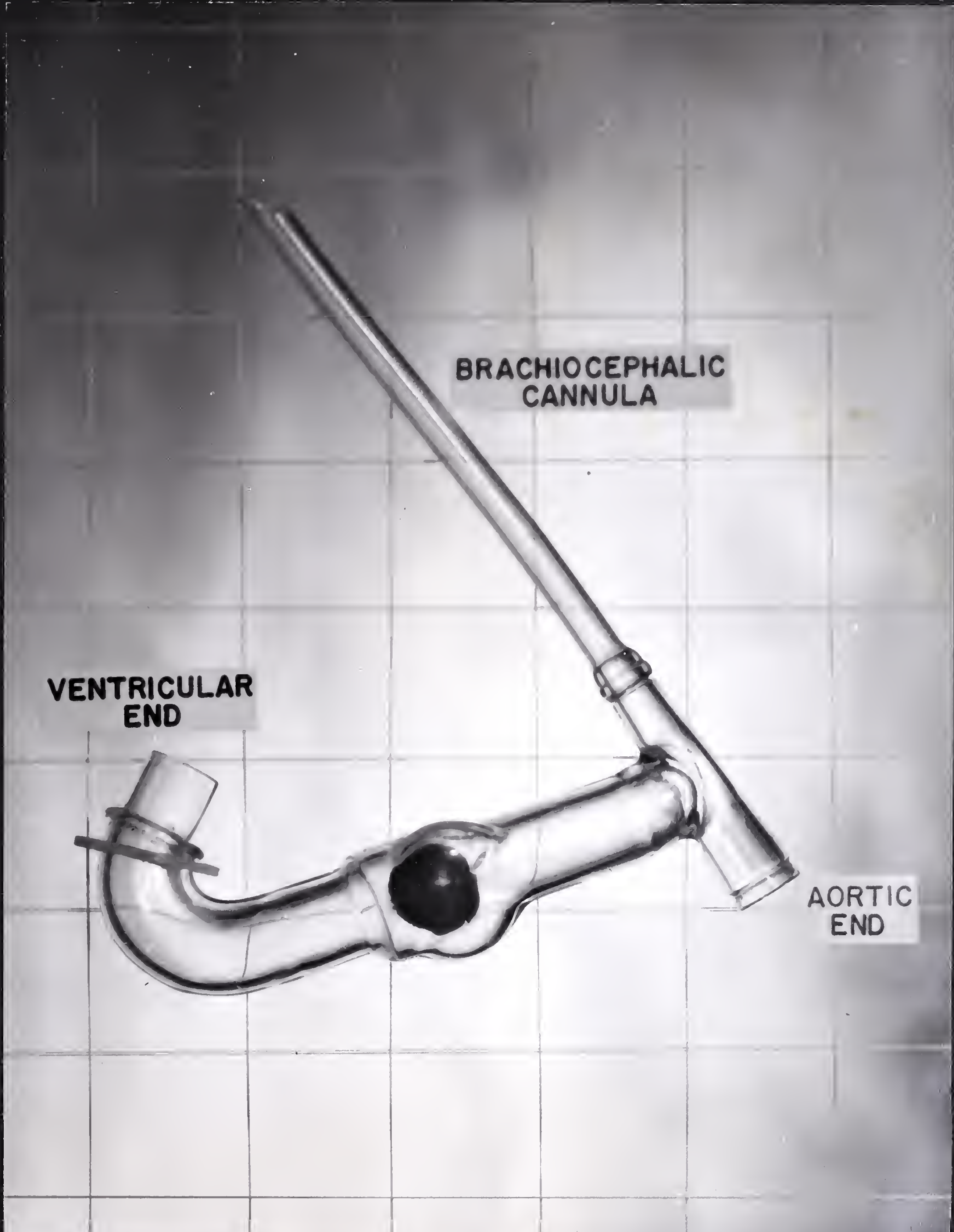


Figure 1. Original prosthesis.

Figure 2. Normal canine anatomy.

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

Figure 8

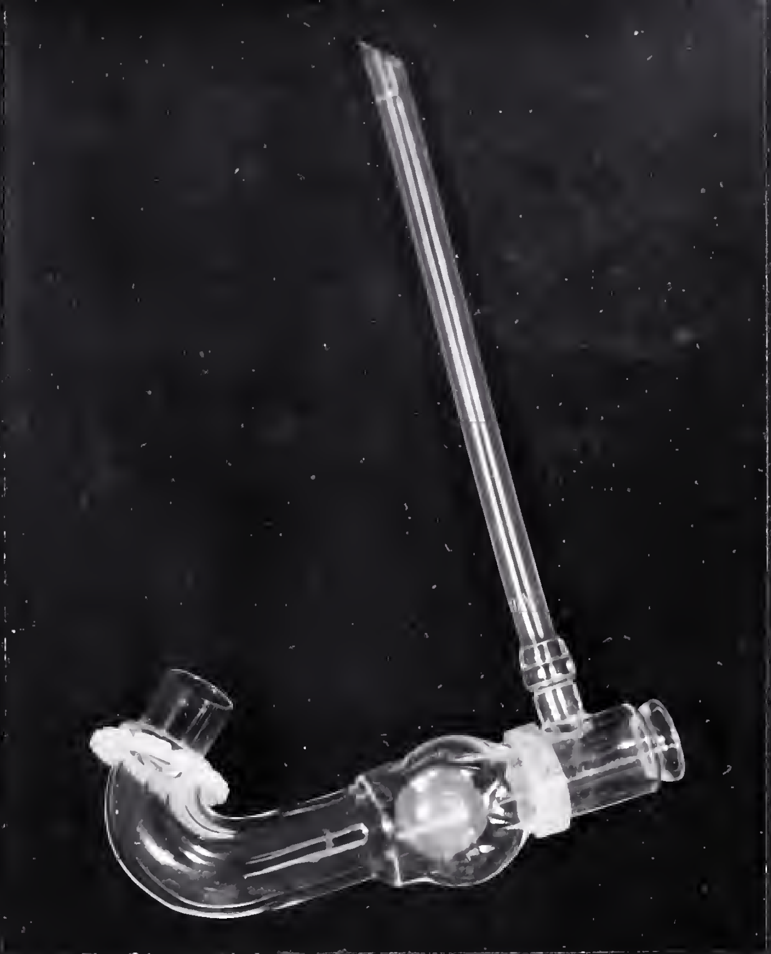


Figure 9
Revised prosthesis.

Figure 10
Dacron arch graft.

Figure 11. Instruments used in placing apical end of prosthesis.

RESULTS

Of the 21 experiments performed, 10 were done with the intention of resecting and replacing the aortic arch. The purpose in the other 11 studies was to determine what physiologic alterations can be expected when blood flow is diverted out the left ventricular apex.

In all cases, the function of the ball valve segment was mechanically sound. Figures 12 and 13 demonstrate the motion of the ball during the cardiac cycle.

Physiologic Studies Of the 11 acute experiments in which physiologic studies were made, five were unsuccessful (Table I). Three of the failures were caused by hemorrhage while ventricular fibrillation occurred in two experiments.

Peripheral Pressures While the femoral artery blood pressure was monitored in both survival and acute experiments, certain of the studies were carried out for the specific purpose of recording simultaneous peripheral arterial pressures. Figures 14, 15, and 16 summarize the results from these animals. The effectiveness of the brachiocephalic sidearm in maintaining the cephalad arterial pressure was measured via the carotid artery in Experiment 2 and via the right brachial artery in Experiments 3 and 10. The femoral artery pressure was recorded simultaneously in all three experiments. After wide fluctuations during placement of the prosthesis and cannulation of the brachiocephalic,

PHYSIOLOGIC STUDIES

EXP. #	WT. & SEX	TYPES OF STUDIES PERFORMED	COMPLICATIONS	OUTCOME
1	18 Kg.F	None accomplished	Hemorrhage from aorta as ventricular end of prosthesis was placed.	No physiologic data
2.	19 Kg.M	Peripheral arterial pressures and oxygen studies	Persistent hemorrhage from mediastinum.	Satisfactory study
3	19 Kg.M	Peripheral arterial pressures and oxygen studies	None	Satisfactory study
4	21 Kg.F	None accomplished	Hemorrhage from tear in aorta during cannulation. Hemorrhage from inadequately secured brachiocephalic cannula. Hemorrhage from apex.	No physiologic data
PROSTHESIS REVISED				
9	17 Kg.F	None accomplished	Prosthesis too long, resulting in tear of diverticulum from aorta as ventricular end was placed.	No physiologic data
REVISED PROSTHESIS SHORTENED				
10	23 Kg.M	Peripheral arterial pressures and oxygen studies	None	Satisfactory study
16	16 Kg.M	None accomplished	Ventricular fibrillation during placement of prosthesis.	No physiologic data
17	18 Kg.M	Femoral artery and intracardiac pressures; EKG; cardiac outputs	Coronary air embolus and ventricular fibrillation following insertion of prosthesis; massage and defibrillation.	Satisfactory study following defibrillation
18	18 Kg.F	Femoral artery and intracardiac pressures; EKG; cardiac outputs	Hemorrhage from diverticulum suture line. Hemorrhage from multiple puncture sites secondary to performing studies.	Limited reliability of data due to prolonged hemorrhage
19	30 Kg.M	None accomplished	Ventricular fibrillation with persistent atrial flutter following defibrillation ([illegible]).	No physiologic data
20	21 Kg.F	Femoral artery and intracardiac pressures; EKG; cardiac outputs.	None	Satisfactory study

TABLE I

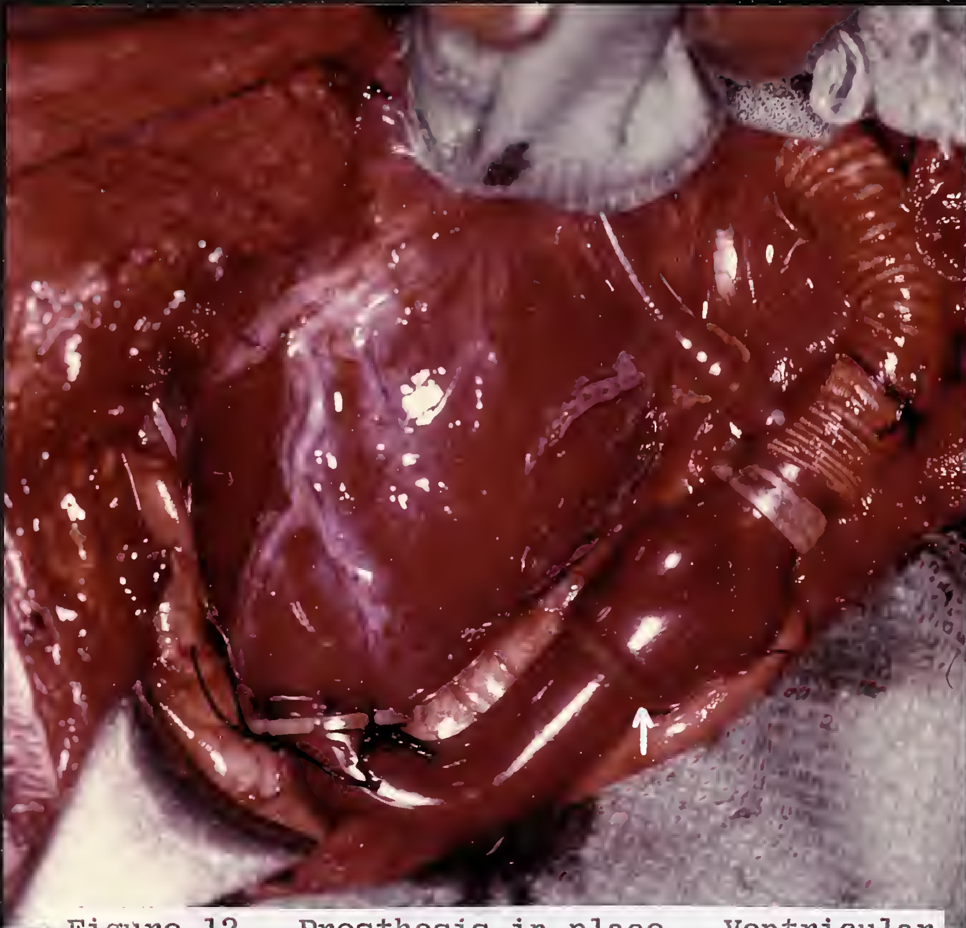


Figure 12. Prosthesis in place. Ventricular diastole. Arrow shows seating of ball during this phase of the cardiac cycle.

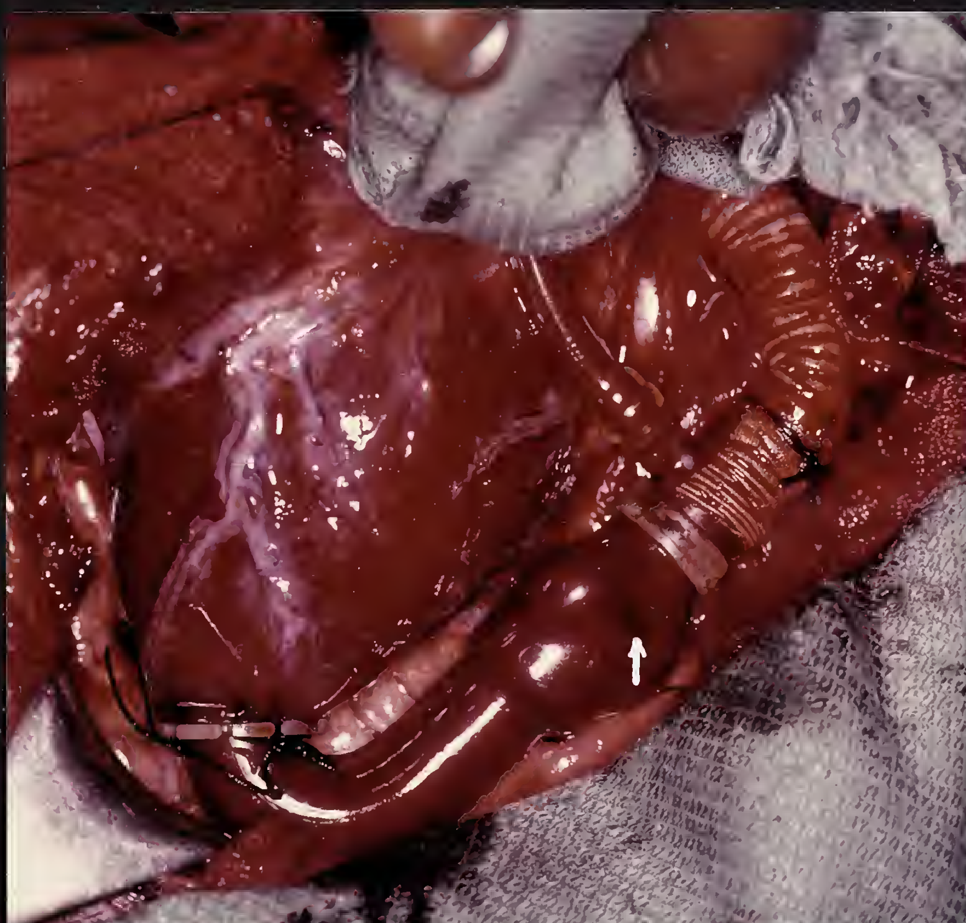


Figure 13. Ventricular systole. Arrow indicates contact point of ball to housing during ejection phase.

arterial pressure was maintained at a satisfactory level for the 60 to 90 minutes that the ascending aorta was cross-clamped.

A persistent superior mediastinal hemorrhage is not reflected in the pressure results from Experiment 2 (Figure 14). Systolic pressures in the carotid and femoral arteries were maintained above 105 and 120 millimeters respectively. Some widening of the pulse pressure from 40 to 60 millimeters following insertion of the prosthesis was noted.

No complications were encountered in Experiment 3 (Figure 15) and with the apical-aortic shunt functioning as the left ventricular outflow tract, femoral artery pressure averaged 140 millimeters and dropped no lower than 105. The lowest point of right brachial artery pressure was 90 with the average being 115 millimeters. Again, widening of the pulse pressure from 25 to 50 millimeters was observed.

After 45 minutes of ascending aorta occlusion in Experiment 10 (Figure 16), a partially-occluding clamp was placed on the descending aorta below the aortic inflow of the prosthesis. This succeeded in altering the femoral artery pressure from 185/60 to 145/80 and the right brachial artery pressure from 120/95 to 120/80. The pulse pressure following partial occlusion compared more favorably with the control level of approximately 50 millimeters.

In association with the intracardiac pressure studies, femoral artery pressures were also observed and these results

are reported in Tables II, III, and IV.

Oxygen Studies Results of the oxygen studies performed in three animals are summarized in Figures 14, 15, and 16. Arterial samples drawn in Experiments 3 and 10 were all above 100 per cent saturated. However, there was a progressive decline in oxygen content of the blood withdrawn from the external jugular vein. In Experiment 2, the control sample from the external jugular prior to the insertion of the prosthesis was 88 per cent saturated, while after 15 minutes of ascending aorta occlusion it had fallen to 68 per cent. At the end of one hour a sample was only 42 per cent saturated.

Similar results were observed in Experiment 3. Oxygen saturations of blood drawn from the right external jugular vein showed an initial control of only 67 per cent but a fall at the end of one hour to 27 per cent.

As previously noted a partially occluding clamp was placed on the distal descending aorta in Experiment 10 (Figure 16) after 45 minutes of ascending aorta occlusion. The initial blood sample drawn from the external jugular vein before implanting the apical-aortic shunt was 95 per cent saturated with oxygen. Forty-five minutes after the prosthesis had begun to function, the saturation was 88 per cent, and another 45 minutes later (with the partial occluding clamp on the descending aorta) the external jugular blood was 76 per cent saturated. Figure 16 also shows the oxygen

content of the blood drawn from the right femoral vein, although this vessel was noted to be in spasm throughout most most of the procedure.

Electrocardiograms   Excerpts from the electrocardiographic records in the three animals in which studies were carried out are demonstrated in Figures 17, 18, and 19.

The most marked change in electrical activity of the myocardium was noted in Experiment 17 (Figure 22) in which ventricular fibrillation secondary to coronary artery air embolus was successfully treated by massage and electric shock. However, a marked ischemic pattern characterized by deviations from the isoelectric of the S-T segments in Leads II, III, AvR, AvL, and AvF persisted throughout the remainder of the experiment.

No ischemic changes were seen in Experiments 18 or 20 and the only abnormalities observed following insertion of the prosthesis were occasional runs of premature ventricular systoles and a mild right axis deviation as compared with the control record in both experiments.

Intracardiac Pressures   Three groups of pressure studies were performed in each experiment by direct needle puncture of the various chambers. Group I was the control and these determinations were made before the prosthesis was placed. Groups II and III were performed with the apical-aortic shunt in place; in the former group the ascending aorta was cross-clamped, while in the latter the aortic end

of the prosthesis was occluded and the ascending aorta was open. The brachiocephalic artery was not cannulated in these animals and flow to this vessel was accomplished retrograde via the apex. In the cardiac output studies to be described subsequently, determinations were made in the same groups as those just stated for the intracardiac pressures.

Tables II, III, and IV summarize the pressure studies from the three animals in which they were successfully accomplished. Experiment 17 was the only study in which a significant left ventricular diastolic pressure was recorded while the shunt was in place and functioning. The right ventricular and femoral artery pressures remained essentially stable throughout the procedures except for a gradual decline in all pressures in Experiment 18 as the result of a slow but persistent hemorrhage from the multiple needle puncture sites in the ventricles and aorta.

Ascending aortic pressures were obtained from a site just above the sinuses of Valsalva. While a rather narrow pulse pressure of 5 to 15 millimeters was observed in two of the three experiments, a consistently favorable systolic level was recorded.

Excerpts of the record from Experiment 20 are reproduced in Figure 20.

Cardiac Outputs   Results of the determinations by the thermal dilution method are recorded in Tables II, III and IV. Also included in the tables is the number of results

used in each output calculation as well as the range of determinations in each group.

In all three experiments the average cardiac output was higher prior to the insertion of the shunt, although in Experiment 17 there was some overlapping of individual studies. In this same experiment the average cardiac output determined with the functioning and non-functioning prosthesis in place are comparable. The same can be said of Experiment 20 in which the average output with the ascending aorta cross-clamped was actually some 200 cubic centimeters per minute higher than when the aorta was released and the prosthesis occluded. Interpretation of the results of cardiac output studies in Experiment 18 are clouded by the slow hemorrhage previously noted.

Samples of the record from Experiment 20 are reproduced in Figure 21.

Puncture of the conus arteriosus for the injection of the cold bolus of saline on occasion produced runs of premature ventricular contractions. Owing to the profound effect of this arrhythmia on cardiac output, these results were not included in the calculation of the average cardiac output. However, the ease with which cardiac output could be simultaneously compared with the femoral artery blood pressure and the electrocardiogram during an arrhythmia was noted and one of these determinations from Experiment 20 is shown in Figure 22.

EXPERIMENT 17 - TABLE II

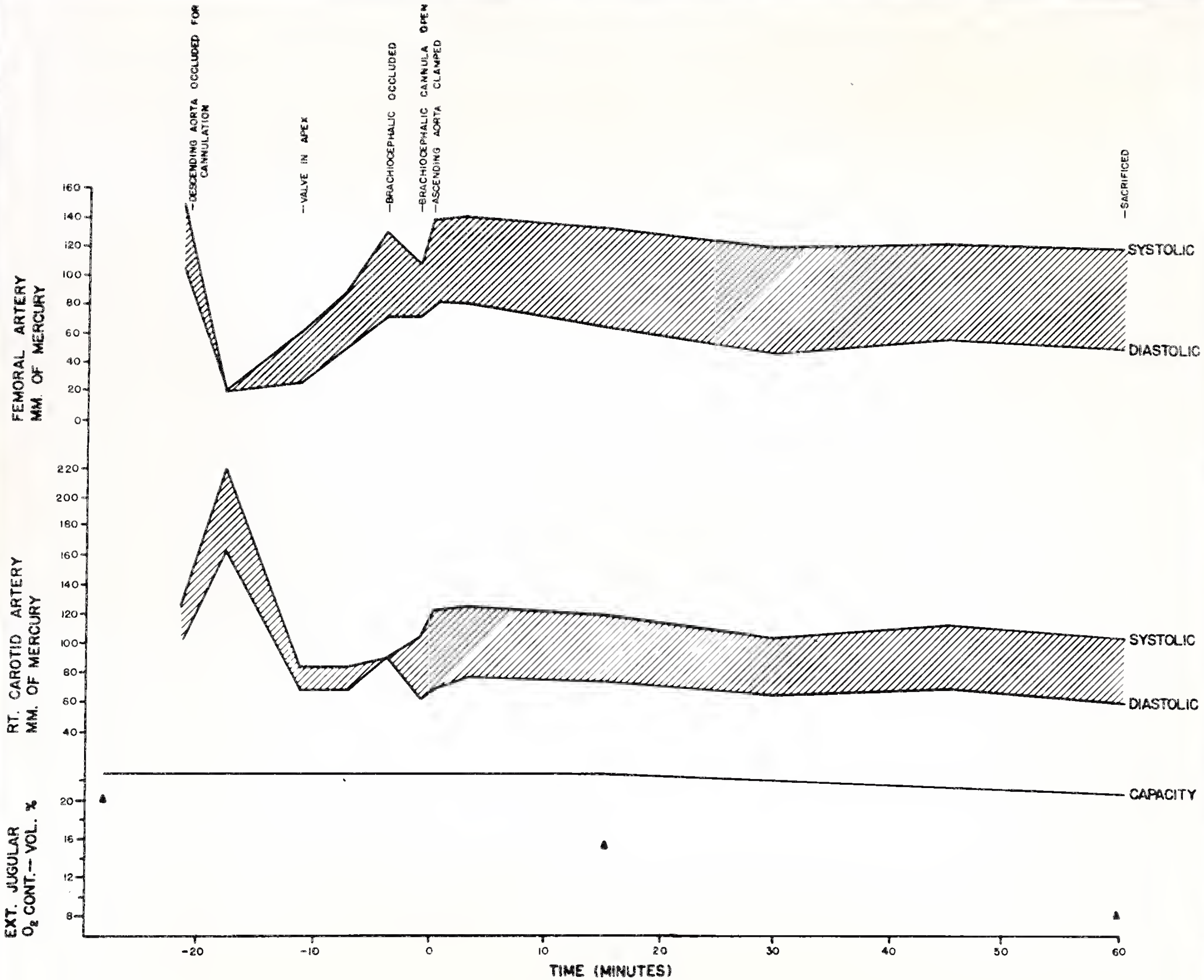
	PRESSURES - MILLIMETERS OF MERCURY				AVERAGE CARDIAC OUTPUT (cc./min.)	NUMBER AND RANGE OF OUTPUT DETERMINATIONS (cc./min.)
	FEMORAL ARTERY	LEFT VENTRICLE	RIGHT VENTRICLE	ASCENDING AORTA		
PRE-INSERTION OF PROSTHESIS	120/85	75/5	35/0	85/65	3150	x7 2825-3470
POST-VENTRICULAR FIBRILLATION: PROSTHESIS FUNCTIONING	100/75	105/35	35/5	75/40	2500	x12 2150-2880
AORTIC END OF PROSTHESIS OCCLUDED; ASCENDING AORTA OPEN	120/85	95/10	30/5	95/75	2730	x4 2390-2890

EXPERIMENT 18 - TABLE III

	PRESSURES - MILLIMETERS OF MERCURY				AVERAGE CARDIAC OUTPUT (cc./min.)	NUMBER AND RANGE OF OUTPUT DETERMINATIONS (cc./min.)
	FEMORAL ARTERY	LEFT VENTRICLE	RIGHT VENTRICLE	ASCENDING AORTA		
PRE-INSERTION OF PROSTHESIS	145/90	105/5	25/0	115/105	2705	x8 2335-3120
PROSTHESIS FUNCTIONING; ASCENDING AORTA CLAMPED	120/60	75/0	25/0	80/70	1405	x8 1085-1560
AORTIC END OF PROSTHESIS OCCLUDED; ASCENDING AORTA OPEN	85/40	35/5	15/0	75/65	835	x6 750-890

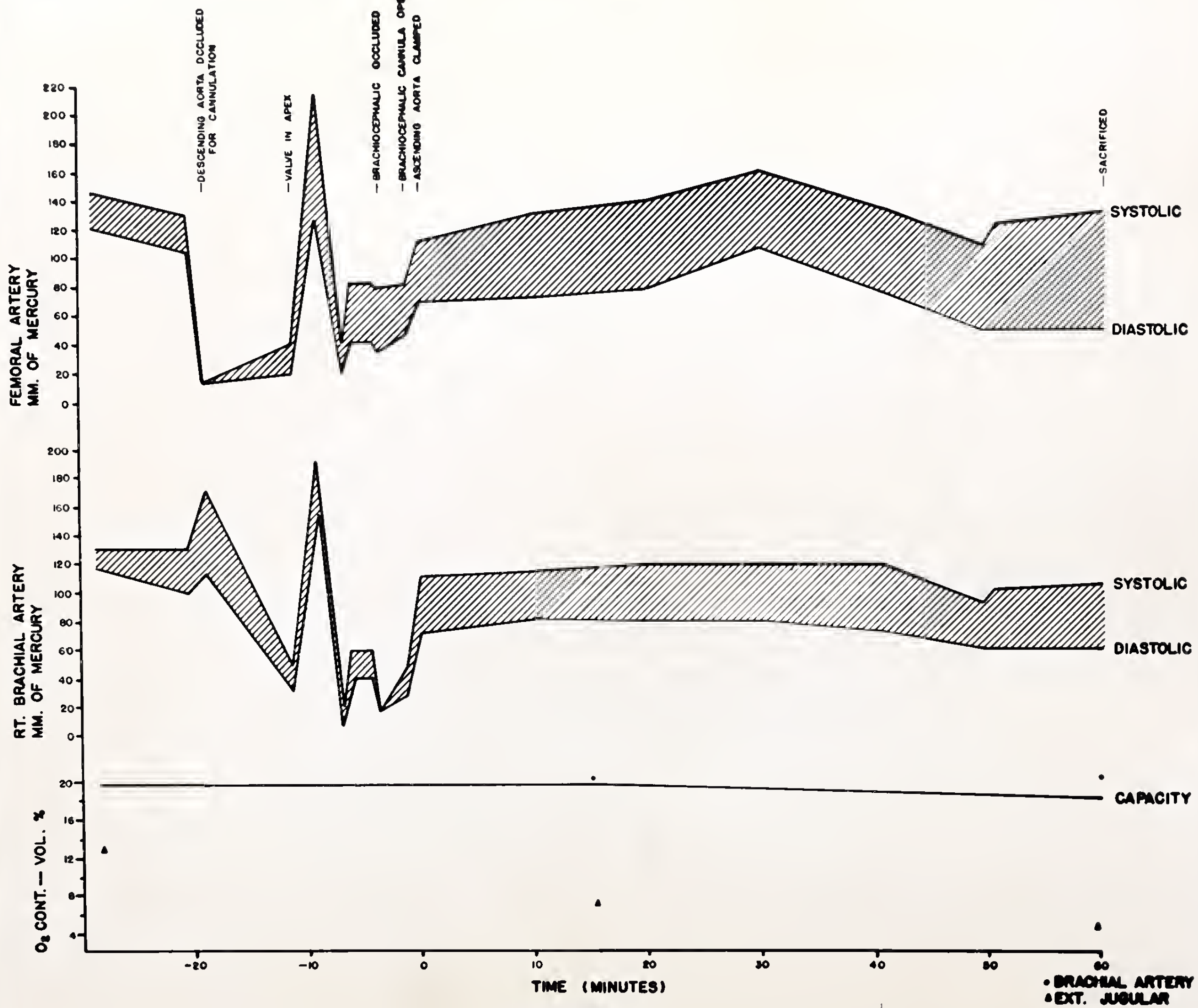
EXPERIMENT 20 - TABLE IV

	PRESSURES - MILLIMETERS OF MERCURY				AVERAGE CARDIAC OUTPUT (cc./min.)	NUMBER AND RANGE OF OUTPUT DETERMINATIONS (cc./min.)
	FEMORAL ARTERY	LEFT VENTRICLE	RIGHT VENTRICLE	ASCENDING AORTA		
PRE-INSERTION OF PROSTHESIS	175/120	110/15	40/10	105/100	4215	x5 3500-4480
PROSTHESIS FUNCTIONING; ASCENDING AORTA CLAMPED	170/115	170/5	35/5	130/115	2510	x3 2430-2520
AORTIC END OF PROSTHESIS OCCLUDED; ASCENDING AORTA OPEN	175/125	120/0	35/0	135/130	2300	x2 2105-2490



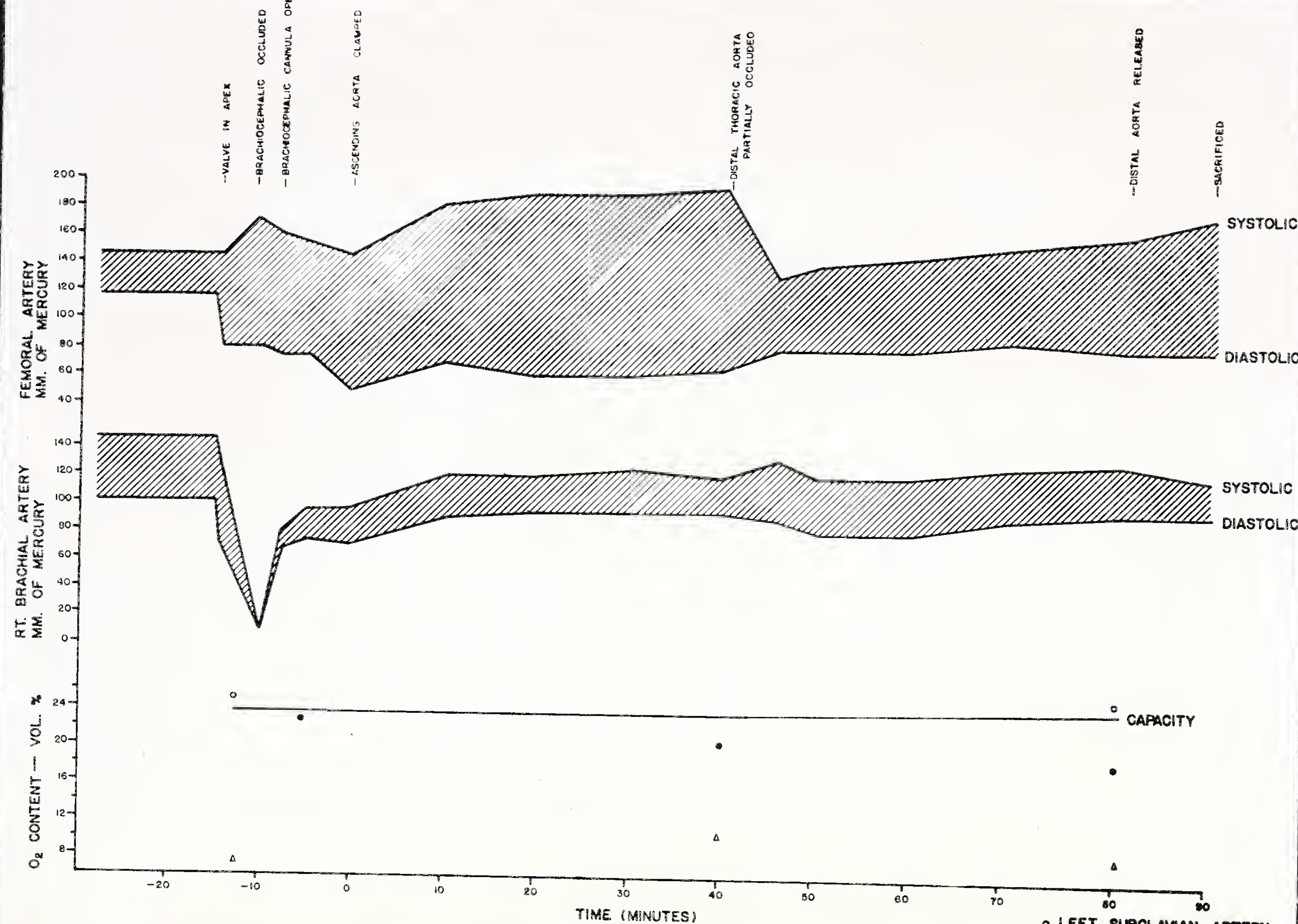
EXPERIMENT 2

FIGURE 14



EXPERIMENT 3

FIGURE 15



EXPERIMENT 10

FIGURE 16

ELECTROCARDIOGRAM—EXPERIMENT 17

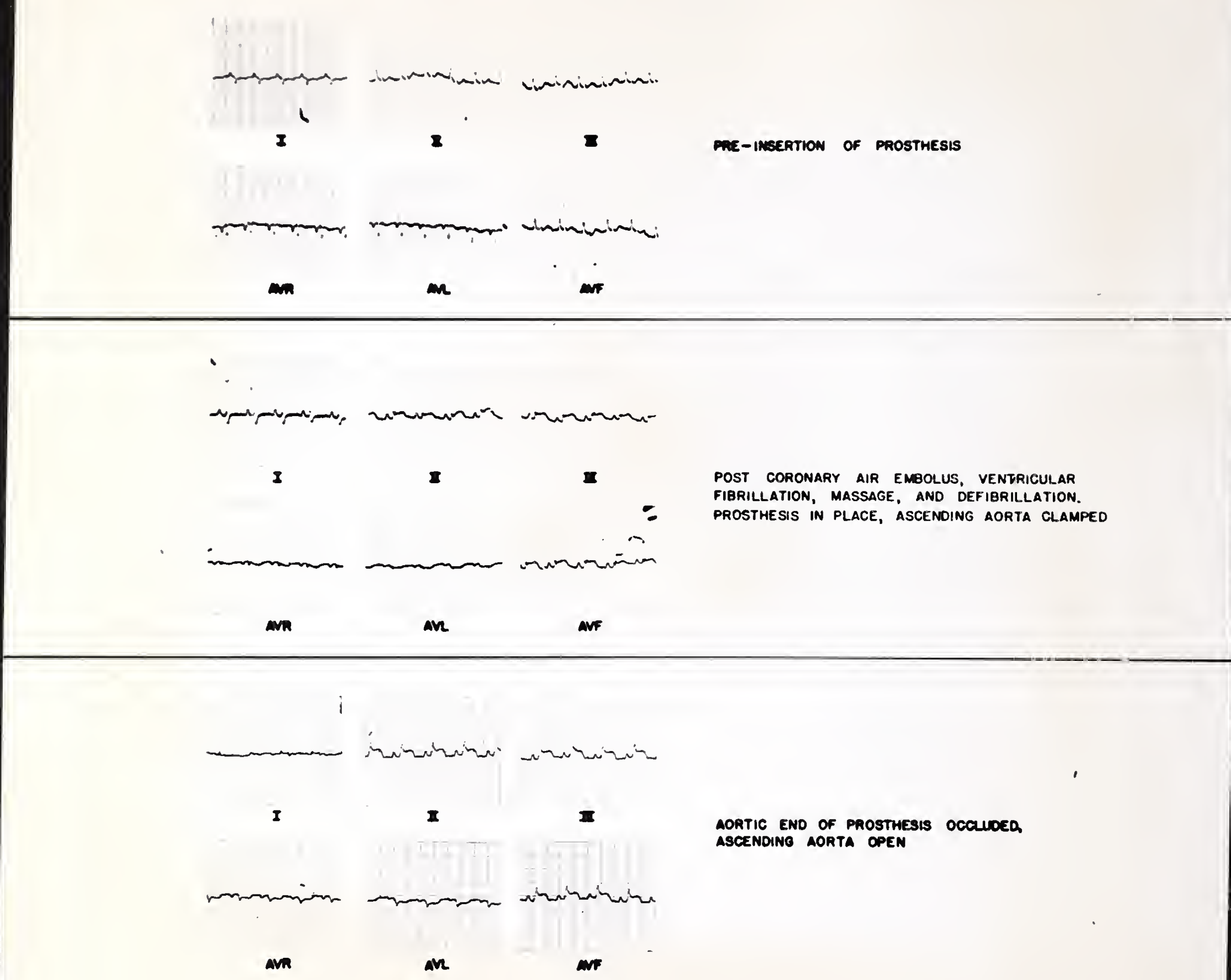
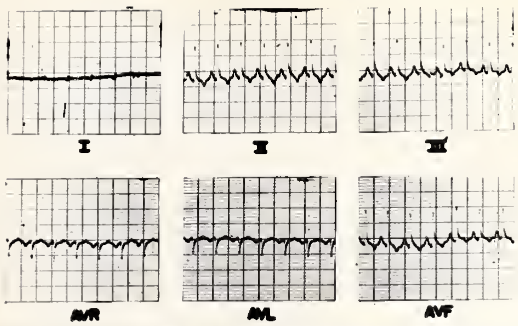
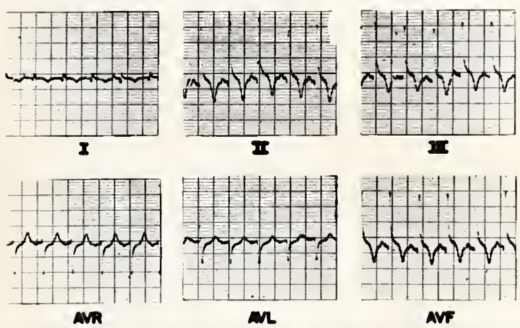


FIGURE 17

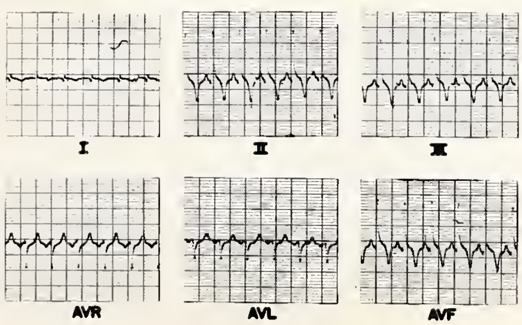
ELECTROCARDIOGRAM — EXPERIMENT 18



PRE-INSERTION OF PROSTHESIS



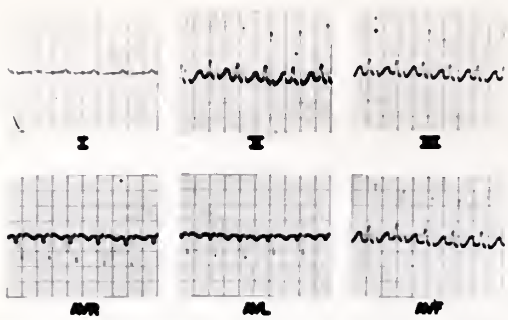
PROSTHESIS IN PLACE, ASCENDING AORTA CLAMPED



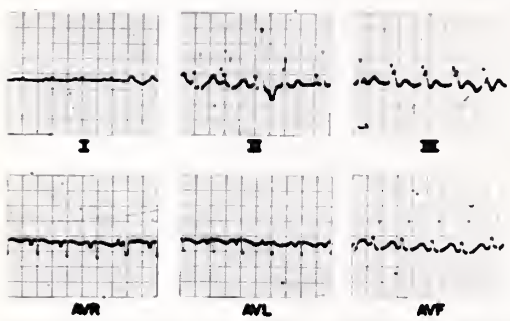
AORTIC END OF PROSTHESIS OCCLUDED,
ASCENDING AORTA OPEN

FIGURE 18

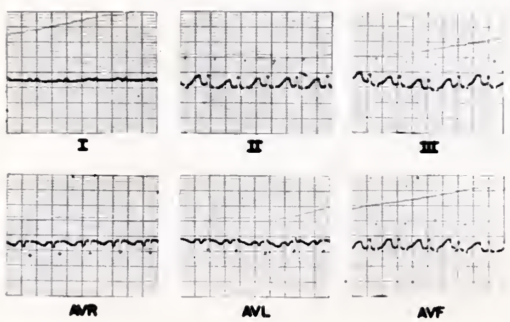
ELECTROCARDIOGRAM — EXPERIMENT 20



PRE-INSERTION OF PROSTHESIS



PROSTHESIS IN PLACE, ASCENDING AORTA CLAMPED



AORTIC END OF PROSTHESIS OCCLUDED,
ASCENDING AORTA OPEN

FIGURE 19

EXPERIMENT 20

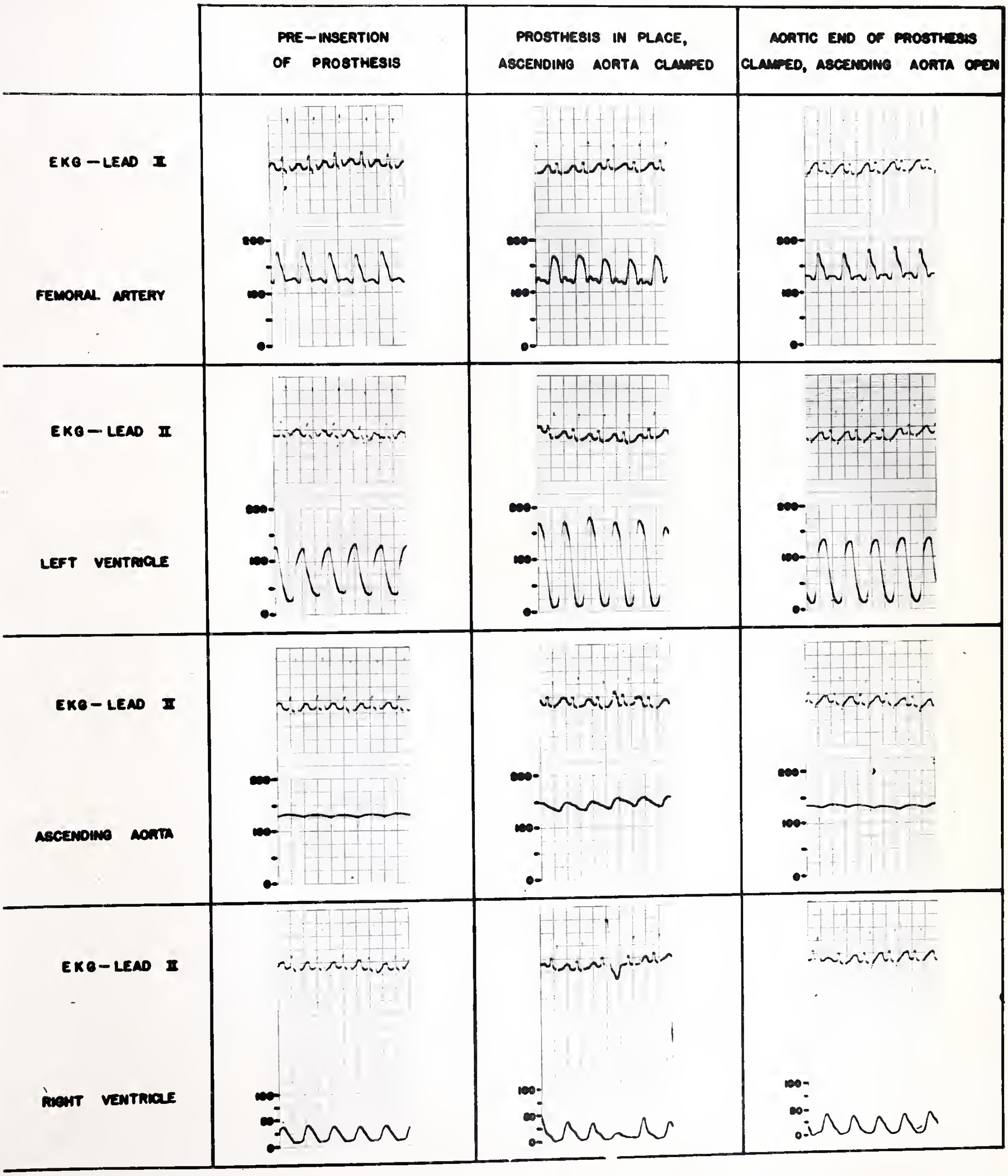


FIGURE 20

EXPERIMENT 20

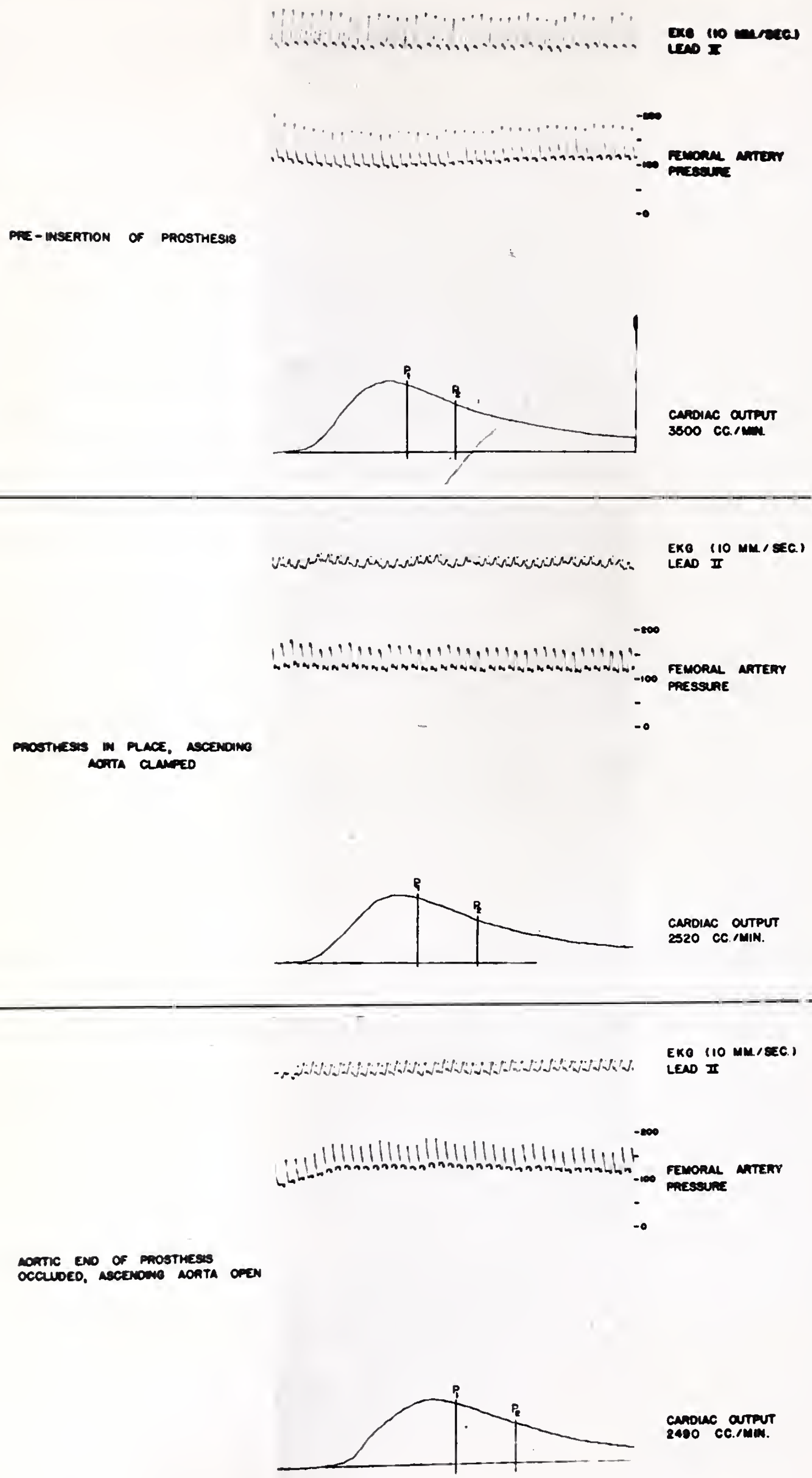


FIGURE 21

EXPERIMENT 20

EFFECT OF EXTRASYSTOLES ON CARDIAC OUTPUT

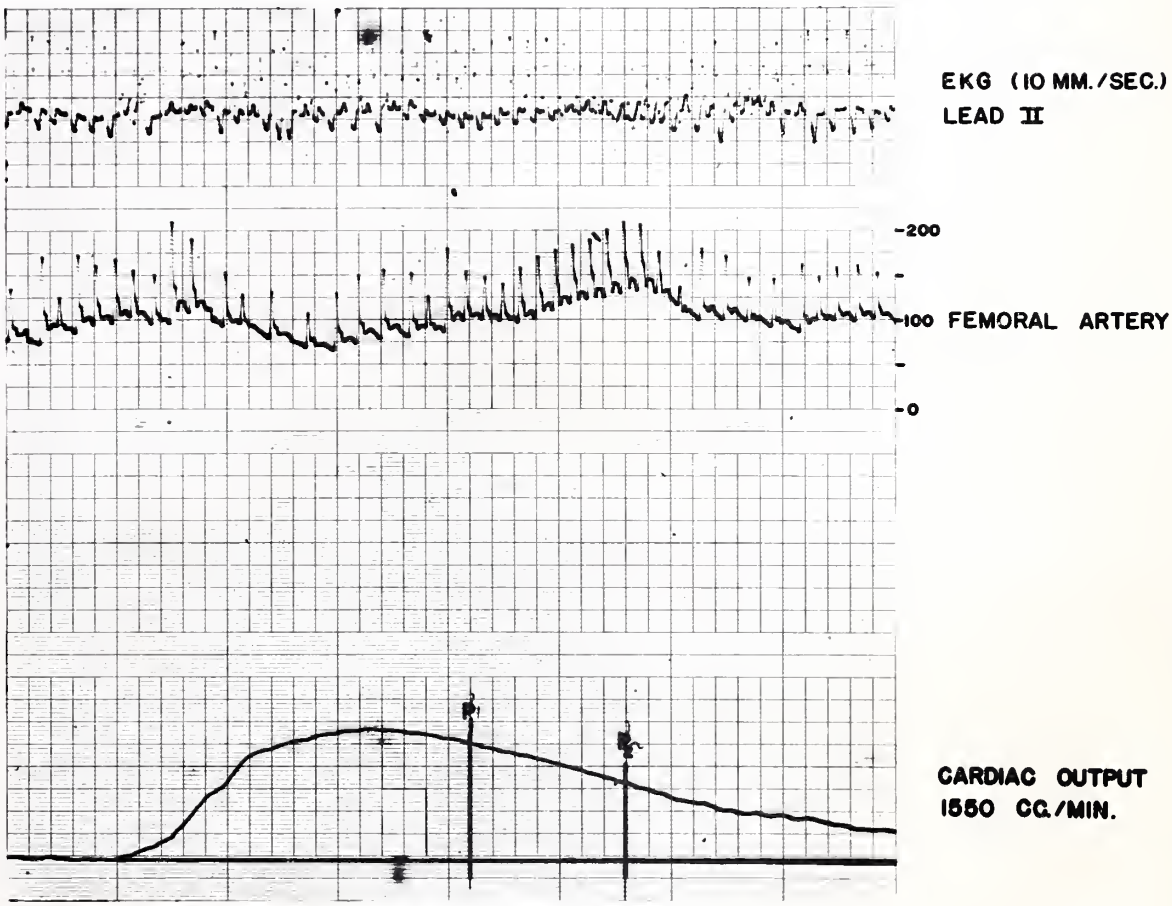


FIGURE 22

Aortic Arch Resections Tables V and VI summarize the results of the sterile arch replacement procedures. The original prosthesis was used in the four animals in Group I while the six experiments in Group II were done with the revised model. Some further information will clarify the brief data presented in the Tables.

It was not until after Experiment 6 that the diverticulum arrangement previously described to accept the aortic end of the prosthesis was used. In Experiments 5 and 6 the aorta was cannulated directly, securing the flanged tip with a multiple point fixation ring. Since only one prosthesis was available and the diameters of the dog's aortas varied considerably, cannulation was abandoned in favor of the diverticulum which was used in all the subsequent studies. The fact that the diverticulum could be sutured to the aorta without completely occluding it, as was necessary with cannulation, was a second consideration.

Hemorrhage was a rather consistent complication, and the first of the arch resections, Experiments 5 and 6, were no exceptions.

Suturing of the aortic diverticulum and placement of the aortic end of the prosthesis in Experiment 7 was accomplished without complication. While major catastrophe was avoided in this animal, a slow hemorrhage from the brachiocephalic and ascending aortic suture lines rapidly exceeded the supply of blood on hand for replacement. During the 35

ARCH RESECTIONS - GROUP I

EXP. #	WT. & SEX	TYPE OF GRAFT	DURATION ASCENDING AORTA OCCLUSION	TOTAL TIME PROSTHESIS FUNCTIONING	DURATION BRACHIOCEPHALIC OCCLUSION	COMPLICATIONS	RESULT	CAUSE OF DEATH
5	27 Kg.M	Homograft	34 mins.	47 mins.	1 min. 15 sec.	Hemorrhage through apical hole during placement of ventricular end of prosthesis. Occlusion of coronary arteries by rotation of ascending aorta clamp.	Died on table	Ventricular fibrillation; Hemorrhage
6	34 Kg.F	----	----	----	----	Tear of thoracic aorta in placing aortic end of prosthesis. Purse-string suture at base of left auricular appendage cut through.	Died on table	Hemorrhage
7	14 Kg.M	Homograft	59 mins.	180 mins.	3 mins.	Hemorrhage from ascending and brachiocephalic suture lines.	Survived 12 hours	Cerebral anoxia secondary to hypovolemia
8	17 Kg.M	----	20 mins.	20 mins.	4 mins.	Tear of diverticulum suture line during placement of ventricular end of prosthesis. Breaking loose of brachiocephalic cannula with hemorrhage.	Died on table.	Hemorrhage

TABLE V

ARCH RESECTIONS - GROUP II

EXP. #	WT. & SEX	TYPE OF GRAFT	DURATION ASCENDING AORTA OCCLUSION	TOTAL TIME PROSTHESIS FUNCTIONING	DURATION BRACHIOCEPHALIC OCCLUSION	COMPLICATIONS OF SURGERY	RESULT	CAUSE OF DEATH
11	25 Kg.M	Dacron	1 min.	1 min.	----	Mechanical difficulty with respirator.	Died on table	Ventricular fibrillation
12	21 Kg.M	Dacron	70 mins.	90 mins.	2 mins. 3 sec.	Hemorrhage from apex with removal of prosthesis.	Survived 30 mins.	Bronchial obstruction
13	25 Kg.M	----	----	----	----	Hemorrhage from diverticulum suture line. Diverticulum inadvertently sutured together. Hemorrhage from apex.	Died on table	Hemorrhage
14	18 Kg.F	Dacron	54 mins.	90 mins.	2 mins. 5 sec. then 7-8 mins.	Brachiocephalic cannula tore base with artery retracting into mediastinum.	Survived	----
15	26 Kg.M	----	----	----	----	Ventricular fibrillation during placement of prosthesis into apex.	Died on table	Ventricular fibrillation
21	16 Kg.M	----	----	----	----	Rupture of aorta during dissection.	Experiment abandoned	Hemorrhage

TABLE VI

minutes that more blood was being obtained the systolic pressure (femoral artery) ranged between 45 and 70 millimeters of mercury (Figure 23). After transfusion the pressure gradually rose to 125 mm. (Figure 23), but the animal failed to respond postoperatively and expired 12 hours later. Postmortem examination revealed all suture lines to be intact (Figure 24) and the repair of the apex to be secure although some slight subendocardial hemorrhage was noted.

A severe hemorrhage from the diverticulum suture line was a fatal complication in Experiment 8.

Since the aorta was no longer being cannulated, it was felt that a straight delivery at the aortic end of the shunt would be more satisfactory in that it would allow the diverticulum to be placed at the mid-thoracic aorta instead of near the diaphragm. Therefore, the prosthesis was returned to the manufacturer for revision. After one trial run with the new shunt in a non-sterile experiment a further shortening of the housing* was found to be necessary and it was this final revised model (Figure 9) which was used in the remainder of the studies.

Although Experiment 11 did not produce a survivor due to a mechanical failure of the respirator, no hemorrhage or other complication was encountered in this procedure and the function of the revised prosthesis was entirely satisfactory.

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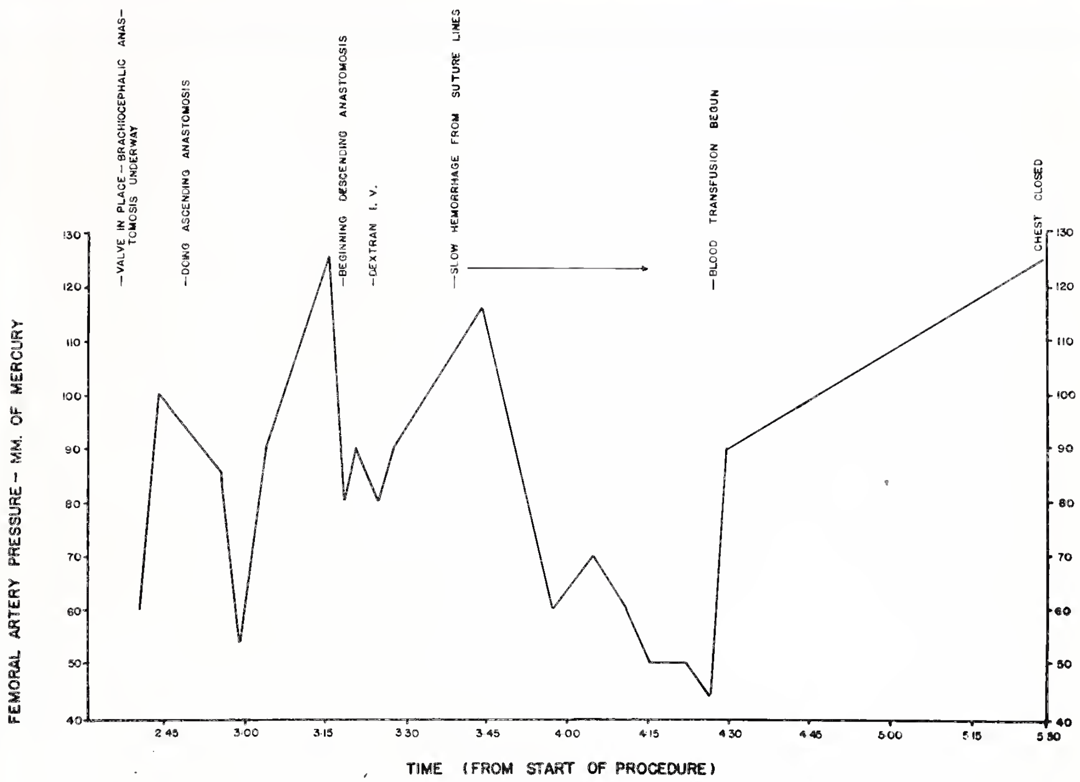
* Work done by Mr. Joseph Fitzpatrick, Yale Medical School Machine Shop.

Two relatively minor hemorrhages occurred during Experiment 12, one from the suture line of the diverticulum and the other from the apex as the shunt was being removed. Both hemorrhages were easily controlled and the blood loss was replaced by transfusion. All other aspects of the surgery were uncomplicated and this animal withstood the procedure well. Except for a brief drop following the blood loss from the apex, the systolic blood pressure taken via the femoral artery was maintained above 90 mm. of mercury. Thirty minutes following closure of the chest, the dog was found dead. Continuous blood pressure recordings revealed a systolic blood pressure of 230 mm. just before his demise and postmortem examination showed mucous plugs obstructing both mainstem bronchi. All suture lines were intact (Figure 25).

The last of the animals that bears extra comment, Experiment 14, is also the only long term survivor and remains in excellent condition at the time of this writing, ten months postoperatively. The animal withstood the procedure well with the aid of a 1500 cc. transfusion of whole dog blood. Systolic blood pressure monitored via the femoral artery was maintained between 100 and 150 mm. of mercury. The early postoperative period was uneventful and 12 hours later the animal was alert and active in his cage. Intravenous arteriography done 50, 183, and 315 days postoperatively revealed a functioning graft with some slight kinking in the transverse portion of the arch (Figures 26, 27, and 28).



EXPERIMENT 7

FIGURE 23

Figure 24.
Experiment 7. Postmortem specimen showing homograft with intact suture lines and origin and exit points of apical-aortic shunt.

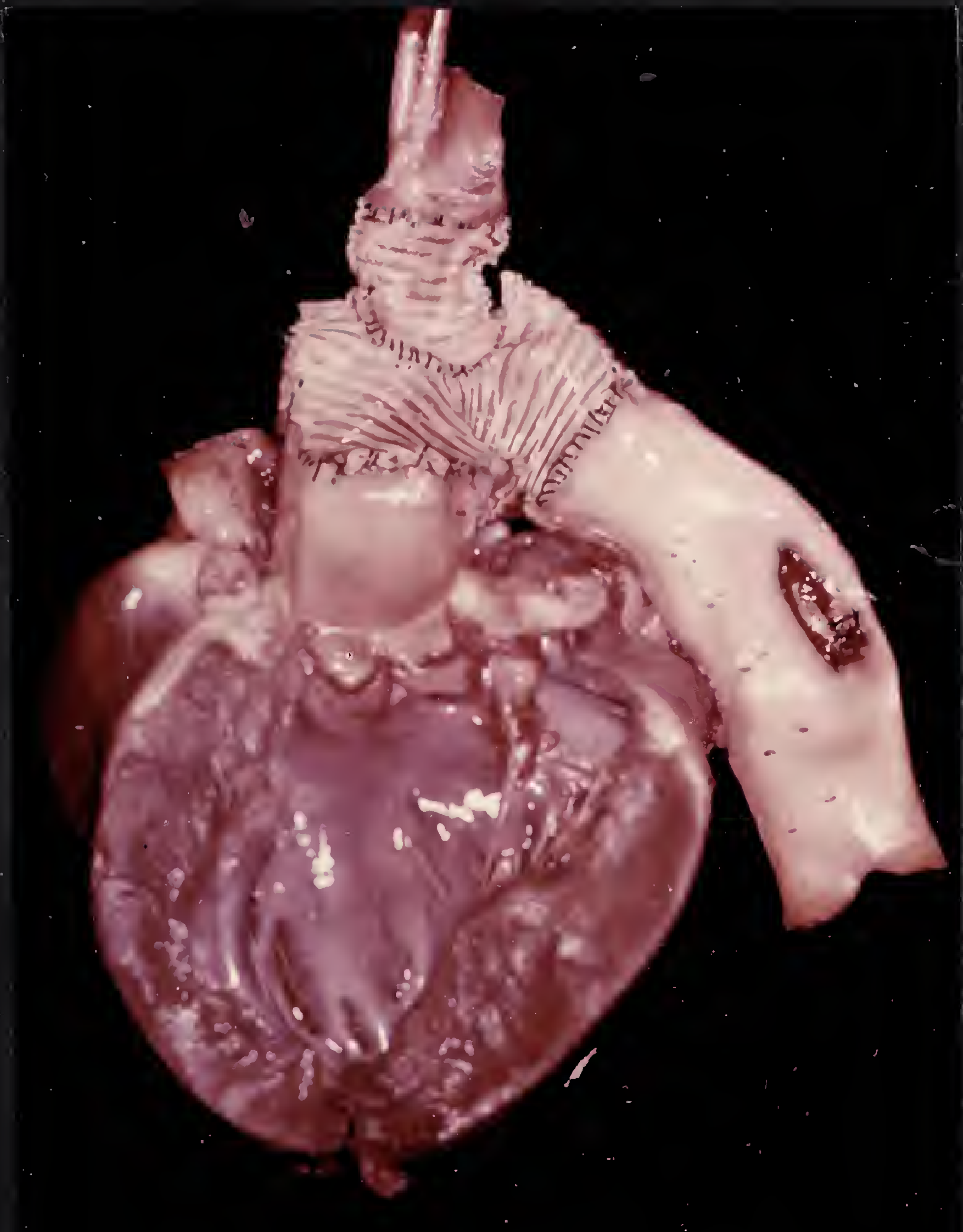


Figure 25.
Experiment 12. Postmortem specimen showing Dacron graft with intact suture lines and origin and exit points of apical-aortic shunt.

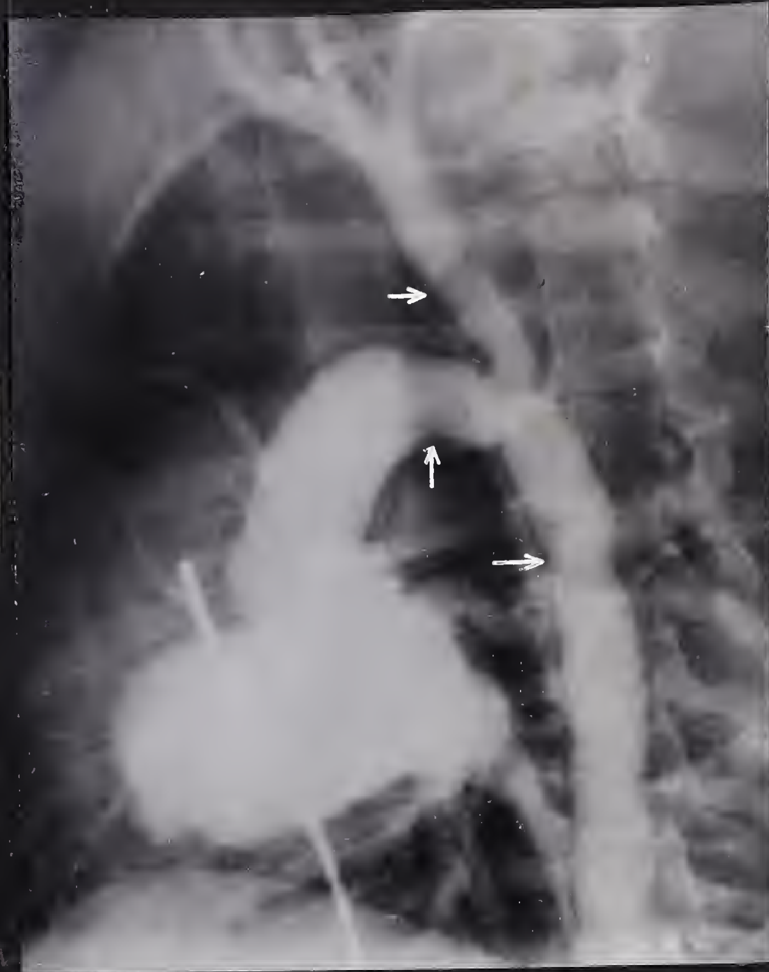


Figure 26.
Experiment 14. Angio-cardiogram 50 days post-operatively. Arrows indicate anastomoses.

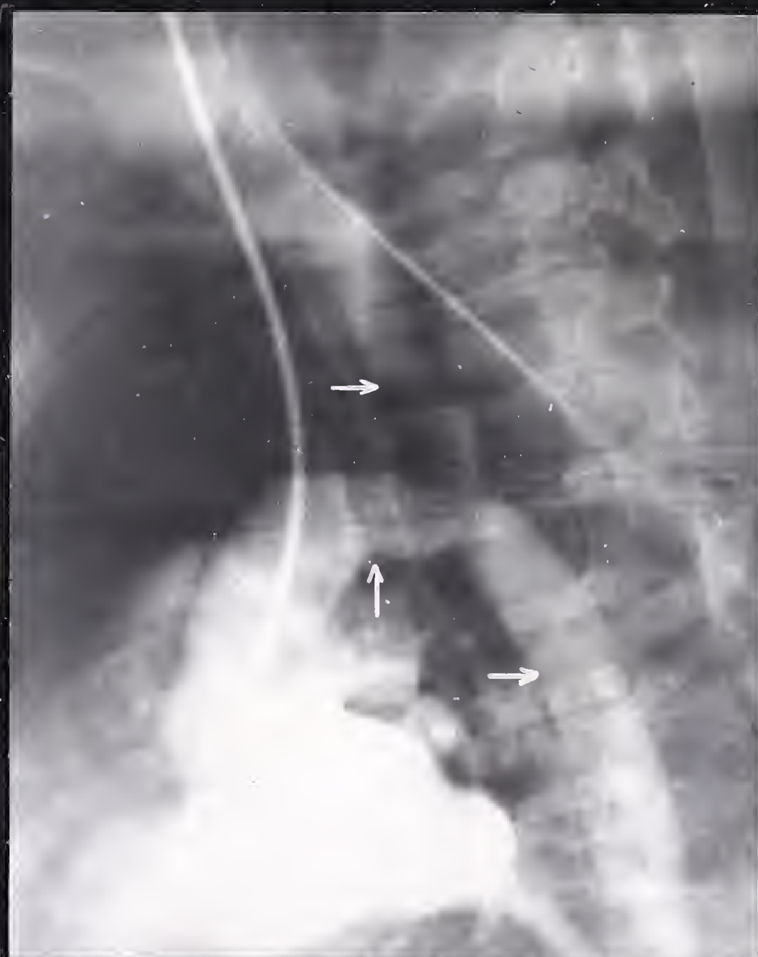


Figure 27.
Experiment 14. Angio-cardiogram 183 days post-operatively.

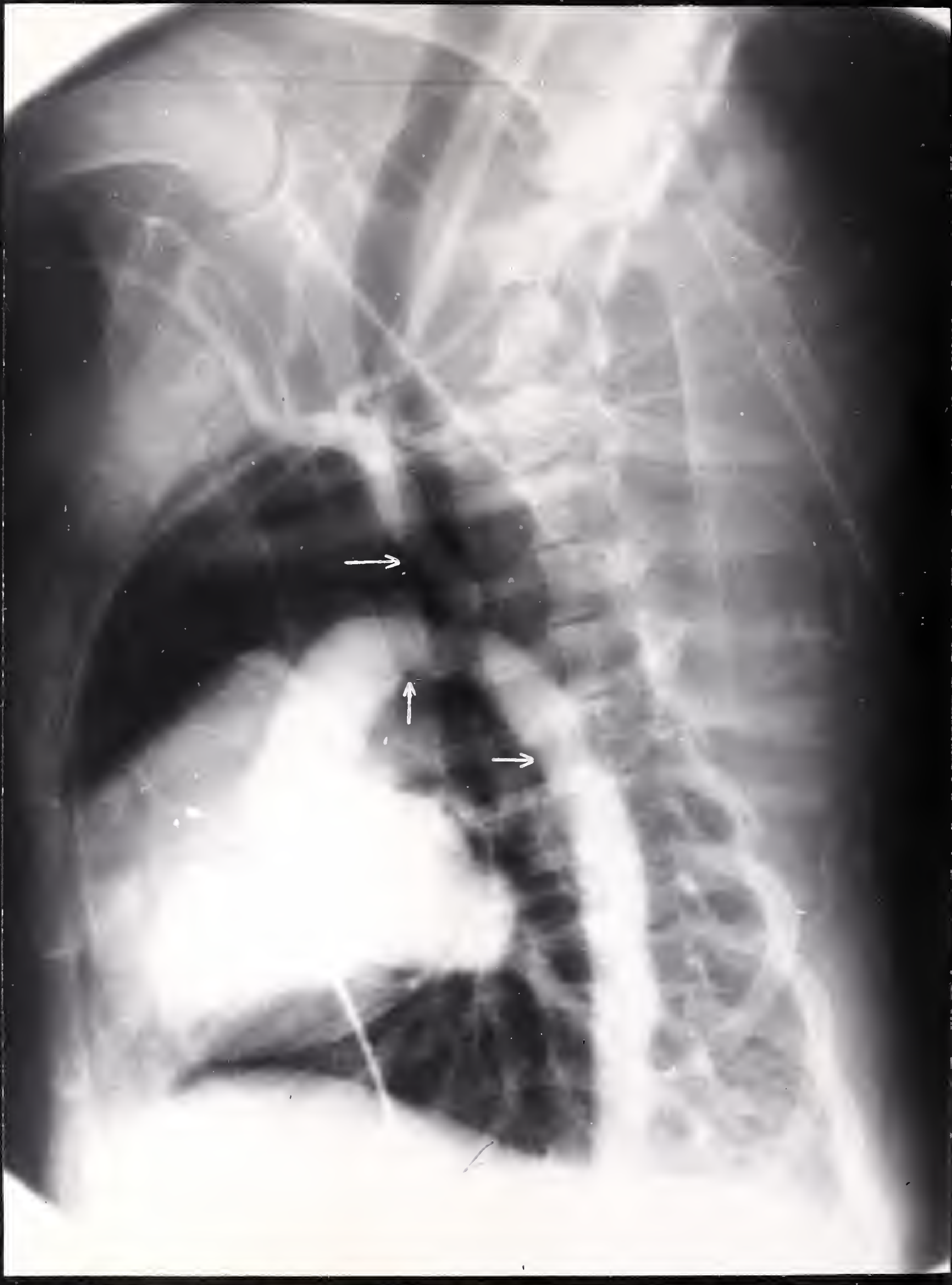


Figure 28. Experiment 14. Angiocardiogram 315 days postoperatively. Arrows indicate anastomoses.

DISCUSSION

In reviewing the use of pump-oxygenators for the resection of the human aortic arch, Muller and his group[57] have recently pointed out that by using means other than extracorporeal circulation the risk of using the pump itself is eliminated even though this risk has become small with present-day systems in the hands of experienced operators. He also states that a second major advantage in avoiding the pump is the absence of the necessity for heparinization. In the light of the results from the present study it is the latter consideration that is impressive.

Of the ten arch resections attempted, significant hemorrhage occurred in eight of the animals. While more often than not the hemorrhage was of the massive variety that heparinization would not have affected one way or another, the slow leakage encountered from the brachiocephalic and ascending suture lines in Experiment 7 would have been been extremely difficult, if not impossible, to control in the heparinized animal. Of course, the problem of dealing with hemorrhage from the bed of a resected aneurysm would be greatly intensified in the heparinized patient.

Resection of the dog's aortic arch is somewhat facilitated by the fact that only two major vessels take their origin from the transverse arch, i.e., the brachiocephalic and the left subclavian, and reinstitution of blood flow to

the latter is purely optional. Application of the shunt described in the present study to resection of the human aortic arch would require the addition of a second sidearm to the prosthesis to supply both the innominate and left common carotid arteries.

A comparison between the arch resections performed with the original prosthesis and those done with the revised model reveals no significant difference in operative complications (Tables V and VI). However, it is notable that of the four operative deaths in the second group, three occurred before the prosthesis was functioning and the fourth was the result of a mechanical failure in the respirator. Furthermore, the facility with which the prosthesis could be placed was considerably improved by the revision.

The progressive decline in the oxygen content of blood drawn from the external jugular vein in the presence of a stable level of oxygen in the arterial samples suggests a somewhat less than adequate perfusion via the brachiocephalic cannula. Partial occlusion of the distal thoracic aorta in an effort to divert a greater proportion of flow out the brachiocephalic cannula (Experiment 10) was successful in preventing the precipitous fall in venous oxygen content observed in the earlier studies. Despite what was apparently a reduced perfusion the arterial blood pres-

sure measured via the brachial artery was well maintained in all of the animals.

The presence of the apical-aortic shunt in the cardiovascular circuit also produced other alterations in function. Electrocardiographic evidence of a mild right axis deviation can be explained by a mechanical shift of the heart to the right by the lucite housing interposed between the apex and the aorta. Three alternate explanations are possible for changes observed in the cardiac output between the control and subsequent measurements.

The first possibility is that the operative trauma necessary to implant the ventricular end of the prosthesis was the cause of the decrease in output. While hemorrhage is an obvious cause, also to be considered is a temporary impairment of cardiac efficiency secondary to the intracardiac manipulations. Secondly, the mechanical deviation of the heart as reflected in the electrocardiograms may have interferred with its capacity to maintain a normal cardiac output. Finally, the possibility arises that in expelling blood out the apex the ventricular musculature does not operate in as efficient a manner as it does under normal circumstances. This last explanation seems least likely since cardiac output did not return to its control level following occlusion of the aortic end of the shunt and release of the ascending aorta.

Vowles, Couves, and Howard [70] have recently been able

to correlate arterial pressure in the ascending aorta with coronary artery flow as measured at the coronary sinus. Their studies were performed with dogs on partial left heart bypass and the ascending aorta cross-clamped. It was found that there was a linear relationship between pressure in the ascending aorta and coronary sinus minute output up to about 150 mm. of mercury, after which an increase in pressure produced less effect on flow. When the pressure in the ascending aorta was between 80 and 100 mm., the coronary sinus output was 40 cc. per 100 grams of heart muscle per minute. At a pressure of 150 mm., the flow was approximately 60 cc. per 100 grams per minute. On the basis of this work, it can be said that the ascending aorta pressures recorded in the present study were adequate to ensure satisfactory coronary artery perfusion.

As previously noted, certain cardiac arrhythmias occasionally negated an individual cardiac output determination. It is suggested that the thermal dilution method of ascertaining cardiac output as applied in this study could be a useful and graphic tool in the experimental demonstration of cardiac output alterations during a variety of arrhythmias.

While the apical-aortic shunt has previously been suggested[60] as a possible treatment for aortic stenosis, studies of physiologic alterations in the long term animal have yet to be published. It is possible that follow-up data similar

to that presented here for the acute experiment might shed some light on the ultimate fate of the chronic ventricular apex to aorta shunt.

SUMMARY

The clinical and experimental literature regarding resection of the thoracic aorta is reviewed.

Eleven experiments were undertaken to determine the effectiveness of an apical-aortic ball valve shunt in maintaining cardiovascular homeostasis. Physiologic studies performed included peripheral arterial pressures, intracardiac pressures, electrocardiograms, blood oxygen content determinations, and cardiac outputs.

The apical-aortic shunt will function as an adequate conduit for left ventricular outflow.

A technic whereby the aortic arch of a dog may be resected by the temporary use of the apical-aortic shunt is presented. Of the ten resections attempted, three animals survived operation, one of these on a long term basis. Hemorrhage was frequently a complicating factor during operation.

Application of the present technic to the resection of the human arch aneurysm would avoid the necessity of heparinization, hypothermia, and the use of the pump-oxygenator, and would allow all of the anastomoses to be performed end-to-end.

The determination of cardiac output by thermal dilution curves is suggested as a graphic and simple method for the study of cardiac arrhythmias.

Follow-up physiologic studies are suggested as a means of evaluating the chronic apical-aortic shunt as a possible treatment for aortic stenosis.

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