Coarctation of the Aorta

By Robert E. Gross, M.D.

Constrictions can occur anywhere in the aorta from the midpoint of the arch down to the bifurcation of the vessel. A few are found in the abdomen or in the lower thorax, but fully 98 per cent of them are located in the first part of the descending aorta, just beyond the arch.

Prognosis

Since most children and young adults with coarctation of the aorta do not have symptoms, there is a rather widespread belief that the malformation is an innocuous affair. The fact that a few humans with aortic narrowing have lived to advanced old age has given a false impression that the prognosis is generally not serious. There is now increasing evidence to show that coarctation leads to crippling complications or even fatality in a very large percentage of cases.

A study of the prognosis for humans with coarctation has indicated that about one fourth of them have lived through a rather long life with little or no incapacitation, that about one fourth have died of rupture of the aorta, that one fourth have died from superimposed bacterial endarteritis, and one fourth have died from the hypertensive state. In the last group, death occurred either from cardiac failure or from intracranial hemorrhage.

As one summarizes available material regarding the prognosis for patients with coarctation, several general statements can be made. The average age at death (including persons who have died from coarctation or one of its complications) has been about 30 years. It has become quite clear that, while some subjects may live a long and useful life with coarctation, the abnormality is one which generally brings great hazards to its possessor. It is this knowledge which prompts surgeons to attempt removal of aortic obstructions in the hope of bettering the outlook, particularly in alleviation of the hypertensive state.

Clinical Picture

Sex

Coarctation is about twice as common in males as in females.

Ease of Recognition

With but rare exceptions, coarctation of the aorta can be detected quickly by finding a few signs which are evident on physical examination. In these days, when there is an increasing tendency to employ expensive and complicated laboratory tests, it is appropriate to point out that coarctation can be diagnosed accurately in a few moments by the intelligent use of one's finger tips, a stethoscope, and a sphygmomanometer.

Differences in Pulsation

Of greatest importance in detecting an aortic obstruction is the disparity between pulsations (or blood pressures) in the arms and legs. Beats in the legs or lower part of the body are diminished or absent. If femoral pulsations appear to be reduced in intensity, the pressures in the popliteal artery should be checked with a sphygmomanometer. Normally, the systolic level in the legs is 20 to 40 mm. Hg higher than that in the arms; in the presence of an aortic block the leg pressures are far below those in the upper part of the body.

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Under normal circumstances, the impulses in the femoral and radial arteries come almost at the same instant. In the presence of coarctation, the femoral artery beat starts at a slightly later time and there is a slow rise of the wave. These lags can be recognized easily by simultaneous palpation of the radial and femoral arteries.

Hypertension

In young subjects with coarctation, pressures in an arm may be normal or only slightly elevated, whereas in older persons one commonly finds hypertension of moderate or marked degree. Certainly, in the majority of patients beyond the second decade, hypertension is the rule. The systolic pressure may be greatly elevated; in advanced cases, the diastolic level can be raised 10 to 30 mm., or more.

Hypertension Varies with Activity. Blood pressure determinations made during an office visit or when a patient is at rest in bed do not indicate the state of affairs when he is undertaking exercise or is undergoing the physical strain of daily life. The value observed during rest is usually distinctly lower than that which occurs during routine activity. It is well known that a normal person reacts to exercise by slight or moderate elevation of blood pressure. In contrast, a patient with coarctation generally responds by an extraordinary rise. The increased demands of the body raise the cardiac output, but the large quantity of blood ejected from the heart meets an obstructed vascular tree; hence, there is a momentary and steep upward swing of pressure in the head and arms.

Pressure Measurements in Both Arms. Arterial pressures should be measured in both arms because this might give a clue to detection of those constrictions which lie in the arch itself. Differences of 10, 20, or even 30 mm. Hg between the two arms can be found in individuals who are normal and also in those who have an obstruction beyond the origin of the left subclavian artery. Conversely, a pressure which is more than 30 or 40 mm. Hg lower in the left arm than in the right suggests that the aorta is narrowed in a place proximal to the origin of the left subclavian artery, an item of great significance when discussing the feasibility of surgery.

It is well to bear in mind that large differences in arm pressures can also be caused by atresia (or hypoplasia) of the first part of the left subclavian artery, a finding in several of our patients. Furthermore, Stephens described a subject in whom the right subclavian artery did not originate from the innominate, but instead arose from the aorta below the obstruction; the arterial pressure in the right arm was distinctly lower than that in the left.

Accessory Arterial Channels

Collateral arterial circulation is by no means constantly observed, but when found it strongly favors the diagnosis of coarctation. By physical examination, it is rarely seen in children, but beyond the first decade it becomes evident both by inspection and palpation. Pulsations may be seen and felt above and below the clavicles, in the axillae, along the intercostal spaces in the forward half of the chest, in the epigastrium, and particularly over the upper half of the back. When collateral circulation is marked, pulsations sometimes appear in the anterior abdominal wall and can be traced downward to the inguinal regions.

Murmurs

There is nothing characteristic about the murmurs which are found; they are extremely variable in form, in intensity, and in location. A few subjects with coarctation have no murmur; a small number have continuous ones. Most often, but by no means constantly, there is a systolic murmur of mild or moderate intensity over the precordium, especially toward the base, which is transmitted with slight diminution to the left side of the interscapular area. In some instances, the murmur is louder in the back than it is in the front of the chest. Murmurs over the back do not, by their point of maximum loudness, give an indication of the actual level of the aortic anomaly.

We have little in the way of accurate information regarding sources of murmurs which
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appear in patients with coarctation. It is tempting to think that blood passing through a narrowed aortic segment sets up the vibration, but there is ample proof that this is not always true. While a systolic murmur in some instances is known to come from the constricted area, in others it almost certainly originates from an angulated collateral channel, an associated septal defect, a bicuspid aortic valve, or other structural change.

Particular attention must be paid to a diastolic murmur. If it is continuous with the systolic element and is loudest in the pulmonary area, it suggests the presence of a patent ductus arteriosus. If a continuous murmur is most prominent over the back, it may be indicative of blood rushing through large and tortuous collateral arteries. If a diastolic murmur is heard in the aortic area or to the left of the sternum, one should strongly suspect aortic valve stenosis and insufficiency. Slight regurgitations may not produce a depression in the diastolic pressure, but marked reflux is accompanied by a definite lowering. While such disturbances in the aortic valve may have a rheumatic background, commonly they are on the basis of a congenitally bicuspid structure of the valve leaflets.

Cardiac Failure

There is little need to comment on the picture of cardiac failure in adults, which is so common and which can follow long-standing hypertension. Myocardial weakness is one of the outstanding causes of death in patients with coarctation. In childhood, failure is rare but it does occur.

It is well to call attention to a small group of babies who have cardiac embarrassment because of an aortic block. Presumably, these youngsters remain in fair health as long as a ductus arteriosus stays patent and blood can flow from the engorged upper portion of the aorta back into the pulmonary bed. When the ductus closes and this relief mechanism is lost, the left ventricle must pump into a vascular system which has a very high resistance because it is almost devoid of collateral channels. We have seen a dozen babies within the first year of life who had marked cardiac enlargement, dyspnea, cough, enlarged liver, and other signs of a failing heart, such decompensation being secondary to hypertension from an aortic block. Two of these infants died of failure, but the others could be tided over (by hospitalization, oxygen therapy, digitalization, and other medical measures) until they regained cardiac compensation. During this precarious interval of one or two months, they probably developed collateral pathways which allowed an easier outflow of blood and which permitted the heart to regain stability.

Neurologic Deficit

Profound neurologic damage, or even fatality, can occur as a result of intracranial hemorrhage. There may be hemiplegia, or widespread and bizarre neurologic findings, depending upon the position and extent of bleeding within the central nervous system. Such disaster can occur from rupture of a normal vessel which is subjected to increased pressure; not infrequently it comes from a congenital aneurysm in the circle of Willis, rupture being particularly prone to take place when such an anomaly is subjected to the hypertension of a coarctation.

Fainting, dizziness, momentary loss of consciousness or even convulsions can also be seen as a result of hypertensive crises, there being no hemorrhage within the brain.

Ballistocardiographic Findings

The diagnosis of coarctation of the aorta can apparently be made from ballistocardiographic tracings; there is a shortening of the J-K stroke. While this phenomenon is an interesting observation, such investigation is not necessary for routine study.

Electrocardiographic Findings

Electrocardiographic tracings are an important part of the examination, not because they help in recognition of a coarctation, but because they might give evidence regarding the presence of some other co-existing cardiovascular anomaly. Furthermore, electrocardiograms can indicate whether hypertension has inflicted any damage upon the myocardium.
In children the electrocardiogram is apt to be normal, but in older subjects a left-axis deviation is the rule. In patients beyond 20 to 30 years of age, patterns of serious left ventricular strain or bundle branch block are ominous findings when discussing the possibility of operative removal of a coarctation.

Roentgenographic Findings

By roentgenographic study there may be certain findings in childhood to help support the diagnosis of coarctation; in adult years the changes usually become more pronounced and clearly indicate the presence of this abnormality.

In infancy one seldom finds more than generalized cardiac enlargement unless, in the rare case, there happens to be additional evidence of circulatory failure. During the first 8 or 10 years of life there may be little variation from normal except possibly for some left ventricular prominence and some diminution in the size of the aortic knob. In and beyond the teens, the roentgenologic findings are more numerous and more conclusive; the heart generally shows mild or moderate increase in size, particularly of the left ventricle. Great enlargements should arouse suspicion regarding the possibility of some concomitant abnormality, myocarditis, coexisting rheumatic disease, or cardiac failure. The base of the ascending aorta is apt to be widened. The left subclavian artery is usually seen to be enlarged; it results in a prominence of the left side of the superior mediastinum. The aortic knob or distal part of the aortic arch is smaller than normal. Though it is by no means a constant finding, the descending aorta appears indented if the patient can be turned to an angle which will separate this shadow from the spine. In many cases, it is impossible to see the constriction of the aorta.

Scalloping of the inferior edges of the posterolateral portions of ribs is pathognomonic of an aortic block with development of collateral circulation. Such erosion is seldom found in the upper or the lower two or three ribs. It rarely appears before 8 or 10 years of age; it is generally present in teen-agers, and it is almost always apparent in adult patients.

Of unusual occurrence is the situation described by Bing and his associates in which the left subclavian artery arose from the aorta below its block; there were collateral channels on the left side of the chest, the rib notchings were confined to the right side. In this same category is the case of Stephens in which the right subclavian artery arose from the aorta below the obstruction; the rib notches were found only on the left side of the chest. We have seen a similar roentgenologic picture on a different basis in a 12 year old girl in whom the first portion of the left subclavian artery was atretic; chest films showed rib notches which were distinctly more marked on the right than on the left.

Though relatively rare, coarctation may appear in the lower portion of the thorax, or even in the abdominal aorta. Under these circumstances, the aortic knob is normal in appearance and the collateral channels are largest over the abdomen and lower part of the chest; notches appear only on the lowest ribs.

With barium in the esophagus, some irregularity is usually found on its left side, the so-called "E-sign." This esophageal compression can come from that part of the aorta which is dilated just beyond the obstruction, and also from right intercostal arteries which cross the mediastinum to enter the distal aorta. Of great importance to the surgeon is a lateral view of the esophagus; prominent serrations on the posterior aspect of the esophagus indicate the presence of very large right intercostal arteries which course to and enter the aorta below its obstruction. These thin-walled vessels are extremely hazardous to deal with surgically; the roentgenographic picture can forewarn the surgeon of their presence.

Angiocardiogram. Further information regarding the exact position of a stricture, the length of the narrowed segment, and allied data, are obtainable by means of angiocardiography. The radio-opaque material can be injected either by the intravenous route or in a retroarterial manner. Seventy per cent Diodrast, if infused quickly into a vein, will often remain in sufficient concentration through the circulation so that the aortic arch and its
branches can be seen in serial films. All too often, the dye becomes diluted and does not show the great arteries very well. An alternative technic is that in which visualization is obtained by introducing a polyethylene catheter into an artery of the left arm, threading it back through the left subclavian artery into the aorta, at which time the injection is made. Burford and Carson\(^6\) and more recently Freeman and co-workers\(^6\) have obtained excellent pictures of the vessels by injecting Diodrast down a neck artery, preferably the left common carotid, while temporarily obstructing the vessel above the site of injection.

On many occasions I have been disappointed or have been misled by angiocardiography in the study of patients with coarctation of the aorta. At times the dye would show the upper end of the narrowed area, but did not give information regarding the length of the stricture. In other cases, where there was a complete aortic block, nothing was learned about the segment of aorta below it. Presumably, angiocardiography should be of assistance in deciding which cases are suitable for surgery and which are not, but often this is not so. This has been especially true in older patients when visualization might show an arrangement of vessels suggesting that removal of the constricted area would be feasible; when the chest has been opened the vessels were found to be very rigid or fixed and surgical attack had to be abandoned.

Angiocardiography is not an essential part of a routine work-up, but it can be of value in those cases where there are unusual or inexplicable findings. Its greatest usefulness is in those patients who have, by physical examination, an aortic block but who do not have an E-sign on the esophagus and do not have notching of the ribs; they might have either a coarctation or a hypoplasia of the entire aorta. Under these puzzling circumstances, visualization of the aorta generally can settle the differential point.

**Selection of Cases for Surgery**

**Surgery Generally Advisable**

It is our belief that almost all patients with coarctation should be operated upon at some appropriate time, provided there are no serious contraindications. Statistics now show that the mortality rates of operation can be kept reasonably low. It therefore seems best to accept these risks, which are almost certainly lower than those of letting the patient go along without therapy. In an occasional case, it might be wise to defer surgery if the blood pressure is in relatively safe levels. However, it is well to remember that, while a child or a young adult may show only slightly elevated pressures, important hypertension is very apt to appear subsequently in later years.

**Contraindications**

Because certain co-existing conditions have been found to increase enormously the operative risks, there are several contraindications to operation. Rheumatic mitral disease of marked degree, aortic valve regurgitation of serious extent (diastolic murmur of more than grade 3 intensity, or appreciably lowered diastolic pressure), conduction bundle defects (by electrocardiogram), or advanced myocardial damage (by clinical picture or electrocardiogram) are generally contraindications to surgical attack on a coarctation.

Many persons with coarctation have a congenitally bicuspid aortic valve; by itself, this is not a contraindication to surgery. Likewise, a mild degree of insufficiency at such a valve (grade 1 to 3 diastolic murmur, with no important depression of the diastolic pressure) does not seriously increase the risks of surgery.

**Optimum Time for Surgery**

The optimum ages for operation lie between 10 and 20 years. In this range the aorta is large enough to work upon with facility, has good elasticity, has little or no degenerative change, and provides the best conditions for making an anastomosis which is sizable and satisfactory. The lumen will be large enough to carry the patient through adult life.

Beyond the second decade, patients begin to present situations which greatly increase the difficulties of operation. The heart has less reserve, the chest is larger, the exposure is more difficult, the aorta is more inelastic, and
aneurysms are more frequently encountered in the distal aortic segment or in one of its intercostal arteries. These and other factors make the operative procedures more troublesome for the surgeon and also less promising for the patient. The various difficulties are more apt to be encountered in men; in contrast, women almost always have vessels which are softer, more elastic, and easier to work upon.

Therapy for Babies. Sometimes babies, in the first year of life, have impressive symptoms indicative of cardiac impairment from a coarctation of the aorta; in a few there is fatality. If these patients get beyond the first year, they are then apt to go through childhood without too much difficulty. This poses the question of whether or not an infant who is having cardiac symptoms, should be operated upon. It has generally been our policy to advise against operation at this early age because it appears that the vast majority of these small subjects can be tided over their period of embarrassment by medical means, after which they do reasonably well; we believe that the best chances for a satisfactory operation will come later, between 8 and 12 years of age. We have steered away from surgery in the infant because, while it is technically possible to work upon the aorta and give it a lumen satisfactory for this size patient, there is little assurance that the growth of the anastomotic site will keep pace with that of the individual. From laboratory observations on aortic unions in growing pigs, several investigators have found that it is possible for the lumen to enlarge reasonably well with the increase in size of the maturing animal, but in some instances it lags somewhat behind. Hence, in a human baby, we generally prefer to carry along on temporizing treatment by medical means, and then perform operation later in childhood when there is a more reasonable promise that the pathway will be large enough to be adequate during adult life. That it is possible to treat coarctation surgically in an infant has been shown by Kirklin and associates. Therefore, if medical therapy does not seem to be sufficient to control cardiac failure in a baby, surgery can be undertaken as the indications require.

Operation in Midadult Life. There is no definite upper age limit, beyond which it is advisable to avoid surgical removal of a coarctation. However, after the ages of 30 or 35, surgery should not be undertaken unless it is reasonably certain that the myocardium is in good enough condition to stand the strain of a long major operation, a point which can be best judged by the patient’s tolerance for exercise and by the electrocardiographic tracings.

Surgical Therapy

Sympathectomy

We do not believe that sympathectomy is of any value in the treatment of hypertension which is based on coarctation.

Bypass with the Left Subclavian Artery

Blalock and Park suggested a form of treatment for coarctation by severing the left subclavian artery high in the chest and turning it downward for union with the aorta beyond the obstruction. In the presence of coarctation, the subclavian is often of very large size; indeed it may approach the diameter of the aortic arch. This suggests that it would provide an excellent pathway if joined to the distal aorta. There are two drawbacks to such an undertaking: (1) The severance of a subclavian artery cuts off many collateral channels, the loss of which is not inconsequential. (2) The base of a subclavian artery is sometimes semirigid, so that attempts to turn the vessel downward result in a kinking which greatly reduces the effective size of its lumen. While the subclavian operations have given a few good results in relief of hypertension, on the whole they are very disappointing; we have abandoned them completely.

Excision of Coarctation. Primary Anastomosis

The ideal method of therapy—feasible in most instances—is excision of a coarctation and reconstruction of the pathway by bringing together the remaining ends of the aortic tube. Without discussing the minutiae of surgical technic, certain points and general principles are well worth stressing here:

Preparation for Transfusion. Blood loss is
apt to be high in these operations. The chest wall is always exceedingly vascular; in spite of the fact that a very large number of vessels are clamped and ligated, bleeding is considerable. It is necessary to prepare ahead of time for infusion of blood during operation to compensate for this. For children, at least 1000 cc. of blood should be matched before operation; for large children or adults 2000 to 3000, or preferably 4000 cc. should be on hand.

Exposure. To give one's self the best chance to work on the aorta, a generous exposure is of considerable help. There are some surgeons who have employed only an incision in the fourth intercostal space or through the bed of the fourth or fifth rib (after removing the same subperiosteally); we believe these to be inadequate, or certainly they are not optimum. A T-shaped wound in the bony cage gives an ideal view; we use it routinely in all cases. The fourth intercostal space is cut along its entire length, with posterior severance of two ribs above this and two below (in large subjects three ribs are always cut below).

Safest Progression in Liberating Aorta. In mobilizing the aorta and related vessels, it is a very sound principle to avoid at first those regions which are apt to be dangerous or difficult to deal with; it is better to begin with the easier parts of the regional dissection. In this way, as one approaches the most risky areas (the upper intercostals, the coarctation, the ligamentum arteriosum), any injury or bleeding can be cared for quickly because the vessels have already been freed and can be handled as needed. Conversely, if one had attacked the most vulnerable parts first and set up a hemorrhage, it is almost impossible to deal with the catastrophe.

With the above thoughts in mind, it is good procedure to start work by freeing up the entire left subclavian artery, carrying this down to include somewhat the anterior and posterior surfaces of the distal arch. Then attention is turned to the aorta below the upper two or three sets of intercostal arteries. Down at this low site, it is not difficult or dangerous to circumvent the aorta and get a tape around it. From here the dissection can be carried cautiously upward around and underneath the aorta, dividing any bronchial arteries which are encountered. By tapes, the aorta can be pulled up slightly into the field and away from the vertebral column, which dislocation will aid in identifying and stretching out the upper thin intercostal arteries which are now freed. The coarctation area, the ligamentum arteriosum, and the undersurface of the aortic arch are cleared last.

Saving Intercostal Arteries. To get all of a coarctation cut out, and in addition have enough cuff for making an anastomosis, it is sometimes necessary to divide intercostals which are nearby. In the vast majority of cases these thin vessels are far enough away from the coarctation so that they can be raised from their beds and can be temporarily compressed by small serrefine clamps without hampering too much the subsequent stages of operation; in this way a maximum amount of collateral circulation is spared. It is important to emphasize that it is pointless to save intercostals if doing so compromises the making of a good aortic pathway; the primary objective should be to make a first-rate union of full aortic size, even though some collaterals might have to be sacrificed in attaining this.

Removal of Sufficient Aortic Tissue. It is a fundamental truism that if surgical therapy is going to be successful in the relief of hypertension, it is essential to remove all of the coarctation. In the tense atmosphere of operation, it is quite tempting for the surgeon to cut away only the more narrowed part of the constricted zone; he may be fearful that more radical excision will lead to difficulties in approximation of remaining aortic ends. Such a compromise is very apt to be followed by incomplete relief of hypertension. To obtain the best possible results, every effort must be made to remove all of the constriction and to establish a pathway which is fully the diameter of the aortic arch.

Form of Anastomosis. In bringing remaining ends of aorta together, it is wrong to attempt an anatomic repair of intima to intima, media to media, and adventitia to adventitia. Though this has been advised and used by some surgeons, it is a distinctly inferior type of union
and it will often give way and disrupt. Overwhelming evidence indicates that the best repair is that in which mattress stitches are taken through the entire thickness of the aortic wall, bringing intima to intima, and turning outward the ends of the vessel. We routinely make the stitches interrupted. The best suture material is 00000 Deknatel silk, carried on a straight needle 5/8 inch long.

Position of Coarctation. The position of a coarctation has much to do with the ease or the difficulty with which it can be excised. Obviously, the surgeon's troubles are least when the block lies well beyond the arch and there is a segment of descending aorta (above the block) which can be comfortably clamped. Unfortunately, many obstructions are at a very high level—just beyond the origin of the left subclavian artery—and indeed they may actually be in the distal part of the arch itself. With high constrictions, the surgeon's problems are tremendously increased, particularly when dealing with older subjects in whom the vessels are rigid. While high blocks should be approached with more caution and apprehension, they do not necessarily present insuperable obstacles. To obtain a proximal stump it may be necessary to place a clamp directly across the aortic arch and across the left subclavian artery so that the latter is partially or totally occluded temporarily.

Excision of Coarctation. Insertion of Graft

Extensive laboratory work (on dogs) has shown that it is possible to transfer an aortic segment from one animal to another (of the same species) and to have it serve as an excellent pathway. Such grafts have been implanted in recipient animals and observed for periods as long as three years. The risk of dilatation, rupture, or thrombosis appears to be negligible. Grafts do show extensive histologic changes, particularly in the media, yet they have a smooth lining and they carry blood in a highly satisfactory manner. While observations from animal work do not necessarily indicate what will happen if aortic segments are transferred from one human to another, there seems to be sufficient experimental background to justify the use of grafts in human subjects to bridge aortic gaps which cannot be treated by any other means.

Aortic segments can be collected from human subjects, preferably young individuals, within four to six hours after death. They can be stored in several ways: (1) If gathered aseptically, they can be stored in a modified Tyrode's fluid at 3 to 4 C., and can be used at anytime up to five or six weeks. (2) Sterile segments can be packaged in cellophane bags, frozen in carbon-dioxide ice at −50 or −55 C., and then kept at this temperature for many months. (3) If segments are contaminated during removal from a body, they can be frozen, and then sterilized by high-voltage Cathode-Ray irradiation; the sterilized frozen segments can be kept many months and still be useful as grafts. We have used the first method for 29 human subjects, the second for three, and the third for five. We have preferred to use the first method if appropriate material is available. We employ the second method only when there is not available material preserved by the first one. We have used the third method only in those instances when we have no segments which have been stored by the first two methods.

There are certain situations wherein it is impossible to perform the ideal operation of excision of a coarctation and primary anastomosis of the remaining aortic ends: (1) The constriction may be a very long one (several centimeters or more). (2) There may be a very rigid and inelastic aorta which cannot be stretched to overcome even a short gap. (3) There may be an aneurysm in the aorta below the constriction. These various problems are best handled by removing all of the pathologic tissue, cutting back to lumen of full size above, and then inserting a graft.

The need for grafting is only seldom met in childhood. It is required more often for adult patients, where complicated pathology and technical difficulties are more frequently encountered.

Anticoagulants

It is not necessary to administer dicoumarin or heparin to prevent local thrombosis. If the aortic intima is not damaged, and if a
proper anastomosis has been made, the danger of regional thrombosis is negligible.

Analgesia for Wound

The extensive posterior chest wound can give a great deal of pain in the postoperative period. It is of considerable help to the patient's comfort to inject, while the chest is still open, 4 to 5 cc. of Nupercaine in oil around each of the upper six or seven intercostal nerves, infiltrating this material between the necks of the ribs. This provides an analgesia to the chest wall for about a week.

Chest Drainage

Because of the extensiveness of the wound, some serosanguinous fluid always accumulates in the chest after operation. It is therefore best to provide intercostal drainage by a tube for three to four days after operation.

Results of Therapy

Mortality Rates

The surgical treatment of coarctation has been placed on a reasonable basis, carrying low fatality rates. To date, we have operated upon 270 patients; in the first 100 of these there were 15 fatalities, in the last 100 there have been but two deaths. This improvement is ascribed to: (1) Avoidance of operation in subjects who are known to have complicated cardiovascular conditions (noted above under Selection of Cases for Surgery). (2) Abandonment of cyclopropane anesthesia. (3) Attainment of sufficient experience with the operation to give greater facility in handling the emergencies which are sometimes encountered.

Exploratory Operation

In some patients it has been impossible to remove an aortic obstruction because: (1) The patient was tolerating anesthesia poorly. (2) The obstruction was too high in the arch. (3) The vessels were densely adherent to surrounding structures and could not be mobilized. (4) The area of constriction was a very long one, prohibiting excision and primary aortic anastomosis. For these various reasons, attempt at surgical removal of the aortic block had to be abandoned, only an exploratory procedure having been made. Such explorations were always a disappointment to the surgical team and to the patient; much work, anxiety, and expense accomplished nothing of value except establishment of the fact that the lesion was "inoperable." Fortunately, exploratory operations have now been reduced to a much lower figure; in our last 100 operations there have been but six (in two of these it was reasonably clear before operation that the condition was not amenable to surgical therapy). This reduction is largely due to the fact that grafts are now available for the treatment of certain situations which previously we would have called inoperable.

Age of Patients Operated Upon

The series of 270 operative cases includes children and adults; the distribution according to ages has been as follows:

<table>
<thead>
<tr>
<th>Age Group</th>
<th>Number of Patients</th>
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<tbody>
<tr>
<td>0-10 yrs.</td>
<td>46 patients</td>
</tr>
<tr>
<td>11-20 yrs.</td>
<td>118 patients</td>
</tr>
<tr>
<td>21-30 yrs.</td>
<td>74 patients</td>
</tr>
<tr>
<td>31-40 yrs.</td>
<td>30 patients</td>
</tr>
<tr>
<td>41-50 yrs.</td>
<td>1 patient</td>
</tr>
<tr>
<td>Above 50 yrs.</td>
<td>1 patient</td>
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In adults, operations have generally been far more arduous than those in the childhood group. Fatality rates have been slightly lower in children than in adults, but the difference is not great.

Blood Pressure Changes

In evaluating postoperative states we are concerned most with objective evidence of what has been accomplished. Changes in blood pressure afford the best record of the readjustments which have been made in the circulatory system. The relief of hypertension is the main purpose of the surgical attack; observations indicate that it is possible to reach this goal in a high percentage of cases. Removal of an aortic block seldom gives a precipitous fall of the arm pressures. Though we have seen them return to normal within 24 hours, the more common reaction is to have a gradual distention of the vascular bed in the lower part of the body during the subsequent two to three weeks, and, concomitantly with this, a progressive fall in the arm pressures. Generally,
the maximum benefit is manifested by the end of several weeks; if relief of hypertension has not been obtained in this period, it is usually wishful thinking to anticipate that it will occur in the more distant future.

Of our patients who have survived excision of a coarctation, follow-up studies have been made from two months to as long as seven years after operation. There has been no relief of hypertension in 2 per cent, a fairly satisfactory relief of hypertension in 10 per cent, and a complete cure of hypertension in 88 per cent (adults with arm pressures below 140, children with pressures lower than this, according to their age).

Postoperative Development of Aneurysm

Routine, long-term postoperative chest roentgenograms have not been obtained in all cases, but in those studies which we have made, no aneurysm has yet been found.

Postoperative Disruption

There has been only one death in patients after discharge from the hospital. This occurred in a 22 year old man who obtained a satisfactory relief of hypertension by removal of his coarctation. One year later there was sudden onset of chest pain and hemoptysis; the roentgenogram showed a fist-sized mass in the chest to the left of the spine which almost certainly represented a hematoma near the operative site. With bed rest, sedation, and transfusions the bleeding subsided, but a few weeks later there was a fatal hemorrhage. No autopsy examination was allowed. Whether the bleeding had come from a thin intercostal artery or from the aortic suture line is unknown.

Use of Aortic Grafts

We have employed aortic grafts in 37 patients. The age distribution of these subjects, and the percentage of cases in each age group requiring grafts were as follows:

<table>
<thead>
<tr>
<th>Age Group</th>
<th>Patients</th>
<th>Per Cent of Cases</th>
</tr>
</thead>
<tbody>
<tr>
<td>1–10 yrs.</td>
<td>3 patients</td>
<td>6 per cent of cases</td>
</tr>
<tr>
<td>11–20 yrs.</td>
<td>11 patients</td>
<td>9 per cent of cases</td>
</tr>
<tr>
<td>21–30 yrs.</td>
<td>17 patients</td>
<td>23 per cent of cases</td>
</tr>
<tr>
<td>31–40 yrs.</td>
<td>6 patients</td>
<td>20 per cent of cases</td>
</tr>
<tr>
<td>Over 40 yrs.</td>
<td>0 patients</td>
<td>0 per cent of cases</td>
</tr>
</tbody>
</table>

The need for grafting in the child is uncommon; the call for it in adult patients is frequent. In the entire series of 270 patients treated for coarctation of the aorta, grafts were employed in 14 per cent. It is quite likely that the more liberal use of grafts would have improved the results in that group of patients who, because of a poor primary anastomosis and a lumen of suboptimal size at the junction, had only fair relief of hypertension.

Certain statements can be made regarding aortic grafting. There has been no sepsis in any case, a fact which we believe is due to meticulous care in collecting and handling the grafts. Three patients died while in the hospital, all from causes unrelated to the grafting. The survivors have been followed for periods of time varying from a few months to as long as five years. In no case has there been rupture of a graft; in no case has there been aneurysm formation. One subject shows roentgenographic evidence of calcification in the graft, but on clinical findings has an excellent aortic pathway. In no instance has there been any symptom or sign suggesting embolism from a graft site.

Viewed from the point of view of therapy for pre-existing hypertension, the over-all picture in the grafted cases has been very pleasing. The results can be classified as failure in one, good in two, fair in two, and excellent in 29. In the "excellent" group, the arm pressures have been restored to normal.

There can be no doubt that the ideal therapy for aortic coarctation is that in which the stricture is removed and a primary aortic anastomosis is made which establishes a lumen of completely normal size. However, sometimes it has been technically impossible to accomplish this; under such circumstances, the use of a graft has permitted treatment of a lesion which could not have been attacked by any other surgical means. Short-term observations of these human grafts up to five years have been extremely gratifying; no final conclusions should be made until the patients have been followed for several decades.

Finding of Aneurysm

In 21 patients an aneurysm was found either in the aorta just beyond the constriction, or
more commonly in the nearby portion of an intercostal artery just as it joined the aorta. These thin-walled lesions were considered to be a great hazard, because of the danger of rupture. It was therefore felt that they always demanded treatment. Because of the friability of the adjacent aortic wall, it was never possible to treat one of the intercostal aneurysms by removal of the mass and closure of the adjacent aortic wall. The aneurysms (intercostal or aortic) were managed by: (1) severing the intercostal artery proximal to the aneurysm and tucking in the aneurysmal sac with adventitial sutures, in seven cases; (2) excision of the aneurysmal segment of aorta and establishment of a primary aortic anastomosis, in three cases; (3) excision of the aneurysmal portion of the aorta and insertion of an aortic graft, in 11 cases.

Postoperative Paralysis

In two patients, aged 31 and 50 years, respectively, there developed during operation, spinal cord damage (probably from ischemia) which left these subjects with severe weakness and neurologic damage of both legs. This distressing complication places these two adults in a far worse condition after operation, (in spite of cure of hypertension) than they were in before. There was nothing at operation in the way of shock, obliteration of intercostal arteries, or other recognized factors that we could blame as specifically being the cause of these disasters. There may have been some abnormality in the anterior spinal artery or sclerosis of regional vessels which, when accompanied by the intrathoracic manipulations of operation accounted for temporary diminution in flow of blood to the spinal cord. These serious complications point out again the trials and tribulations of aortic surgery in adults in comparison with the more favorable results which are obtained in childhood and in the teen-ages.

Period of Recovery

Most patients have been discharged from the hospital 12 to 14 days after their surgery; occasionally they have had to remain as long as three weeks. They usually restrict their activity during convalescence for the subsequent two or three weeks. They have generally returned to full employment by six weeks after operation. Frequently patients have some pain, or discomfort, in the left shoulder or side of the chest which might require the use of codeine; such sequelae always disappear in a month or two. Limitation of motion in the left shoulder girdle clears up spontaneously in a few months.

General Observations

Following relief of an aortic obstruction there have been various findings in some—not all—patients which are worthy of note. When there had been headaches or epistaxes before operation, these have usually disappeared. When there had been cramps or weakness in the legs, these have vanished. Many patients have volunteered the information that their legs are warmer and now “beat” after operation, sensations which they had not previously experienced. Where there had been symptoms of cardiac embarrassment, these have been greatly improved by reducing the cardiac burden. Five of the adult females have subsequently passed through normal pregnancies and deliveries without any cardiac symptoms (one of them has gone through three pregnancies).

While surgical therapy for coarctation of the aorta has been available only since 1944, it is now quite evident that it rests on a sound basis and has a great deal to offer most persons who are afflicted with the abnormality. These operations are formidable undertakings which tax greatly the ingenuity and physical strength of the surgical team, but the efforts have been fully justified and rewarded by the results which have been obtained for the patients.

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Coarctation of the Aorta
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