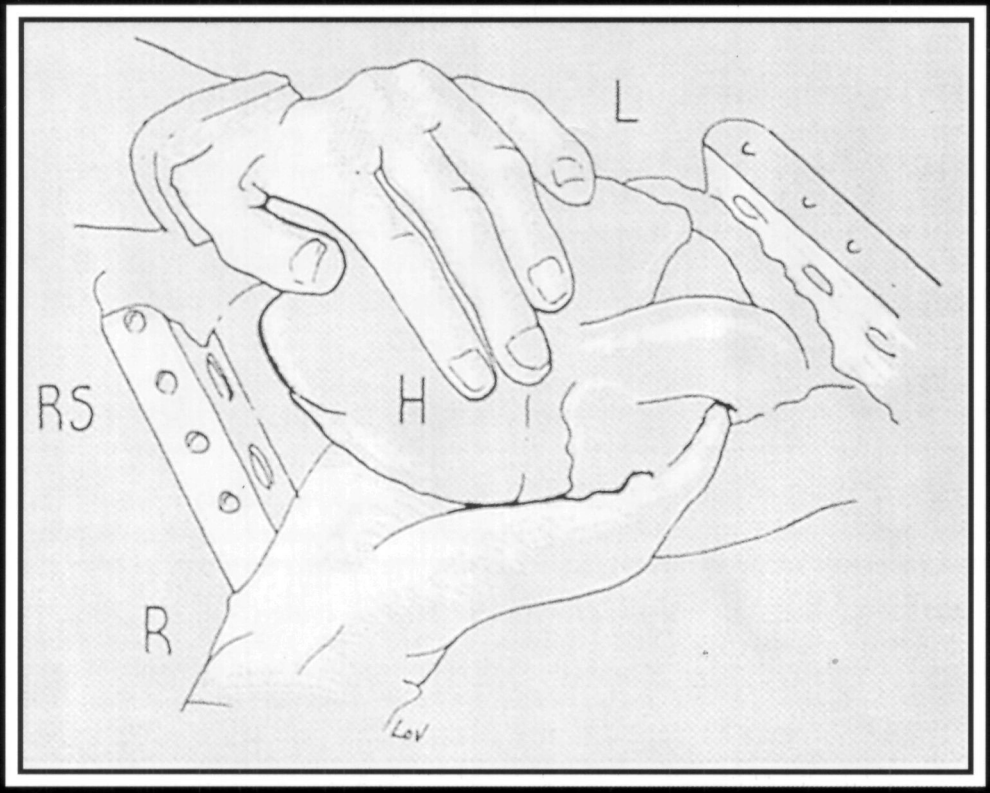
The History of Anesthesiology

Reprint Series: Volume Twenty-nine

Anesthesia for Operations on the Heart



Method of performing open chest manual systole. ***R,*** right hand; ***L,*** left hand; ***H,*** heart; ***RS,*** rib spreader.
(After M. Codding)

Leroy D. Vandam, M.D.
Artist

THE HISTORY OF ANESTHESIOLOGY
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Anesthesia for Operations on the Heart

Introduction

Insofar as operations on the heart are concerned, little doubt exists that surgeons have perforce been the innovators. Anesthetists followed in their wake utilizing whatever anesthetics were available, the same situation applying to methods of monitoring the circulation. In the latter half of the 19th century, interests of surgeons focused on trauma to the chest, pericardium and heart, so that by the century's end there had been 124 reports of operations directed thereto. Nonetheless, in 1893, the eminent German surgeon, Theodor Billroth was led to remark, "Let no man who hopes to retain the respect of his medical colleagues, dare to operate on the human heart."

However, surgeons were "itching" to approach the heart of the circulation, an irresistible urge, following a preliminary era of mysticism, later experimentation and ultimately the modern era. The introduction of surgical anesthesia in the 1840s and then the advent of aseptic surgery truly provided the background for progress.

Not surprisingly then, in 1929, Cutler and Beck, after their initial efforts in 1923, reported on the use of surgical procedures in valvular disease of the heart (finger fracture and use of dilators), some 12 cases in all. Merely mentioned was the employment of N_2O-O_2 or N_2O-ether anesthesia and with an early mortality of 90 percent. Then came "deluge" in the thirties and forties: Robert Gross' first successful ligation of a patent ductus arteriosus (cyclopropane employed): Blalock and Taussig's correction of pulmonic stenosis (Harmel and Lamont, later McQuiston, were using clyclopropane or ether, sometimes endotracheally) and repair of coarctation of the aorta—all extra-cardiac maneuvers.

The application of hypothermia was a major step forward, thereby affording intracardiac procedures with the heart in standstill (Robert Virtue was a pioneer in its anesthetic application), Kenneth K. Keown would then, in a 1956 monograph, share his experiences with anesthesia for surgery of the heart. The keystone, to be sure, was the perfection of a mechanical heart and lung apparatus offering relatively unlimited time to make operative corrections during cardiac standstill. At present, with the employment of anesthetics that treat the heart physiologically kindly, use of intraoperative transesophageal echocardiography, minimally invasive surgery, application of ventricular assist devices, and employment of endovascular dilation and stents, the future is ever more encouraging. Read these papers and gain a heightened sense of the progress made by our specialty since the last one was written.

Leroy D. Vandam, M.D. and B. Raymond Fink, M.D.

October 1999

ANESTHESIA FOR OPERATIONS ON THE HEART

Selected Papers

1. Cutler, EC, Beck CS. The present status of the surgical procedures in chronic valvular disease of the heart: Final report of all surgical cases. *Arch Surg* 1929; 18:403-416.

2. Gross RE, Hubbard JP. Surgical ligation of a patent ductus arteriosus: Report of first successful case. *JAMA* 1939; 112:729-731.

3. Blalock A, Taussig HB. The surgical treatment of malformations of the heart in which there is pulmonary stenosis or pulmonary atresia. *JAMA* 1945; 128:189-202.

4. Harmel MH, Lamont A. Anesthesia in the surgical treatment of congenital pulmonic stenosis. *Anesthesiology* 1946; 7:477-498.

5. McQuiston WO. Anesthetic problems in cardiac surgery in children. *Anesthesiology* 1949; 10:590-600.

6. Bigelow WG, Callaghan JC, Hopps JA. General hypothermia for experimental intracardiac surgery: The use of electrophrenic respirations, an artificial pacemaker for cardiac standstill, and radio-frequency rewarming in general hypothermia. *Ann Surg* 1950;132: 531-539.

7. Swan H, Zeavin I, Blount SG Jr, Virtue RW. Surgery by direct vision in the open heart during hypothermia. *JAMA* 1953; 153:1081-1085.

8. Gibbon JH Jr. Application of a mechanical heart and lung apparatus to cardiac surgery. *Minn Med* 1954; 37:171-180, 185.

THE PRESENT STATUS OF THE SURGICAL PROCEDURES IN CHRONICAL VALVULAR DISEASES OF THE HEART

FINAL REPORT OF ALL SURGICAL CASES

Elliott C. Cutler, Claude S. Beck

Reprinted from
Archives of Surgery 1929; 18:403-416.
Courtesy of the American Medical Association

THE PRESENT STATUS OF THE SURGICAL PROCEDURES IN CHRONIC VALVULAR DISEASE OF THE HEART

FINAL REPORT OF ALL SURGICAL CASES *

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Because the major topic for discussion at the meeting this year is the heart it seems opportune to review the cases of valvular disease in which surgical treatment has been used. In summarizing these cases, we shall attempt to evaluate the general idea of subjecting such disorders to surgical therapy and we shall also attempt to emphasize the problems that must in the future be overcome to make surgical procedures on the cardiac valves useful and beneficial.

Operation has been performed in twelve cases of chronic valvular disease of the heart. These cases have been reported in detail except the last two in which we performed the operation. For the details of these procedures, the reader is referred to the original reports.

SUMMARY OF CASE REPORTS

The table shows, in chronological order, the cases in which operation has been performed.

CASE 1 (Doyen [1]).—A woman, aged 20, had a condition which was diagnosed congenital pulmonary stenosis. The chest was opened and the heart exposed. A small tenotome knife was inserted into the right ventricle and an attempt was made to divide the stenotic valve. Death occurred several hours after operation. At autopsy, there was found a narrowing of the conus arteriosus rather than a localized stenosis of the valve. In addition, and as is usual in cases of congenital disease of the heart, other defects were present, viz., perforated interventricular septum (Roger's disease) and incomplete development of the lungs.

CASE 2 (Tuffier [2]).—A young man showed signs of a marked and progressive aortic stenosis. The thorax was opened, and the root of the aorta was exposed. It

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* From the Department of Surgery of the Western Reserve University School of Medicine and the Lakeside Hospital.

1. Doyen, E.: Chirurgie des malformations congenitales ou acquises du coeur, 26th Cong. de l'assoc. franç. de chir., Presse méd. **21**:860, 1913; La chirurgie du coeur et des vaisseaux, Soc. d. l'inter. d. hôp de Paris, ibid. **21**:987, 1913; La chirurgie du coeur et des gros vaisseaux, Soc. de l'inter. d. hôp. de Paris, ibid. **22**: 282, 1914.

2. Tuffier, T.: État actuel de la chirurgie intrathoracique, Tr. Internat. Cong. Med., 1913, London, 1914, Sect. 7, Surgery, pt. 2, p. 249; discussion, p. 326, 1914; La Chirurgie du coeur, Cinquième congrès de la Société internationale de chirurgie, Paris, July 19-23, 1920, Rapports Procés-Verbaux et Discussions, publiés par le Docteur L. Mayer, Brussels, Hayez, 1921, pp. 5-75.

was the intention of the operator to insert a knife above the aortic ring and to incise the stenosed valve, but the procedure was changed to a dilatation of the aortic ring by invaginating the wall of the aorta just above the valve and pushing the wall into the stenosis on the fore-finger. As late as 1924, this patient was reported living and improved.

CASE 3 (Cutler and Levine[3]).—A girl, aged 11, did not give any history of acute rheumatic fever. There was dyspnea on exertion for three years. For eight months previous to operation, she was confined to bed, and during this period had alarming attacks of hemoptysis. A diagnosis of mitral stenosis was made. A

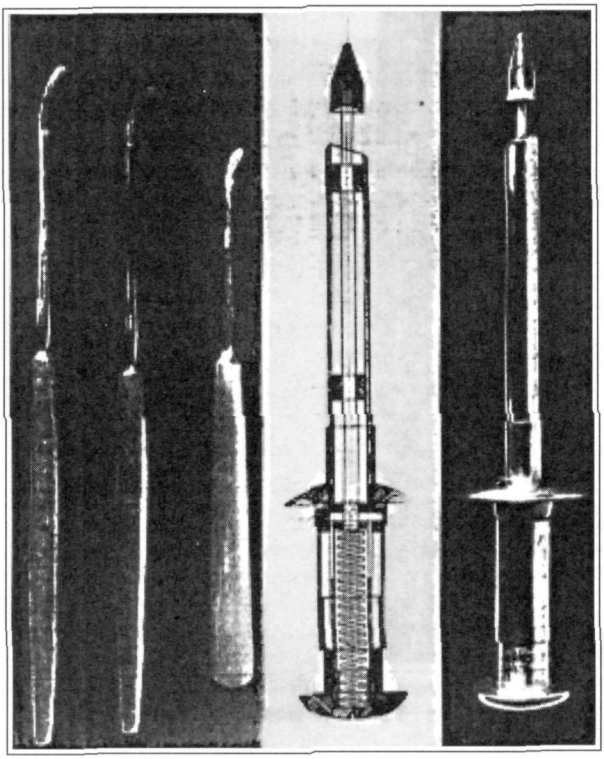

Fig. 1.—Tenotome knives and cardiovalvulotome. The former were used in cases 3, 5 and 6; the later was used in cases 7, 8, 10, 11 and 12.

roentgenogram showed that the left auricle was prominent. The patient was anesthetized with ether, and the chest was opened by a median thoraco-abdominal incision. A tenotome knife (fig. 1) was inserted into the left ventricle, and an attempt was made to incise each cusp of the obstructing ring. The wound in the heart was sutured with silk. The pericardium was closed tightly without drainage.

3. Cutler, E. C., and Levine, S. A.: Cardiotomy and Valvulotomy for Mitral Stenosis, Boston M. & S. J. **188**:1023, 1923. Cutler, E. C.; Levine, S. A., and Beck, C. S.: The Surgical Treatment of Mitral Stenosis, Experimental and Clinical Studies, Arch. Surg. **9**:689 (Nov.) 1924.

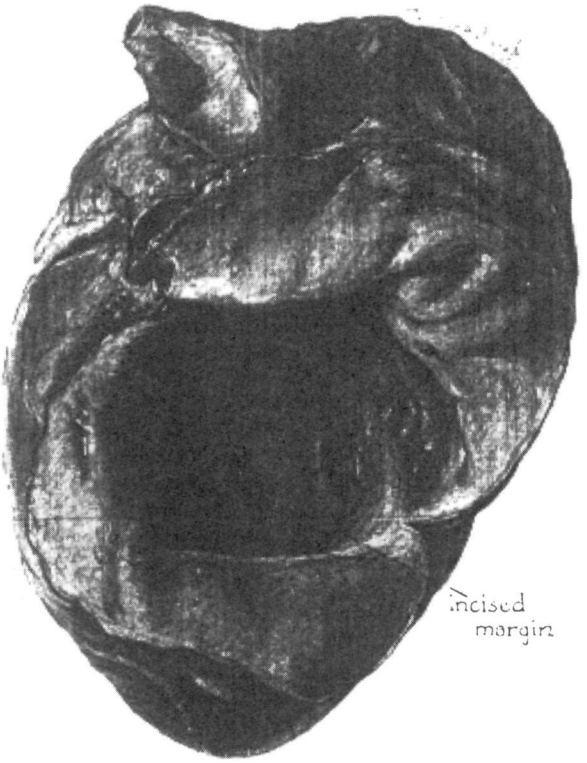

Fig. 2 (case 3).—The mitral valve as seen from the auricle.

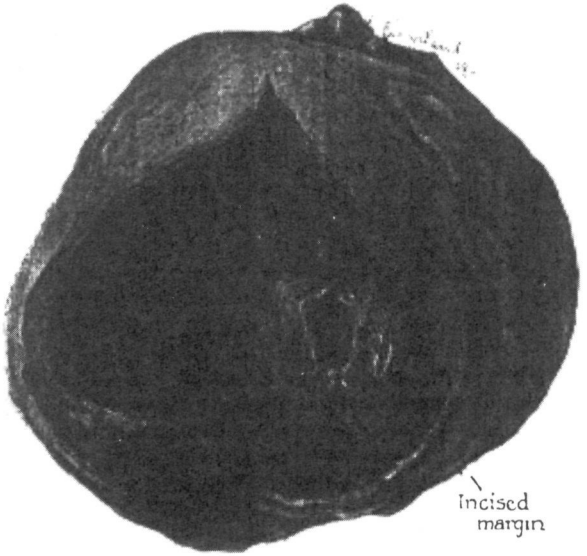

Fig. 3 (case 3).—The mitral valve as seen from the ventricle. The site of the incision is indicated.

An effusion developed in the pericardial cavity during the first three days after operation producing heart-tamponade, and the condition of the patient was critical. With absorption of the fluid, however, the condition improved. Signs of mitral stenosis persisted; the diastolic murmur was somewhat changed and there was some prolongation of the systolic murmur. The patient lived four and a half years following the operation, and during this period her activities were restricted; on several occasions, she had to be admitted to the hospital for rest in bed. The terminal illness was abrupt. Dyspnea increased; a hacking cough developed; the temperature rose to 103 F.; there were râles at each base; there was no peripheral edema. The dyspnea became severe, and the patient died on Nov. 17, 1927.

Necropsy showed a marked anterior bulge of the sternum and thoracic wall. The longitudinal incision in the sternum was well healed. The pericardium was adherent to the sternum. The pericardial cavity was obliterated by generalized adhesions between the heart and pericardium. The heart was markedly enlarged. Both auricles were capacious, but the left was markedly enlarged and could contain easily a good sized fist. The mitral valve was moderately stenosed and thickened. The other valves were normal. A bougie, 40 mm. in circumference, readily passed through the mitral orifice (figs. 2 and 3). The site of the incision made in the mitral valve at operation was easily determined. It was at the anterior junction of the aortic and posterolateral cusps. There is no doubt that the orifice was enlarged by this incision. The scar in the ventricle was well healed. The lungs were markedly congested and showed some bronchopneumonia.

Case 4 (Allen and Graham[4]).—A woman, aged 32, did not give any history of rheumatic fever. Dyspnea had been present for many years and hemoptysis for one year. There were orthopnea, distressing cough, edema of the ankles and cyanosis. A presystolic murmur with a thrill was present, also a systolic murmur. The heart was enlarged. The systolic blood pressure was 95 mm. of mercury, and the vital capacity was reduced. A diagnosis of mitral stenosis was made. The operation was carried out in three stages. At the first stage the costal cartilages of the first, second and third ribs were removed under procaine hydrochloride anesthesia. At the second stage, the incision was opened under nitrous oxide-oxygen anesthesia and the pericardium was exposed. The pleura was opened, but because the patient's respirations became embarrassed the operation was discontinued. At the third operation, the incision was reopened under gas-oxygen anesthesia. The pericardium contained 500 cc. of clear fluid. The left auricular appendix was distended. There was no thrombus in it. The cardioscope was inserted into the left auricle. At this stage in the operation respirations, which were greatly embarrassed, ceased and the heart stopped beating. Epinephrine was injected into the heart, but the patient died.

Case 5 (Cutler, Levine and Beck[5]).—A woman, aged 35, did not give any history of rheumatic fever. Dyspnea on exertion and precordial pain were present for four years, and these symptoms required frequent hospital care. Edema of the ankles, enlargement of the liver and auricular fibrillations developed. The patient was bedridden. The systolic blood pressure was 85 mm. of mercury preceding operation. A diagnosis of mitral stenosis was made. A median thoraco-abdominal incision was carried out under ether anesthesia. The auricle was a huge, pulseless sac of blood. Three attempts were made to incise the stenosed mitral valve with the tenotome knife inserted through the left ventricle. After the third attempt the

4. Allen, D. S., and Graham, E. A.: Intracardiac Surgery, a New Method, J. A. M. A. 79:1028 (Sept. 23) 1922.

5. Cutler; Levine and Beck (footnote 3, second reference).

heart stopped momentarily, but almost immediately began at the rate of 50. The immediate postoperative recovery seemed good, but the circulation gradually failed and death occurred ten hours later from myocardial failure. Necropsy examination showed the mitral valve to have been only slightly enlarged (fig. 4).

CASE 6 (Cutler, Levine and Beck[5]).—A man, aged 26, presented a history of rheumatic fever in childhood. Dyspnea and substernal pain were the first symptoms. There was a diastolic and presystolic murmur with a thrill. The second sound was accentuated. The systolic blood pressure was 105. The vital capacity

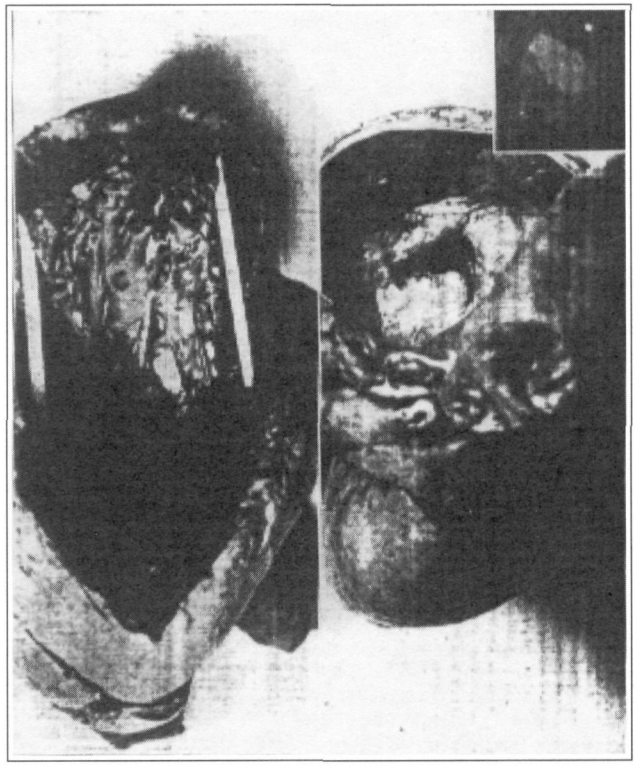

Fig. 4 (case 5).—Auricular and ventricular views of the mitral orifice; the roentgen-ray film (inset) shows some calcium deposition. The sharp border of the valve edge in the ventricular view where the incision was made at operation may be noted.

was 72 per cent of normal. A diagnosis of mitral stenosis was made. Under ether anesthesia, the operation was carried out. The chest was opened by a median thoraco-abdominal exposure. Extensive fibrous adhesions between the heart and the pericardium were cut. Two attempts were made with the tenotome knife through the left ventricle to incise the calcareous mitral ring. The pericardium was closed tightly without drainage. The procedure was well tolerated. During the postoperative period which lasted twenty hours, the patient presented the picture of a failing circulation. At necropsy, 350 cc. of fluid were found in the pericardial

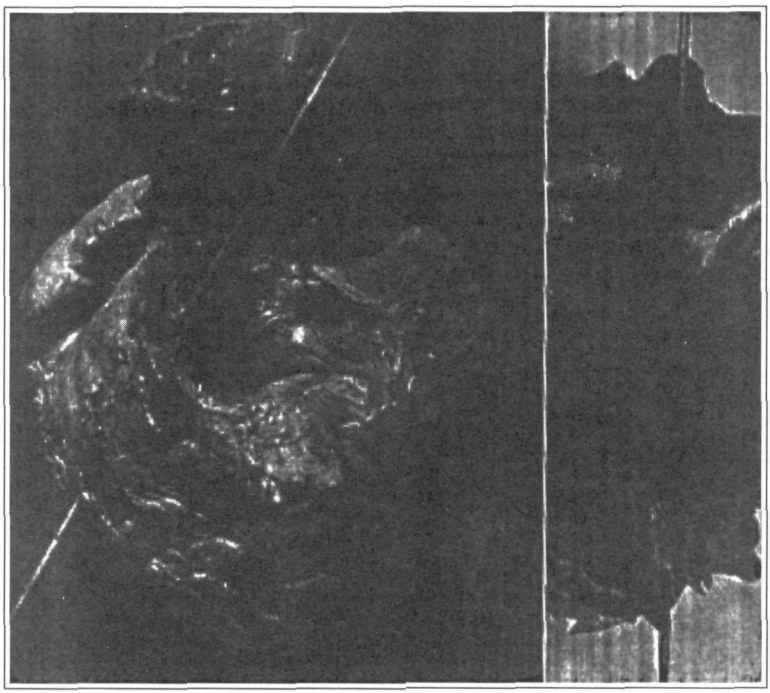

Fig. 5 (case 6).—*A* shows the ventricular aspect of the heart: pericardial tags and roughness may be noted. The mitral orifice shows divided chordae tendineae and slight notching at either end of the long diameter made by the knife at operation. *B* shows the auricular aspect.

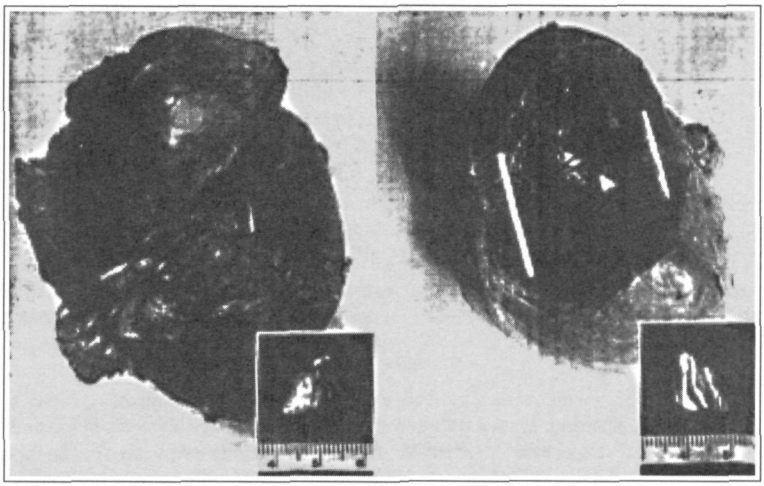

Fig. 6 (case 7).—Auricular and ventricular views of mitral orifice; the insets represent the auricular and ventricular views of the valve segment removed at operation. The operative defect occurs in the aortic cusp without involving the margin of the stenosed valve.

cavity, the rapid formation of which undoubtedly produced tamponade. The mitral ring had been only slightly enlarged by the operation (fig. 5).

CASE 7 (Cutler, Levine and Beck[5]).—A young woman, aged 19, did not give any history of rheumatic fever. Shortness of breath on exertion was present for fifteen months. A few months before operation, because of dyspnea, her work as an office clerk had to be discontinued. Palpitation of the heart was present, as were also recurrent attacks of substernal pain. The rhythm of the heart was regular. There was a long, rough crescendo murmur in diastole, a palpable thrill and a systolic blood pressure of 95 mm. of mercury. A diagnosis of mitral stenosis was made. The operation was carried out under ether anesthesia, a midsternal incision being used. The operation of partial valvulectomy was performed, the cardiovalvulotome (fig. 1) being used for the first time. A segment of the mitral valve was excised and removed from the blood stream in the cardiovalvulotome and the incision

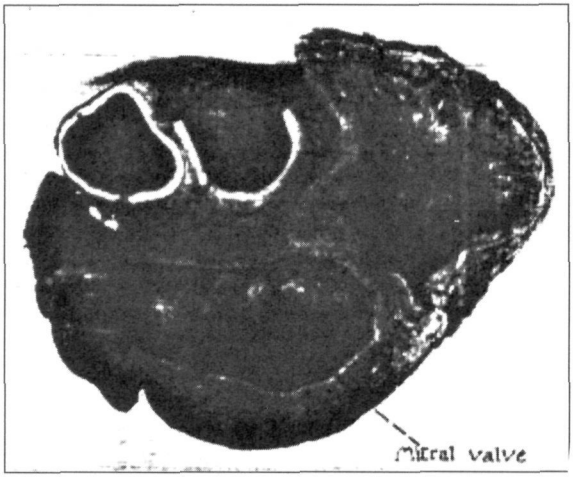

Fig. 7 (case 8).—Auricular view of the mitral valve.

in the ventricle was sutured. The pericardium was not closed completely so that if pericardial fluid should form it might drain into the mediastinum and thus prevent cardiac tamponade. During the first three days after the operation, the condition was apparently satisfactory. The blood pressure was at the preoperative level. The diastolic rumble present before operation had changed to a presystolic murmur. The thrill had disappeared, and a short systolic murmur was heard at the apex. Bilateral pneumonia developed, the heart dilated and death occurred on the sixth day. Autopsy showed bilateral congestion in the lungs with scattered areas of infiltration with leukocytes. An opening about 1 cm. in diameter was present in the aortic cusp (fig. 6) where the cardiovalvulotome had pushed through and excised a fragment from the valve.

CASE 8 (Cutler, Levine and Beck[5]).—A woman, aged 21, had rheumatic fever at the age of 14. Dyspnea on exertion, cough and palpitation of the heart had been present for two years. There was no hemoptysis. The left auricle was prominent in the roentgenogram. There was a long rough diastolic murmur and thrill and a

slight systolic murmur. The vital capacity was 80 per cent of normal. The operation was carried out under ether anesthesia and a midsternal incision was used. At operation, two attempts were made to excise a segment from the mitral valve with the cardiovalvulotome inserted into the left ventricle. Each attempt was unsuccessful. The difficulty lay in locating the mitral valve so that the valve could be engaged between the cutting edges of the instrument. Further attempts were not carried out. The pericardium was not completely closed so that cardiac tamponade might be prevented. The patient recovered from the operation. Thirty hours later, signs of pulmonary congestion appeared. The heart dilated, and death occurred on the third day. At necropsy, marked congestion in the lungs was present. The mitral orifice was about 1 cm. in diameter. It had not been enlarged by the operation (fig. 7).

CASE 9 (Souttar[6]).—A young woman, aged 19, presented a history of chorea. Circulatory failure with cyanosis, marked dyspnea and occasional hemoptysis were present for four years. The heart was enlarged and there was some prominence of the anterior thoracic wall. A long diastolic murmur and a soft blowing systolic murmur were present. There was no thrill. The systolic blood pressure was 95 mm. of mercury. A diagnosis of mitral stenosis and insufficiency was made. The operation was carried out under intratracheal ether anesthesia. The thorax was opened by an osteoplastic flap over the second, third and fourth ribs. The lungs partially collapsed as the pleura was opened. The pericardium was opened and the left auricular appendix was drawn into the opening. The base of the appendix was clamped, its tip was incised, the finger was thrust into the auricle, the clamp was removed, and the mitral ring was examined. The mitral orifice readily admitted the finger, thus revealing only a moderate stenosis with little thickening of the valve. The orifice in the valve was dilated by the finger. The finger was withdrawn, and the opening in the auricle was closed with silk. The lung was expanded by increasing the intratracheal pressure; the wound was closed in layers. The recovery from the operation was satisfactory. There seems to have been no change in the physical signs since the operation.

CASE 10 (Pribram[7]).—A woman, aged 28, had rheumatic fever in childhood. For several years dyspnea and palpitation were present, and finally the patient became bedridden, and cyanosis was marked. There was a loud diastolic and presystolic murmur. The pulse rate was irregular; the systolic blood pressure was 90. The diagnosis was mitral stenosis. Under ether anesthesia, the thorax was opened, using the median thoraco-abdominal exposure. The cardiovalvulotome of Beck and Cutler was inserted through the left ventricle; the edge of the mitral valve was engaged between the cutting edges of the instrument, and a segment of the valve was excised and removed. The pericardium was partially closed. The immediate postoperative recovery seemed satisfactory. Auscultation showed marked changes in the diastolic murmur and there was less cyanosis. The temperature rose to 39 C. (102.2 F.) on the second day. Aspiration of the pericardium did not yield fluid. Pneumonia developed, and the patient died on the sixth day. Autopsy showed a freshly recurrent endocarditis with stenosis of the aortic valves. The defect in the mitral valve made at operation was seen (fig. 8). Pulmonary congestion was present.

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6. Souttar, H. S.: The Surgical Treatment of Mitral Stenosis, Brit. M. J. **2**:603, 1925.

7. Pribram, E. O.: Die operative Behandlung der Mitralstenose, Arch. f. klin. Chir. **142**:458, 1926.

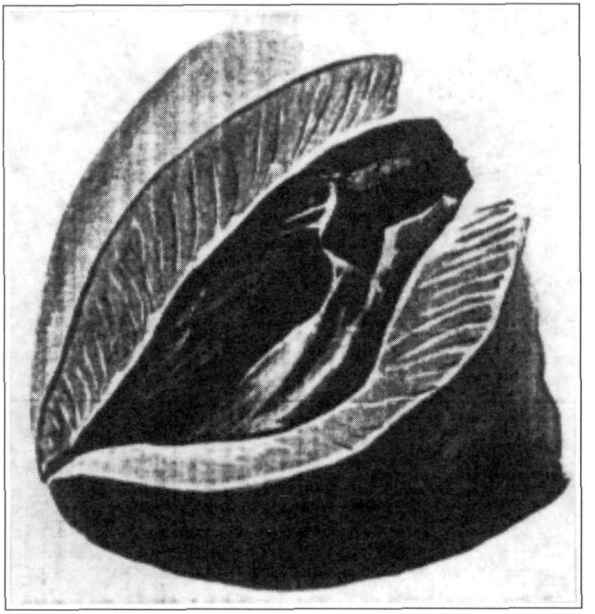

Fig. 8 (case 10).—Reproduction of the original illustration from Pribram's article showing the defect created by the cardiovalvulotome.

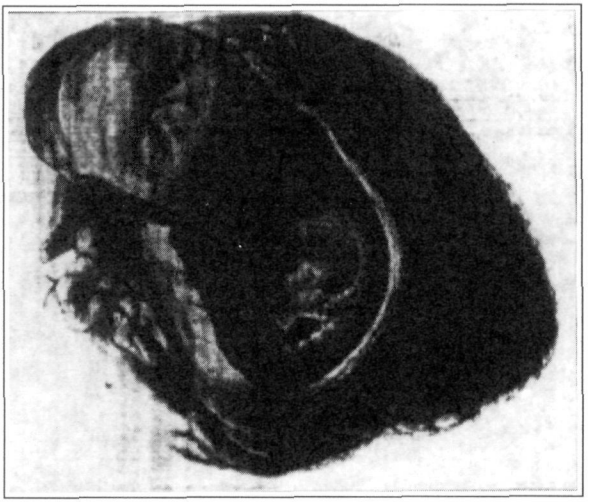

Fig. 9 (case 11).—Ventricular view of the mitral orifice, showing defect made at operation. The defect was made near the base of the valve.

CASE 11 (Cutler and Beck, first report).—A man, aged 34, had rheumatic fever in childhood. He had attacks of palpitation of the heart for six years; precordial pain, dyspnea on exertion were also present and during the last two years there were frequent attacks of hemoptysis. There was a palpable diastolic thrill. A roentgenogram of the heart showed a prominence in the left auricle. There was a presystolic crescendo murmur. There was no systolic murmur and the heart was irregular. A diagnosis of mitral stenosis was made. Under nitrous oxide-oxygen-ether anesthesia, the median thoraco-abdominal exposure was carried out; the cardiovalvulotome was inserted into the left ventricle. Great difficulty was experienced in locating the orifice of the mitral valve. It was only after considerable effort that a segment of the mitral valve was excised and removed. The pericardium was closed partially to allow drainage. The patient never fully regained consciousness and died sixteen hours after operation with signs of circulatory failure. In this case, the trauma inflicted at operation may have been an important factor in the fatality (fig. 9).

CASE 12 (Cutler and Beck, first report).—A man, aged 47, did not give any history of rheumatic fever. The condition began insidiously, the first symptoms being precordial pain and generalized weakness appearing seven years before. Dyspnea on exertion developed as the next symptom. Three years before, he probably had a pulmonary infection lasting ten days accompanied by fever, cough, sputum, dyspnea and weakness. Following that illness, the patient returned to work, but some weakness persisted. During the last two years, he had to rest about three days every two or three weeks. On one occasion, fluid was aspirated from the chest. He continued his work, which was that of a laborer, with frequent periods of rest until about two months before admission to this hospital. There was a slight degree of cyanosis and an occasional irritating and unproductive cough. The pulse rate was regular. There was some enlargement of the left auricle as shown in the roentgenogram. A diastolic murmur with a presystolic rumble was present, and a diastolic thrill could be felt in the fourth interspace just inside the nipple line. The liver was not enlarged. There was slight edema over the ankles. A diagnosis of mitral stenosis was made.

Operation was carried out under nitrous oxide-oxygen and ether anesthesia. A parasternal incision was made and the costal cartilages of the second, third, fourth and fifth ribs were removed together with a portion of the sternum. The pleura was dissected laterally without opening it and the pericardium was incised. The appendix of the auricle was brought into the wound. An attempt was made to palpate the mitral valve by invaginating the wall of the auricle, but the auricle was so turgid that this was impossible. A clamp was placed on the base of the appendix and the tip of the auricular appendix was incised. The cardiovalvulotome was inserted into the auricle. Some difficulty was experienced in orientating the instrument in relation to the valve. After it was believed that the orifice of the mitral valve had become engaged between the edges of the instrument, the excision of a small piece of tissue was carried out. The instrument was then removed from the heart and the opening in the auricular appendix was closed with a ligature. On making the cut with the cardiovalvulotome, active bleeding occurred so that the pericardium filled with blood. Active bleeding continued for a few minutes, and the heart was finally turned forward so that its appendix protruded into the thoracic wound. The bleeding point was not located. The heart was returned to the pericardial cavity; its stroke was rather feeble and the bleeding had stopped.

The heart soon took on a more vigorous systole, and as the bleeding did not begin again, further manipulation was not carried out to locate and suture the opening which had been accidentally made in it. The systolic blood pressure was 40 mm. of mercury. The pericardium was closed partially, an opening being left to allow the escape of serum or blood to prevent cardiac tamponade. The wound was closed in layers with silk. The patient regained consciousness, but died three hours later from a failing circulation. Postmortem examination was not obtained.

Statistical Table of Operations for Chronic Valvular Disease

Case	Author or Operator	Date	Diagnosis	Method or Instrument	Result
1.	Doyen [1]	1913	Congenital pulmonary stenosis; patent interventricular septum	Tenotome	Died, few hours after operation
2.	Thiffier [2]	1914	Aortic stenosis	Finger dilatation	Recovery, improved
3.	Cutler and Levine: Boston M. & S. J. 188: 1028, 1923	5/20/23	Mitral stenosis	Tenotome	Died, 4 years and 6 months after operation
4.	Allen and Graham [4]	8/ 7/23	Mitral stenosis	Cardioscope	Operative death
5.	Cutler, Levine and Beck [5]	10/ 7/23	Mitral stenosis	Tenotome	Died, 10 hours after operation
6.	Cutler, Levine and Beck [5]	1/12/24	Mitral stenosis	Tenotome	Died, 20 hours after operation
7.	Cutler, Levine and Beck [5]	2/25/24	Mitral stenosis	Cardiovalvulotome	Died, sixth day after operation
8.	Cutler, Levine and Beck [5]	6/11/24	Mitral stenosis	Cardiovalvulotome	Died, third day after operation
9.	Souttar [6]	5/ 6/25	Mitral stenosis and aortic insufficiency	Finger dilatation	Recovery, living and improved
10.	Pribram [7]	11/14/25	Mitral stenosis and aortic vegetative endocarditis	Cardiovalvulotome	Died, sixth day after operation
11.	Cutler and Beck (first report)	12/ 8/26	Mitral stenosis	Cardiovalvulotome	Died, 15 hours after operation
12.	Cutler and Beck (first report)	4/15/28	Mitral stenosis	Cardiovalvulotome	Died, 3 hours after operation
Totals: 12 cases 1 aortic stenosis, acquired 1 pulmonary stenosis, congenital 10 mitral stenosis, acquired			2 finger dilatations 4 tenotome attempts 5 cardiovalvulotome attempts 1 cardioscope attempt		Mortality, 83 per cent

COMMENT

The foregoing summary includes one case of pulmonic stenosis, one case of aortic stenosis and ten cases of mitral stenosis. We have not had any personal experience with pulmonic stenosis and aortic stenosis. It seems that mitral stenosis offers greater promise than do any other of the valvular lesions, and for this reason we shall confine discussion to the cases of mitral stenosis.

Of the ten patients with mitral stenosis who were operated on, only one is living, giving a mortality of 90 per cent. Eight of the ten patients died so soon after operation that the changes brought about in the mechanics of the circulation could not be adequately studied. One

patient lived four and a half years after the operation. It is difficult to say definitely whether in this case the enlargement effected in the mitral valve by the operation was followed by an improvement in the circulation. We believe, however, that there was an improvement in the patient's condition. If it be true that the mechanics of the circulation were improved by reduction of the stenosis, a definite advance in this subject has been brought about. It will require, however, a number of cases in which operation is successful to determine definitely whether an improvement in the circulation can be expected by enlarging the orifice in the stenosed valve. Such physiologic observations have not been produced in animals. Unfortunately, it seems that the basic idea underlying this development will have to be established by attempts on human patients.

If it be taken for granted that the mechanics of the circulation become more compatible with life when the degree of mitral obstruction is decreased, there remain the technical problems of the operation. These problems are: the approach to the valve, the localization of the valve and the question of valvulotomy versus partial valvulectomy. The median sternotomy exposure was used in seven of the ten patients operated on. An excellent exposure of the heart is obtained by this method and it also has the added advantage of not opening the pleura. However, it is an extensive operation in itself, probably too extensive to warrant its use. In one case, an osteoplastic flap was turned back and the pleura opened. In two cases, a less extensive exposure of the heart was obtained by resection of costal cartilages, with or without resection of a portion of the sternum. The type of exposure is determined largely by the method of approach to the valve itself. If the mitral valve is approached through the ventricle, the midline sternotomy or large osteoplastic flap is necessary. If the valve be approached through the auricle, a less extensive exposure by resection of costal cartilages and sternum may be adequate. The ventricular approach to the valve was used in seven cases and the auricular approach in three cases. After having utilized the midline sternotomy and the ventricular approach in six cases, in our seventh case (case 12) we adopted the less radical exposure by resection of costal cartilages and sternum and the approach to the mitral valve through the auricle. It was our hope that the auricle might furnish a more exact approach to the mitral valve. We feel that our failure in the last case cannot be considered too strongly as a contraindication to the auricular approach. The exposure of the auricle is a less extensive operation than that of the ventricle, and it may be possible that instruments with special curves can be made so that the posterior position of the auricle will become less of a handicap in the operation.

Our previously expressed opinion that wide exposure of the heart and approach to the valve through the ventricle is more desirable has

not been altered. We have felt, however, that the great difficulty in locating the stenosed valve from this side, the valve being commonly sucked down into the ventricle and funnel shaped, thus deflecting the tip of the instrument away from the orifice unless it directly engages there at the first attempt, is sufficient to justify further attempts from the auricular side. In approaching from this side, the instrument would constantly be guided into the funnel and toward the valve. In approaching the valve through the auricle, two methods must be considered: (1) a direct attack across the pleural space, so placed that a straight instrument can be pushed from behind and upward, downward and forward, or (2) an attack from in front which may be kept extrapleural, this appearing highly desirable, in which case it will be necessary to have a curved instrument so that though the instrument enters the auricular appendix from in front to behind it would gradually turn downward and finally somewhat forward as it enters the funnel that leads to the valve. Such a curved instrument in our last case might have prevented the unfortunate outcome.

From the foregoing summary of cases, it will be seen that three kinds of procedures were utilized in the attempts to enlarge the stenotic orifice. These methods were finger dilatation, incision of the stenotic valve and excision of a segment of the stenotic valve. We have not had any experience with dilation of the stenosis. We feel, however, that the method may be worthy of trial. A small instrument similar to the Kollmann's dilator of the urologist could be devised, and this instrument could be inserted into the stenotic ring and the latter stretched and dilated. It will be seen that the only two patients of the series living are those on whom dilatation was done. Incision of the stenotic valve was carried out in four cases. From our experience in cases 5 and 6, we felt that the enlargement effected by a simple incision of the stenotic valve was inadequate. We then devised an instrument which could excise a segment from the valve and remove it from the blood stream. This instrument was used in five cases. In each of the four patients that we operated on, some difficulty was experienced in orientation within the heart. We feel at the present time that that is one of the most serious problems in cardiac surgery. The cardioscope devised by Allen and Graham affords a slight degree of visualization of the endocardium at the point of contact with the instrument. The examination that can be carried out with this instrument, however, is so slight that we have not used it in any human cases.

Finally, it may be that we already have the evidence that the success in the finger dilatation method and the success in our first case are due to the fact that only a slight change was made in the size of the orifice of the valve. It may be that the cardiovalvulotome with its actual removal of a piece of valve creates a too sudden change. We know that

all the changes created by nature are slow and gradual; could we return a stenotic valve to the insufficient type by a gradual procedure, we might well achieve success. This question unfortunately cannot be answered until we can experimentally produce stenosis similar to what occurs in man, and then suddenly change this to an insufficiency. We have convinced ourselves that a simple knife cannot enlarge a typically stenosed, thickened and often calcareous valve; we do not know whether the actual removal of a piece of the valve by the powerful cardiovalvulotome is deleterious or not. And we have not yet available evidence as to what excision of a segment of a stenosed valve will result in when the operative procedure is simplified (as performed in our last case), and the postoperative course, therefore, less of a strain on the already lowered vitality.

It may seem that the information obtained from the twelve cases of chronic valvular disease in which operation was performed is so meager that further attempts are not justified. However, in view of the preceding discussion, we feel that a few more attempts are necessary in order to answer certain questions already mentioned. Should it be possible to produce experimental stenoses, these questions could be answered in the laboratory. Unfortunately, our own attempts for seven years along this line have been as unsuccessful as the attempts of other and more experienced investigators.

It is our conclusion that the mortality figures alone should not deter further investigation both clinical and experimental, since they are to be expected in the opening up of any new field for surgical endeavor.

SURGICAL LIGATION OF A PATENT DUCTUS ARTERIOSUS

REPORT OF FIRST SUCCESSFUL CASE

Robert E. Gross, John P. Hubbard

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SURGICAL LIGATION OF A PATENT DUCTUS ARTERIOSUS

REPORT OF FIRST SUCCESSFUL CASE

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The continued patency of a ductus arteriosus for more than the first few years of life has long been known to be a potential source of danger to a patient for two reasons: First, the additional work of the left ventricle in maintaining the peripheral blood pressure in the presence of a large arteriovenous communication may lead eventually to cardiac decompensation of severe degree. Second, the presence of a patent ductus arteriosus makes the possessor peculiarly subject to fatal bacterial endarteritis. While it is true that some persons have been known to live to old age with a patent ductus of Botalli, statistics have shown that the majority die relatively young because of complications arising from this congenital abnormality. Dr. Maude Abbott [1] presented a series of ninety-two cases which came to autopsy in which it was shown that the patient had had a patent ductus arteriosus without any other cardiovascular abnormality. Of these patients, approximately one fourth died of bacterial endarteritis of the pulmonary artery and an additional one half died of slow or rapid cardiac decompensation. The average age of death of patients in this series was 24 years.

The complications arising from the persistence of a patent ductus arteriosus would seem to make surgical ligation of this anomalous vessel a rational procedure, if such a procedure could be completed with promise of a low operative mortality. Dramatic results have previously been obtained in persons with cardiac enlargement and decompensation resulting from a peripheral arteriovenous aneurysm when the short-circuiting vessels have been ligated or excised.[2] On similar theoretical grounds, future cardiac embarrassment should be averted if a shunt between the aorta and the pulmonary artery could be removed. It would also seem plausible to expect that the shutting off of the anomalous stream of blood pouring into the pulmonary artery would lessen the formation of the thickened endothelial plaques within the pulmonary artery, which are so likely to be the seat of later bacterial infection. The surgical approach to the aortic arch and pulmonary conus having been studied previously in animal experimentation,[3] it seemed within reason that a patent ductus could be adequately exposed in man and possibly ligated without undue danger. It was therefore decided to undertake the operation in a child who presented the classic signs of a patent ductus arteriosus. At the age of 7 years she already had cardiac hypertrophy, which developed presumably from the embarrassment resulting from the anomalous communication. It was to be expected, therefore, that she would have increasingly severe disability in the future, aside from the danger of having bacterial endarteritis develop.

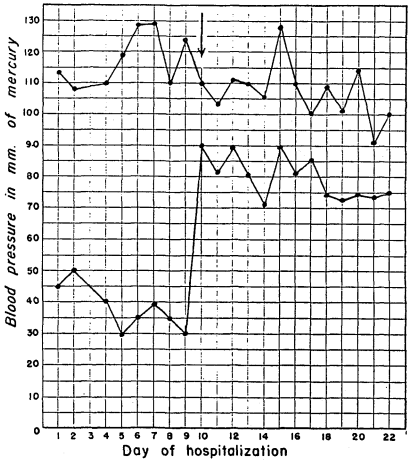
From the Surgical and Medical Services of the Children's Hospital and the Departments of Surgery and Pediatrics of the Harvard Medical School.

1. Abbott, Maude E.: Atlas of Congenital Heart Disease, New York, American Heart Association, 1936, pp. 60-61.
2. Holman, Emile: Arteriovenous Aneurysm, New York, Macmillan Company, 1937, pp. 169-178.
3. Gross, R. E.: A Surgical Approach for Ligation of a Patent Ductus Arteriosus, New England J. Med., to be published.

REPORT OF CASE

History.—L. S., a girl aged 7½ years, entered the hospital Aug. 17, 1938, for study of her cardiac condition. The family history was irrelevant. She was born normally at full term. No cyanosis was noted at birth or during the postnatal period. The records of the hospital where she was born give no information about an examination of the heart at that time. At the age of 3 years she was seen in the cardiac clinic of another hospital, where it was found that she had physical signs suggesting congenital malformation of the heart. At that time she had a precordial thrill and a loud murmur. The carotid pulsations were abnormally marked, and pistol shot sounds could be heard over the brachial and femoral arteries. The blood pressure was recorded in both arms as 104 mm. of mercury systolic and 0 diastolic. There was definite cardiac enlargement, as shown by teleoroentgenograms. The diagnosis made at that time was "congenital malformation of the heart with a patent ductus arteriosus."

During the next four years she was seen in several different hospitals, where the same diagnosis was made. At no time



Daily blood pressure readings of the patient with a patent ductus arteriosus before and after operation. Prior to operation the large ductus opening from the aorta produced a low diastolic pressure. Following operative closure of the ductus, the diastolic pressure rose to twice its former level. The average daily diastolic pressure preoperatively was 38 mm. of mercury. The average diastolic pressure postoperatively was 80 mm. of mercury. The arrow points to the time of operation.

had cyanosis been observed. Dyspnea developed after moderate exercise, and her physical activities had been limited accordingly. She had never had peripheral edema or other evidence of cardiac decompensation. Frequently the child had been conscious of "something wrong in the chest" and her mother spontaneously offered the information that she had heard a "buzzing noise" in her daughter's chest when standing nearby.

Physical Examination.—At the time of admission, the patient was slender and undernourished. The pulsations of the carotid arteries were abnormally forceful. The radial pulse was of the Corrigan type, and a capillary pulsation was readily seen. The veins over the chest were somewhat prominent. There was a precordial bulge. The heart was definitely enlarged by percussion, the enlargement being for the most part to the left. Over the entire precordium there was a prominent coarse thrill which was most intense in the third interspace to the left of the sternum. This thrill was continuous but was accentuated during systole. There was a rough "machinery" murmur heard with maximal intensity over the pulmonic area to the left of the sternum in the second and particularly in the third interspace. It was continuous throughout the cardiac cycle but like the thrill was greatly accentuated during systole. It was transmitted to the left along the third interspace and into the axilla with only slightly diminished intensity. The systolic element was heard faintly over the vessels of the neck and could be heard clearly in the right axilla and over the midthoracic region posteriorly. Blood pressure readings were respectively right arm 115/40, left arm 110/50, right leg 150/55, left leg 140/40 mm. of mercury. There was no clubbing of the fingers and no evidence of peripheral edema. The liver edge was palpable at the costal margin. The examination in other respects was negative.

Laboratory Data.—A 7-foot x-ray film of the chest showed the transverse diameter of the heart to be 11.7 cm., compared to an internal diameter of the chest of 20 cm. There appeared to be definite enlargement of the left ventricle. There was questionable prominence of the pulmonary artery. A mottled increased density around the lung hili was interpreted as representing circulatory congestion. Fluoroscopic examination showed a "hilar dance." An electrocardiogram was normal, showing no deviation of the axis. The red blood count was 5,080,000 cells per cubic millimeter and the hemoglobin was 85 per cent (Sahli). Circulation time with dehydrocholic acid was 10 and 8 seconds, respectively, on two tests.

Operation.—August 26, operation was undertaken (by R. E. G.) under cyclopropane anesthesia. The approach to the mediastinum was made through the left pleural cavity anterolaterally. Incision was made through the left third interspace, cutting the third costal cartilage, and the third rib was retracted upward. As the left lung was allowed to collapse inferiorly, an excellent view was gained of the lateral aspect of the mediastinum. The parietal pleura covering the aortic arch and left pulmonic artery was then incised and these structures were directly exposed. A large patent ductus arteriosus was found, which was from 7 to 8 mm. in diameter and from 5 to 6 mm. in length. A palpating finger placed on the heart disclosed a continuous and very vibrant thrill over the entire organ, which was increasingly prominent as the finger reached up over the pulmonic artery. A sterile stethoscope was employed and an extremely loud continuous murmur was heard over the entire heart. When the stethoscope was placed on the pulmonary artery there was an almost deafening, continuous roar, sounding much like a large volume of steam escaping in a closed room.

A number 8 braided silk tie was placed around the ductus with an aneurysm needle, and the vessel was temporarily occluded for a three minute observation period. During this time the blood pressure rose from 110/35 to 125/90. Since there was no embarrassment of the circulation, it was decided to ligate the ductus permanently. The ductus was too short to tie double and divide, so that ligation alone was resorted to. When the thread was drawn up tight the thrill completely disappeared. The chest was closed, the lung being reexpanded with positive pressure anesthesia just prior to placing the last stitch in the intercostal muscles.

Postoperative Course.—The child underwent the operative procedure exceedingly well and showed no signs of shock. Prior to operation blood had been taken from a donor in order to have it ready whenever needed, but the patient's condition was so good that it was not given. There was only mild discomfort on the afternoon of the day of operation, and on the following morning the child was allowed to sit up in a chair. By the third day she was walking about the ward. When the skin sutures were removed on the seventh day the wound was well healed, but because of the interest in the case the child was detained in the hospital until the thirteenth day. After the dressing was removed and the chest could be examined adequately the thrill had completely disappeared, there was a faint systolic murmur in the left third interspace which was not transmitted over the precordium, and no murmur could be heard in the axilla, in the neck or over the back. The daily blood pressures which had been taken prior to operation and subsequent thereto showed a striking change in the diastolic levels, as is shown by the accompanying chart. The average of the daily pressures prior to operation had been 114 systolic and 38 diastolic as contrasted with a postoperative daily average of 108 systolic and 80 diastolic.

SUMMARY

A girl aged 7½ years had a known patency of the ductus arteriosus and beginning cardiac hypertrophy. In the hope of preventing subsequent bacterial endarteritis and with the immediate purpose of reducing the work of the heart caused by the shunt between the aorta and the pulmonary artery, the patent ductus was surgically explored and ligated. The child stood the operative procedure exceedingly well. The most objective finding, which indicated that the serious loss of blood from the aorta into the pulmonic artery had been arrested by operation, was a comparison of the preoperative and postoperative levels of the diastolic blood pressure. Prior to operation the daily blood pressure showed an average diastolic level of 38 mm. of mercury as compared with a postoperative diastolic level of 80 mm. of mercury. This is the first patient in whom a patent ductus arteriosus has been successfully ligated.

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THE SURGICAL TREATMENT OF MALFORMATIONS OF THE HEART IN WHICH THERE IS PULMONARY STENOSIS OR PULMONARY ATRESIA

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THE SURGICAL TREATMENT OF MALFORMATIONS OF THE HEART

IN WHICH THERE IS PULMONARY STENOSIS OR PULMONARY ATRESIA

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Heretofore there has been no satisfactory treatment for pulmonary stenosis and pulmonary atresia. A "blue" baby with a malformed heart was considered beyond the reach of surgical aid. During the past three months we have operated on 3 children with severe degrees of pulmonary stenosis and each of the patients appears to be greatly benefited. In the second and third cases, in which there was deep persistent cyanosis, the cyanosis has greatly diminished or has disappeared and the general condition of the patients is proportionally improved. The results are sufficiently encouraging to warrant an early report.

The operation here reported and the studies leading thereto were undertaken with the conviction that even though the structure of the heart was grossly abnormal, in many instances it might be possible to alter the course of the circulation in such a manner as to lessen the cyanosis and the resultant disability. It is important to emphasize the fact that it is not the cyanosis, per se, which does harm. Nevertheless, since cyanosis is a striking manifestation of the underlying anoxemia and the compensatory polycythemia, a brief discussion of the causes of cyanosis and the factors operative in congenital malformations of the heart is essential in order to understand the principles underlying the present operation.

Cyanosis is due to the presence of reduced hemoglobin in the circulating blood. It is a well established fact that there must be at least 5 Gm. of reduced hemoglobin per hundred cubic centimeters of circulating blood for cyanosis to become apparent. It has long been recognized that one of the principal factors in the production of cyanosis in malformations of the heart is the direct shunting of venous blood into the systemic circulation. Lundsgaard and Van Slyke[1] in their classic studies on the causes of cyanosis showed that there were four important factors in the production of cyanosis: the height of the hemoglobin, the volume of the venous blood shunted into the systemic circulation, the rate of utilization of oxygen by the peripheral tissues and the extent of the aeration of the blood in the lungs. Their studies demonstrated the great importance of pulmonary factors. The extent of the oxygenation of the blood in the lungs clearly depends on the vital capacity of the individual, the rate of the flow of blood through the lungs, the partial pressure of the oxygen in the inspired air and also on specific pulmonary factors, which these authors designated as the *a* factor. These investigators showed that in most, if not in all, cases in which there was a pronounced polycythemia, secondary changes occurred in the lungs of such a nature that all of the blood that passed through the lungs was no longer in effective contact with the oxygen in the alveoli. The importance of this factor can be demonstrated by the prolonged inhalation of oxygen. In almost every case in which there is polycythemia, cyanosis can be greatly lessened by the prolonged inhalation of oxygen. The fact that all of the blood which circulated through the lungs is not fully oxygenated made it seem improbable that if more blood circulated through the lungs a larger proportion of the blood would be oxygenated. Thus the demonstration of the *a* factor completely overshadowed another vitally important factor, namely the volume of blood which reaches the lungs for aeration.[1a]

Expressed in the simplest terms, the circulation of the blood through the lungs after birth is essential for life; any one deprived of such circulation dies. Indeed there is a point at which, even though none of the other pulmonary factors are operative in the production of cyanosis and all of the blood that passes through the lungs is fully oxygenated, the volume of blood that reaches the lungs for aeration and hence the volume of oxygenated blood returned to the systemic circulation is insufficient for the maintenance of life. For example, in all cases of pulmonary atresia in which the circulation to the lungs is by way of the ductus arteriosus the closure of the ductus arteriosus renders the condition incompatible with life.

Undoubtedly the importance of the diminution of flow of blood to the lungs has not been fully appreciated, mainly because studies on the nature of cyanosis have been made on older children and young adults, and it is only when this factor is not of vital importance that the individual has survived to that age. All infants with pulmonary atresia with or without a right ventricle and with or without dextroposition of the aorta, in whom the closure of the ductus arteriosus cuts off the circulation to the lungs, die at an early age. In cases of complete pulmonary atresia death occurs before the complete cessation of circulation of blood through the lungs; hence in such cases there is always slight patency of the ductus arteriosus. In cases of a tetralogy of Fallot with an extreme pulmonary stenosis, the ductus arteriosus may become entirely obliterated before death.

There are two different types of congenital malformations which illustrate the importance of the volume of the pulmonary circulation in the production of cyanosis. The first is that of a single ventricle with a rudimentary outlet chamber in which it is common to find that one great vessel is given off from the common ventricle and one from the rudimentary outlet chamber. Usually the vessel which arises from the common ventricle is of normal size and that from the rudimentary outlet chamber is diminutive in size.[2] If the great vessels occupy their normal positions, the aorta arises from the common ventricle and is of large caliber, whereas the pulmonary artery which arises from the rudimentary outlet chamber is of small caliber. Under such circumstances a large volume of blood goes to the systemic circulation and only a small volume of blood goes to the lungs. Consequently a large volume of unoxygenated blood is mixed with a small volume of oxygenated blood and cyanosis is intense.[3] When, however, the great vessels are transposed and the pulmonary artery is large and the aorta is small, a large volume of blood goes to the lungs for aeration. Under these circumstances a large

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From the Departments of Surgery and Pediatrics of the Johns Hopkins University and the Johns Hopkins Hospital and the Cardiac Clinic of the Harriet Lane Home.

1. Lundsgaard, C., and Van Slyke, D. D.: Cyanosis, Medical Monographs, vol. 2, Baltimore, Williams and Wilkins Company, 1923.

1a. The relative importance of this factor and of the [illegible] will be discussed in a forthcoming paper by Taussig and Blalock.

2. Taussig, H. B.: Clinical Analysis of Congenital Malformations of the Heart, to be published by the Commonwealth Fund, New York.

3. Taussig, H. B.: A Single Ventricle with a Diminutive Outlet Chamber, J. Tech. Meth. & Bull. I. A. M. M. 19: 120-127, 1939.

volume of oxygenated blood is mixed with a relatively small volume of venous blood and cyanosis is minimal or absent, as in the case reported by Glendy and White.[4]

The same phenomenon is also seen in cases of truncus arteriosus. When the pulmonary arteries are given off directly from the aorta there is adequate circulation to the lungs, and cyanosis is minimal or absent. In contrast to this, if the pulmonary artery fails to arise from the heart or connect with the aorta and the circulation to the lungs is by way of the bronchial arteries only a small volume of blood reaches the lungs for aeration, and cyanosis is intense.[5]

The importance of adequate circulation to the lungs is further illustrated in the anomalies of the venous return in which all of the pulmonary veins drain into the right auricle; consequently within this chamber there is complete admixture of venous and arterial blood. In such cases a large volume of blood goes to the lungs for aeration and a large volume of oxygenated blood is returned to the right auricle. There is great right-sided cardiac enlargement but no cyanosis until the terminal collapse of the circulation.[6]

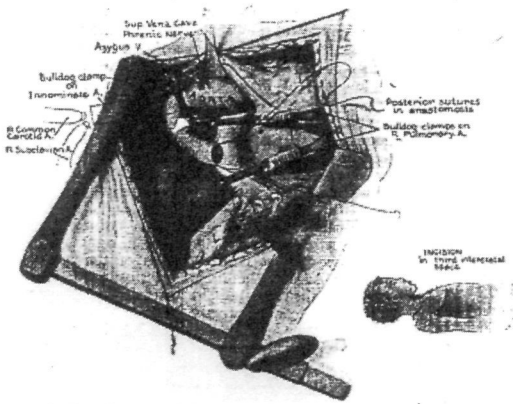

Fig. 1.—General exposure of the operative field on the right side. The end of the innominate artery is being anastomosed to the side of the right pulmonary artery. The posterior row of sutures is complete. The anterior row has not been inserted.

These observations clearly indicate that many gross malformations of the heart are compatible with life provided there is adequate circulation to the lungs, and furthermore that lack of circulation to the lungs is the primary cause of death in many infants with congenital malformations of the heart. Furthermore, one of us (H. B. T.) has seen several infants with pulmonary stenosis in whom cyanosis was not apparent until the ductus arteriosus closed. In other words, there was no "visible" cyanosis while the circulation to the lungs was adequate. It was an appreciation of these facts (H. B. T.), together with an extensive previous experience with the experimental use of large arteries for the purpose of conducting blood to sites not usually supplied by such vessels, that led to the development of the clinical work recorded in this paper.

The feasibility of anastomosing a systemic artery to one of the pulmonary arteries in experimental animals has been demonstrated by Levy and Blalock.[7] As far as we are aware, this was the first time that both the course and the function of a large artery were altered. Similar experimental alterations were produced subsequently by Eppinger, Burwell and Gross[8] and by Leeds.[9] Blalock and Park[10] have reported the suturing of the severed proximal end of the subclavian artery to the aorta as a means for conducting blood beyond the point of an experimental coarctation of the aorta. In unreported observations by Kieffer and Blalock the divided proximal end of the splenic artery has been connected to the distal end of the divided left renal artery and there has been no evidence of renal failure even though the right kidney was removed. In other words, arterial anastomoses have been performed in animals for the purpose of conducting blood to sites other than those ordinarily supplied by these vessels.

Before undertaking the operations on patients, many experiments were performed in an effort to produce pulmonic stenosis in dogs. This work met with little success. Finally, in an effort to cause a significant decrease in the oxygen saturation of arterial blood, one or more lobes of the lungs were removed from each side of the chest, and the main arteries and veins of these lobes were connected end to end by suture. In other words, bilateral pulmonary arteriovenous fistulas were produced. These procedures resulted in some instances in a pronounced reduction in the oxygen saturation of the arterial blood. As the result of an artificial patent ductus arteriosus made in two such experiments, there was a significant increase in the arterial oxygen saturation. Although this experimentally produced condition is quite different from that seen in patients, it is of interest that the making of an anastomosis between systemic and pulmonary arteries caused an increase in the oxygen saturation of the arterial blood despite the fact that several lobes of the lungs had been removed.

Since the present operation was devised to compensate for an inadequate flow of blood to the lungs, it seemed desirable that the anastomosis be made in such a manner that the blood from the systemic artery would be able to reach both lungs. It is obvious that the suture anastomosis could not be made to the main pulmonary artery since occlusion of this vessel for more than a few minutes causes death. It appeared, therefore, that the anastomosis should be made just distal to the division of the main pulmonary artery and, furthermore, that the side of the chosen vessel should be used in order that the blood might flow to both lungs.

It was our original idea that the subclavian artery would be the ideal systemic vessel and that after division

4. Glendy, Margaret M.; Glendy, R. E., and White, P. D.: Cor Biatriatum Triloculare, Am. Heart J. **28**: 395-401, 1944.

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6. Taussig, H. B.: Clinical and Pathological Findings in the Anomaly of Venous Return in Which All of the Pulmonary Veins Drain into the Right Auricle, to be published.

7. Levy, S. E., and Blalock, A.: Experimental Observations on the Effects of Connecting by Suture the Left Main Pulmonary Artery to the Systemic Circulation, J. Thoracic Surg. **8**: 525-530, 1939.

8. Eppinger, Eugene C.; Burwell, C. Sidney, and Gross, Robert E.: The Effects of the Patent Ductus Arteriosus on the Circulation, J. Clin. Investigation **20**: 127-143 (March) 1941.

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10. Blalock, A., and Park, E. A.: The Surgical Treatment of Experimental Coarctation (Atresia) of the Aorta, Ann. Surg. **119**: 445-456 (March) 1944.

of this artery its proximal end should be anastomosed to the side of the left pulmonary artery. The fortunate experience to be reported in regard to the second patient has led us to prefer the use of the innominate artery in patients with a severe degree of anoxemia. This patient had a right aortic arch, and the innominate artery was directed to the left side of the chest and neck.

Although there were slight variations in each of the operations, the major features were as follows: Light general anesthesia was produced by the inhalation of ether or cyclopropane. The patient was placed on the table on his back with a slight elevation of that side of the chest which was to be exposed. The patient's arms were strapped in place along his sides. The operation was performed on the right or left side depending on the position of the great vessels and the artery to be used in the anastomosis. The incision was made in the third interspace and extended from the lateral border of the sternum to the axillary line. The pleural cavity was entered and the third and fourth costal cartilages were divided. A rib spreader was introduced and a good exposure of the upper half of the pleural cavity was obtained. This area is shown in figure 1. The right or left pulmonary artery was then exposed and the vessel was dissected from the adjacent tissues for as great a distance as possible. This was more difficult on the right side than on the left and it was necessary to ligate and divide the azygos vein and to retract the superior vena cava medially. Nothing further was done to the pulmonary artery at this time. Attention was then focused on the systemic artery which was to be anastomosed to one of the pulmonary arteries. The subclavian or innominate artery was dissected free of the adjacent tissues and the vessel chosen was occluded temporarily at the point where it arose from the aorta by the use of a bulldog arterial clamp. In cases in which the innominate artery was chosen, its branches (subclavian and common carotid) were ligated at their origins and the innominate artery was cut across just proximal to the ligatures. In the 1 case in which the left subclavian artery was used for the anastomosis to the pulmonary circulation it was necessary to divide the thyrocervical trunk, the vertebral artery and the internal mammary artery in order to gain access to a sufficient length of the vessel. After the removal of some of the adventitia from the systemic vessel the pulmonary artery was further prepared for the anastomosis. A bulldog arterial clamp was placed on the left or right pulmonary artery just distal to the point of division of the main pulmonary artery. A second bulldog arterial clamp was placed on the left or right pulmonary artery just proximal to the point where the vessel gave off a branch to the upper lobe of the lung. A transverse opening was made into the side of the pulmonary artery approximately midway between these two arterial clamps. This opening was of about the same diameter as that of the end of the systemic vessel which was to be anastomosed to it. It must be emphasized that the pulmonary artery was not occluded until all preparations for the anastomotic procedure had been made.

The anastomosis between the end of the systemic artery and the side of the pulmonary artery was carried out in the following manner: Fine silk on a curved needle was used as suture material. Before placing the posterior row of sutures, a stay suture was placed at one end. This was followed by the insertion of a running suture, which was not drawn taut until the greater part of the posterior row had been placed. The stay suture was then tied and the running suture was in turn tied to the stay suture. The posterior row was completed and was tied to another stay suture. The anterior row consisted of a simple through and through continuous suture which approximated intima to intima. The anastomosis is shown diagrammatically in figure 2. The bulldog clamps were then removed from the pulmonary artery, and this was followed by removal of the clamp from the systemic vessel. If bleeding from the suture line did not cease spontaneously, it was stopped by the use of additional sutures. The lung was reexpanded and the incision in the chest wall was closed. Two encircling sutures of braided silk were used for approximating the third and fourth ribs. The soft tissues of the chest wall were closed in multiple layers with interrupted silk sutures.

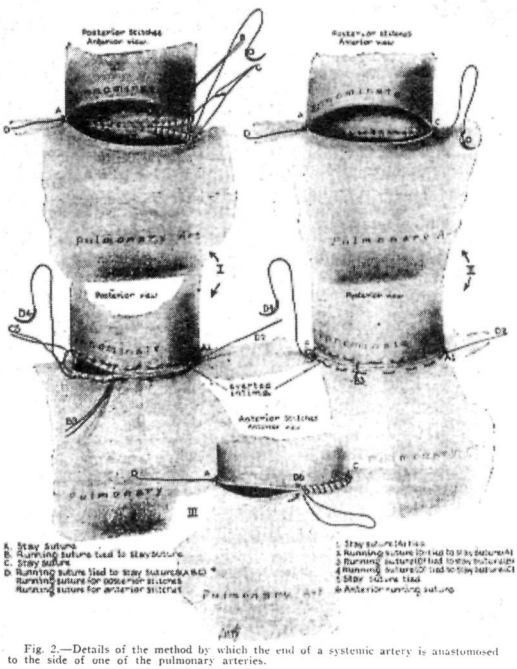

Fig. 2.—Details of the method by which the end of a systemic artery is anastomosed to the side of one of the pulmonary arteries.

There follows a detailed report of the 3 cases in which such an operation has been performed.

REPORT OF CASES

CASE 1.[11]—*History.*—E. M. S., a girl, was born prematurely in the obstetric service of the Johns Hopkins Hospital on Aug. 3, 1943. Her birth weight was 1,105 Gm. A systolic murmur was noted shortly after birth. Slight cyanosis was noted on the fourth and fifth days of life; this subsequently disappeared. The baby gained weight slowly and was finally discharged at 4 months of age weighing 2,900 Gm. After discharge the baby was followed in the dispensary. She was at first thought to have a simple interventricular septal defect, because the heart was normal in size and there was no cyanosis.

At 8 months of age the baby had her first attack of cyanosis, which occurred after eating. It was then for the first time that we thought she had a tetralogy of Fallot and not a simple interventricular septal defect. It soon became evident that cyanosis was increasing. It seemed probable that this increase in cyanosis was due to the fact that the ductus arteriosus was undergoing obliteration and thereby lessening the circulation to the lungs. By March 1944 it was obvious that the baby had a serious congenital malformation of the heart. After eating she would become deeply cyanotic, roll up her eyes, lose consciousness and appear extremely ill. Fluoroscopy showed that the heart was slightly enlarged; there was no fulness

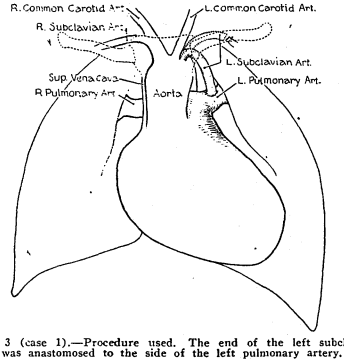

Fig. 3 (case 1).—Procedure used. The end of the left subclavian artery was anastomosed to the side of the left pulmonary artery.

in the region of the pulmonary conus. In the left anterior oblique position the right ventricle appeared slightly enlarged and the pulmonary window was abnormally clear. The clinical diagnosis was tetralogy of Fallot with a severe degree of pulmonary stenosis.

On June 25, 1944 she was first admitted to the Harriet Lane Home. Physical examination showed that she was poorly nourished and poorly developed. She had a glassy stare. Her lips were cyanotic. The heart was slightly enlarged and there was a harsh systolic murmur best heard along the left sternal border. The liver was at the costal margin. The baby was given oxygen and phenobarbital but remained very irritable and would become intensely cyanotic when taken out of the oxygen tent. During her three weeks' stay in the hospital she gained 200 Gm. and weighed 4.66 Kg. on discharge. She was sent home because it was felt that her condition was hopeless.

She was followed in the cardiac clinic for three months, during which time she showed increasing cyanosis and failed to gain weight. She was readmitted on October 17 because of increasing spells of cyanosis, coma and great venous distention of the head and body.

The weight on admission was 4.6 Kg. The venous distention was so great that the possibility of a subdural hydroma or hematoma was considered. Subdural tap was performed, with the removal of 8 cc. of clear fluid from the right side and a small amount of bloody fluid from the left.

The size of the heart as seen in the anteroposterior view was essentially the same as noted previously. There was still a harsh systolic murmur. In the left anterior oblique position the contour of the heart appeared as a little round ball with a narrow aorta and a clear pulmonary window (fig. 4); this, we believe, is characteristic of a very severe tetralogy of Fallot with a functional pulmonary atresia, that is, a pulmonary stenosis which is so extreme that the condition is not long compatible with life.[2] It was questioned at that time whether in addition to the malformation of the heart she suffered from mental retardation.

During the next six weeks she refused most of her feedings; she lost weight and just before operation weighed only 4 Kg. The red blood cell count, which had been 7,000,000 on admission, had fallen to 5,000,000. Cyanosis was proportionally less conspicuous; indeed, at times while lying quietly, cyanosis was not visible. The clinical diagnosis was again tetralogy of Fallot which was so severe that the baby's condition was becoming critical.

Operation.—This was performed on November 29. The procedure consisted in the anastomosis of the divided proximal end of the left subclavian artery to the side of the left pulmonary artery, as shown diagrammatically in figure 3. The anesthetic agent was administered by Dr. Merel Harmel.

Under ether and oxygen anesthesia, administered by the open method, an incision was made on the left side of the chest extending from the edge of the sternum to the axillary line. The pleural cavity was entered through the third interspace. The left lung appeared normal. No thrill was felt on palpating the heart and pulmonary artery. The left pulmonary artery was identified and was dissected free of the neighboring tissues. It appeared to be of normal size. The superior pulmonary vein, on the other hand, seemed considerably smaller than normal. The left subclavian artery was identified and was dissected free of the neighboring tissues. In order to secure access to a sufficient length of this vessel it was necessary to ligate and divide the vertebral artery, the internal mammary artery and the thyrocervical axis. A bulldog arterial clamp was placed on the subclavian artery at a point just distal to its origin from the aorta. The subclavian artery was ligated distal to the point at which the thyrocervical trunk had been ligated and divided, and the vessel was cut across just proximal to this ligature. Two bulldog clamps were placed on the left pulmonary artery, the first clamp being placed at the origin of the left pulmonary artery and the second clamp being placed just proximal to the point where the pulmonary artery entered the lung. There was ample space between these two clamps for our purpose. A small transverse incision was made in the wall of the pulmonary artery at a point approximately equidistant between the two clamps. By the use of china beaded silk on fine needles an anastomosis was performed between the end of the left subclavian artery and the side of the left pulmonary artery. There was practically no bleeding following the removal of the clamps.

From a technical point of view the anastomosis seemed to be satisfactory. The main cause for concern was the small size of the left subclavian artery. It was somewhat disturbing that one could not feel a thrill in the pulmonary artery. We were confident, however, that the anastomosis was patent. A small quantity of sulfanilamide was placed in the left pleural cavity and the incision in the chest wall was closed. The patient was given 200 cc. of isotonic solution of sodium chloride and 50 cc. of blood during the operative procedure. The operation required slightly less than an hour and a half and the left pulmonary artery was occluded for approximately thirty minutes. The patient's condition at the end of the operation seemed moderately good.

Postoperative Course.—This was stormy. The patient's left arm and hand were observed frequently. The radial pulse was not palpable and this extremity was cooler than the opposite one, but it was apparent that the circulation was adequate to maintain life of the part. The child suffered from repeated bilateral pneumothoraces, and frequent aspirations were required.

11. This case was discussed briefly at the meeting of the Southern Surgical Association, Dec. 5, 1944, in a paper by Dr. Arthur Blakemore.

Probably the pneumothorax on the right was due to the use of too great pressure in the reexpansion of the left lung at the completion of the operative procedure. As it was found to be a positive pressure pneumothorax, constant suction was exerted through a needle inserted into the right pleural cavity. Had it not been for the excellent care given by the pediatric house staff, particularly Dr. Kaye, Dr. Whitemore, Dr. Steinheimer, Dr. Hammond, Dr. Gilger and Dr. Helfrick, in all probability the child's life would not have been saved.

The child's condition began to improve two weeks after operation. Thereafter further aspirations of the pleural cavity were not required. The occasions on which the patient would become cyanotic became less frequent. Otitis media developed and responded to treatment. The systolic murmur became somewhat louder, but a continuous murmur could not be heard in the pulmonary area.

The patient was discharged from the hospital on Jan. 25, 1945, almost two months after the day of operation. Her condition was considerably better than it had been before operation. More recent follow-up studies have shown that she is gaining weight and that she is only occasionally cyanotic. If the cyanosis increases, it may be necessary to perform a similar operation on the opposite side. Roentgenograms of the patient's heart both before and after operation are shown in figure 4.

It is unfortunate that we do not have a quantitative degree of improvement such as might have been afforded by determinations of the oxygen saturation of the arterial blood. In view of the small size of the child we did not feel warranted in doing arterial punctures. The clinical improvement, however, has been striking. The baby takes her feedings well, is alert and active and has gained a kilogram in weight (that is, 25 per cent of her former body weight).

CASE 2.—*History.*—B. R., a white girl born July 9, 1933, was first seen at the Harriet Lane Home at 9 years of age, referred by Dr. Dexter Levy of Buffalo. The patient was cyanotic at birth. The birth weight was 6½ pounds (2,955 Gm.). She was breast fed for six months. In infancy she gained extremely slowly. She had erysipelas at 1½ years of age, a septic sore throat at 4½ years of age, chickenpox at 7 years, measles at 8 years and mumps at 9 years.

The patient was first seen in the Harriet Lane Home on Feb. 13, 1943. She was intensely cyanotic, became dyspneic on slight exertion and would constantly squat to get her breath. There was intense cyanosis and clubbing of the fingers and the toes. The buccal mucous membranes were of a deep mulberry color. There was suffusion of the conjunctiva. The chest was barrel shaped. Her heart was within normal limits in size. There was no thrill over the precordium. On auscultation there was a harsh systolic murmur which was maximal low down in the third and fourth interspaces. The murmur was much louder in the recumbent position than in the erect position, and louder when she bent forward than when she tried to sit erect. The murmur was not widely transmitted and was not audible in the back. The second sound at the base was pure. The lungs were clear. The liver was at the costal margin and the spleen was not palpable. The femoral arteries were readily palpable. The extremities, as previously mentioned, showed intense cyanosis and pronounced clubbing. At this time she climbed half a flight of stairs and walked, almost ran, leaning forward, 60 feet to her room, and then fell forward on the bed and lay in a knee-chest position, panting heavily and without speaking for half an hour.

The red blood cell count was 8,700,000; the hemoglobin was 25 Gm.; the hematocrit reading was 78.

The electrocardiogram showed a normal sinus mechanism, PR interval of 0.16 second, normal upright T waves in all four leads, and considerable right axis deviation.

X-ray examination and fluoroscopy showed the heart to be of normal size with a concave curve at the base to the left of the sternum (fig. 6). To the right of the sternum the superior vena cava cast a wide ribbon-like shadow. After the administration of barium, the aorta was seen to indent the esophagus to the left on its right margin. Examination in the left anterior oblique position showed that the right ventricle was not greatly enlarged; indeed, the left ventricle appeared larger than the right ventricle. The esophagus was seen to be indented by the aorta in the left anterior oblique position; in the right anterior oblique position its descent was independent of the aorta. There was no enlargement of the left auricle.

The clinical diagnosis was an extreme tetralogy of Fallot with a right aortic arch.

On Jan. 6, 1945 the patient returned for a check-up and because her parents wished to discuss the possibility of operation. The physical findings were essentially the same as previously noted but she was even more severely incapacitated. She could not walk 30 feet without exhaustion, and she panted when she moved from a wheel chair to the examining table. The fluoroscopic findings were essentially the same as noted previously except that the shadows at the hili of the lungs were more conspicuous. There were, however, no pulsations visible in this region.

The patient returned on January 29. Studies on the arterial blood are recorded in table 1.

A sample of venous blood showed that the red blood cell count was 7,500,000, the hemoglobin was 24 Gm., the hematocrit reading was 71 (Wintrobe) and the white blood cell count was 5,200. The electrocardiogram was essentially the same as that taken in 1943. A roentgenogram of the heart showed a small heart with a right aortic arch. The maximal right diameter was 4 cm. and the maximal left was 7 cm. The total transverse diameter was 26 cm. The cardiothoracic ratio was 42.4.

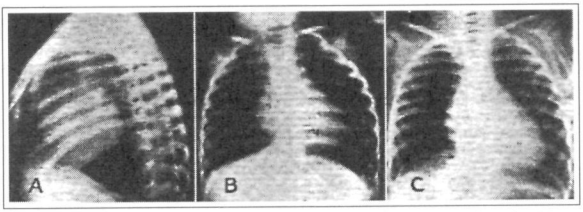

Fig. 4 (case 1).—Appearance before and after operation: *A*, left anterior oblique view before operation; *B*, anteroposterior view before operation; *C*, anteroposterior view after operation.

Operation.—This was performed on February 3. The procedure consisted in anastomosing the divided proximal end of the innominate artery to the side of the left pulmonary artery. This is shown diagrammatically in figure 5. The anesthetic agent was administered by Dr. Austin Lamont.

TABLE 1.—*Studies on Arterial Blood (Case 2)*

Dates	Arterial Oxygen Content, Volumes per Cent	Arterial Oxygen Capacity, Volumes per Cent	Arterial Oxygen Saturation, per Cent	Arterial Carbon Dioxide Content, Volumes per Cent
2/ 1/45	11.7	32.3	36.3	34.9
2/ 3/45	Innominate artery anastomosed to left pulmonary artery			
2/12/45	20.3	27.5	73.8	37.8
3/ 1/45	19.8	23.9	82.8	37.2

Cyclopropane with a high percentage of oxygen was administered through an endotracheal tube. The incision extended from the left costal margin to the anterior axillary line. The pleural cavity was entered through the third interspace. There were no adhesions between the lung and the chest wall, and the lung looked normal. Although the surgeon had been informed by his pediatric colleague that this patient almost

certainly had a right aortic arch, no special thought was given to the fact, and it caused some surprise when it was noted that the aorta was not on the left side. It was fortunate, however, that the incision had been made on the left because this allowed the use of the innominate artery rather than the subclavian artery. There was a very tortuous artery, which

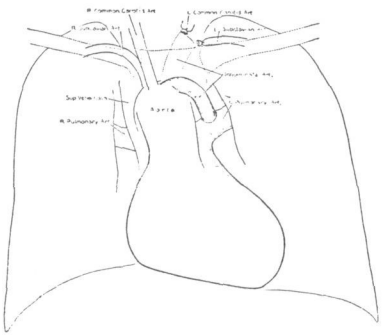

Fig. 5 (case 2).—Procedure used. The patient had a right aortic arch, and the innominate artery was directed to the left. The end of the innominate artery was anastomosed to the side of the left pulmonary artery.

was lying anterior to the vertebral column and which appeared to run from the region of the hilus of the lung toward the upper part of the left pleural cavity. Compression of this vessel indicated that the blood was flowing from above downward. It is believed that this vessel was a large accessory bronchial artery. It was estimated that the lumen of this artery was approximately 3 mm. in diameter. Still another abnormal finding was the large size of the posterior portions of the intercostal arteries. It seems likely that these vessels were also supplying blood to the hilus of the lung. The evidence of extensive collateral circulation led us to believe that we were probably dealing with a case of complete pulmonary atresia.

The innominate artery was located and dissected free of the surrounding tissues. The encouragement of the first assistant, Dr. William Longmire, played no small part in the continued effort to find a large systemic artery. A bulldog arterial clamp was placed on the innominate just distal to its origin from the aorta. The subclavian and common carotid arteries were ligated near their points of origin from the innominate. The innominate artery was divided just proximal to these ligatures. It was estimated that the diameter of the lumen of the innominate artery was approximately 1.3 cm. The left main pulmonary artery was then prepared for the anastomosis. A bulldog clamp was placed just distal to the origin of this vessel from the main pulmonary artery, and a second clamp was placed proximal to its entrance into the lung. A transverse opening was made into the lumen of the vessel midway between the two clamps. A suture anastomosis was performed between the end of the innominate artery and the side of the left pulmonary artery. The length of time that the left pulmonary artery was occluded was fifty to sixty minutes. The bulldog clamps were removed. There was bleeding from one point, which was controlled by an additional suture. An easily palpable thrill was felt in the pulmonary artery both proximal and distal to the anastomosis. The pulmonary artery seemed to be considerably larger than before this new current of systemic blood was admitted to it. The systemic arterial pressure was 110 systolic and 70 diastolic at the time that the arterial clamps were removed. Immediately following the removal of the clamps the systemic pressure declined 30 mm. of mercury. There followed a rise in systolic pressure of 20 mm. of mercury, but the pressure then declined gradually during the next thirty minutes until it reached 60 systolic and 30 diastolic. The pulse rate during this time rose from 72 to 120 per minute.

After the completion of the anastomosis and the removal of the clamps, several grams of sulfanilamide were placed in the pleural cavity. The left lung was partially inflated by the use of positive pressure, and the incision in the chest wall was closed. The patient was given a slow continuous intravenous drip of isotonic solution of sodium chloride during the operation and her condition at the end of the operation appeared to be satisfactory.

The operation required two hours and forty minutes. A considerable part of this time was consumed in studying the tortuous vessel which was seen above the hilus of the lung and also in trying to locate the innominate artery.

The patient awakened from the anesthesia a short time after the closure of the incision. She could move the left arm without difficulty. The left arm and hand were slightly cooler than the right, but it was evident that the circulation was adequate to maintain life. There was no evidence of a cerebral disturbance as the result of the ligation of the common carotid. No pulse could be felt in the left arm or the left side of the neck and face.

Postoperative Course.—This was smooth. There was no vomiting following operation, and fluids were taken by mouth. She was placed in an oxygen tent. The administration of penicillin was started immediately after operation and was continued for nine days. The left pleural cavity was aspirated twenty-four hours after operation; 250 cc. of air and 70 cc. of blood were removed. There were no other thoracenteses. Although a thrill was palpable at the site of the anastomosis immediately on release of the bulldog clamps, no murmur was audible immediately after the chest was closed. By the second evening a faint diastolic murmur was audible over the base and at the apex. By the third postoperative day an extraordinarily loud continuous murmur was audible throughout the chest on both the right and the left side. The oral administration of dicumarol was begun on the fourth postoperative day; 50 to 200 mg. was given daily for several weeks. Prothrombin determinations were performed daily. The dose of dicumarol was such as to keep the clotting time of the patient's blood approximately twice that of the normal control.

Femoral arterial punctures were performed on the ninth and twenty-sixth postoperative days. The results of the analyses are given in table 1. Before operation the red blood cell count was 7,500,000, the hemoglobin 24 Gm. and the hematocrit reading 71. Three days after operation the red blood cell count had decreased to 6,000,000, the hemoglobin to 19 Gm. and the hematocrit reading to 61. By the twenty-first day the red blood cell count was 6,000,000, the hemoglobin was 17.5 Gm. and the hematocrit reading was 55.

A roentgenogram of the heart taken ten days after operation showed that the heart had increased in size; that taken twenty-one days after operation revealed no further increase in size.

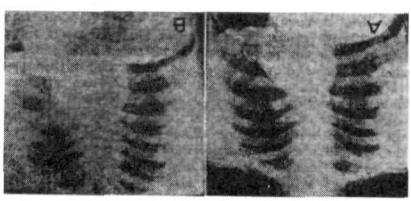

Fig. 6 (case 2).—Heart *A*, before operation and *B*, one month after operation.

Indeed, the heart was a trifle smaller than on the previous date. Roentgenograms of the heart before and after operation are shown in figure 6. Before operation the cardiothoracic ratio was 42.4 and three weeks after operation it was 44.7. The electrocardiogram showed no change (fig. 7). The stethocardiogram showed a continuous murmur (fig. 8). There was a significant increase in the pulse pressure. The preoperative arterial pressure had been 110 systolic and 90 diastolic. On

the thirty-seventh postoperative day the arterial pressure was 98 systolic and 66 diastolic.

An appreciable diminution in the cyanosis of the lips and fingernails was apparent several days after operation. The patient was allowed to walk, beginning two and a half weeks after operation. This exercise resulted in a slight increase in the cyanosis, but it was evident that cyanosis was much less than it had been preoperatively. By the end of the third week she could walk 60 feet in an erect posture without panting, whereas before operation, stooping and leaning forward, she could walk only 30 feet and would then stop and pant. There has been a slow but steady recession of the clubbing of the fingers and toes. The patient was discharged from the hospital on the thirty-eighth postoperative day.

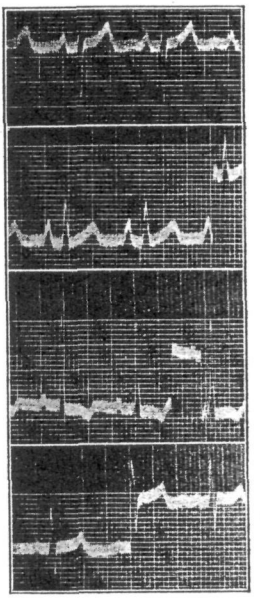

Fig. 7 (case 2).—Electrocardiogram.

CASE 3.—*History.*—M. M., a boy born July 15, 1938, was first seen at the Harriet Lane Home at 8 months of age with the complaint of heart trouble.

The family history is of importance in that the maternal grandfather was known to have heart trouble and had had a heart murmur throughout his life. The mother's brother and sister are both reported to have dextrocardia; both have refused examination.

The past history stated that the patient was a full term baby. The birth weight was 6½ pounds (2,955 Gm.). Development was slow; he held his head up at 5 months and sat alone at 6½ months. At 8 months the patient weighed 13½ pounds (6 Kg.). When lying quietly he showed slight persistent cyanosis, which became intense when he cried. On examination of the heart there was no thrill but a very definite systolic murmur, which was audible all over the precordium and well heard in the back. Fluoroscopy showed that the heart was within normal limits in size. There was a wide shadow above the heart which was interpreted as a large thymus. There was no fulness of the pulmonary conus, and the shadow at the base of the heart was concave. The clinical diagnosis was tetralogy of Fallot.

The patient was followed in the cardiac clinic until January 1940, when the family moved to California. They returned to Baltimore in the fall of 1944 and the patient was again brought to the clinic on September 29. At that time the boy, 6 years of age, was thin and undernourished, intensely cyanotic and dyspneic on slight exertion. The temperature was 99.2 F., weight 34½ pounds (15.6 Kg.), height 42 inches (107 cm.), pulse 140, respirations 20 and blood pressure 90 systolic and 60 diastolic.

There was manifest suffusion of the conjunctiva. The lips were purple and the buccal mucous membranes were a deep mulberry color. The teeth were in bad condition; the tonsils were not unduly enlarged. The chest was barrel shaped. The increase in the size of the heart was in proportion to the growth of the child. There was a systolic thrill at the apex and a harsh systolic murmur, which was maximal along the left sternal border in the third interspace. The second sound at the base of the heart was clear but not accentuated. The lungs were clear. The liver was at the costal margin; the spleen was not palpable. The femoral arterial pulsations were easily felt. The extremities showed deep cyanosis and pronounced clubbing. Although the patient had learned to walk by November 1944, he was so incapacitated that he was unable to walk and even refused to try to take a few steps. The diagnosis was tetralogy of Fallot with a severe degree of pulmonary stenosis.

The patient was referred to the dental clinic, where several teeth were extracted. Sulfadiazine was given for two days. One month later the patient returned to the cardiac clinic with a rectal temperature of 100.4 F. and with numerous petechiae on his legs, which the mother said were of two days' duration. A blood culture taken at this time was sterile and no further petechiae appeared.

TABLE 2.—*Studies on Arterial Blood (Case 3)*

Dates	Arterial Oxygen Content, Volumes per Cent	Arterial Oxygen Capacity, Volumes per Cent	Arterial Oxygen Saturation, per Cent	Arterial Carbon Dioxide Content, Volumes per Cent	Comment
2/ 8/45	7.3	31.2	23.4	27.5	Patient struggling
2/ 9/45	10.7	30.2	35.5	29.3	Patient quiet
2/10/45	Innominate artery anastomosed to right pulmonary artery				
2/19/45	17.7	22.2	79.7	37.4	Patient crying
3/ 6/45	17.7	21.1	83.8	35.2	Patient quiet

The family was desirous of prompt operation and the patient was admitted to the hospital on Feb. 7, 1945. The results of analyses of blood obtained by arterial puncture are shown in table 2. With venous blood the red blood cell count was 10,000,000, the hemoglobin 26 Gm. and the hematocrit reading 81. The patient continued to have a daily elevation of temperature.

An electrocardiogram showed a normal sinus mechanism, a normal PR interval of 16, high P waves in L_2, and normal upright T waves in leads 1, 2 and 4, and T_2 inverted and an apparent right axis deviation.

X-ray examination (fig. 10) showed that the maximal right diameter of the heart was 2.1 cm., the maximal left 7 cm. and the total transverse diameter 18.8 cm.; the cardiothoracic ratio was 47.5. There was no fulness of the pulmonary conus. Fluoroscopy showed that the aorta descended on the left, and there were no visible pulsations in the lung fields.

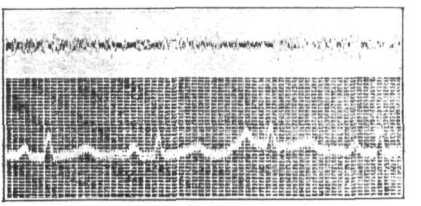

Fig. 8 (case 2).—Stethocardiogram.

Operation.—This was performed on February 10. The procedure consisted in anastomosing the divided proximal end of the innominate artery to the side of the right pulmonary artery. This is shown diagrammatically in figure 9. The anesthetic agent was administered by Dr. Merel Harmel.

Anesthesia was produced by cyclopropane with a high concentration of oxygen. It is of interest that the patient's color was much better under anesthesia than it had been previously.

This patient did not have a right aortic arch. In view of the great improvement in the second case we wished to use the innominate artery, and therefore the incision was made on the right side. There were no adhesions between the lung and the chest wall, and the lung appeared normal. The right upper lobe was retracted downward and the azygos vein was visual-

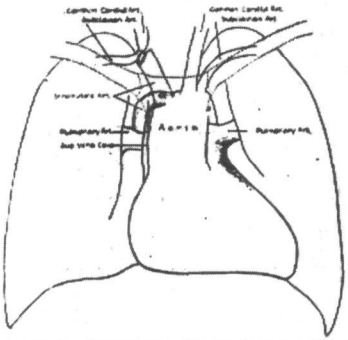

Fig. 9 (case 3).—Procedure used. The end of the innominate artery was anastomosed to the side of the right pulmonary artery.

ized. It was doubly ligated and divided. The superior vena cava and phrenic nerve were retracted medially, and the artery to the right upper lobe of the lung was seen. This was followed medially and the main right pulmonary artery was exposed. This exposure was considerably more difficult than that on the left side. Attention was then turned to the innominate artery. By dissecting under and medial to the superior vena cava the innominate artery was exposed and was dissected free of the surrounding tissues. This vessel was occluded temporarily by the use of a lung tourniquet which was equipped with a catheter overlying a piece of braided silk. The subclavian artery and the common carotid artery were ligated just distal to their origins from the innominate artery. The innominate artery was cut across proximal to these ligatures. Two bulldog clamps were placed on the right main pulmonary artery, and a transverse incision was made into the vessel between these clamps. The proximal bulldog clamp was not of sufficient length to secure entire control of the flow of blood. This resulted in a moderate loss of blood, and another clamp was substituted.

With 5-0 silk on a small curved needle an anastomosis was made between the divided proximal end of the innominate artery and the side of the right main pulmonary artery. This anastomosis was more difficult than that in the previous cases because the exposure was less satisfactory. Following the removal of the bulldog clamps from the pulmonary artery there was a rather copious flow of blood from one point along the anterior row of sutures. The clamps were reapplied, and this opening was closed with a mattress suture. Subsequent removal of the clamps did not result in further bleeding. The patient's condition up to the time of this blood loss had been excellent. Occlusion of the right pulmonary artery had not seemed to increase the cyanosis. There was an increase in the cyanosis and a decline in pressure when this loss of blood occurred. It was estimated that at least 250 cc. of blood was lost.

The anastomosis seemed to be a satisfactory one. An easily palpable thrill could be felt in the pulmonary artery both proximal and distal to the anastomosis. It was estimated that the lumen of the innominate artery was slightly less than 1 centimeter in diameter. The right lung was partially inflated and the incision in the chest wall was closed.

The patient received 500 cc. of a mixture of isotonic solution of sodium chloride and glucose and 200 cc. of plasma during the operative procedure. The operation required a total of three hours, the greater part of this time being consumed in making the anastomosis. It was obvious that a better instrument for occluding the pulmonary artery proximal to the site of the anastomosis is needed. The right pulmonary artery was occluded for approximately ninety minutes.

The patient's condition at the completion of the operation was very good. He was conscious a few minutes after the incision had been closed, was asking for water and was moving his right arm. This arm was slightly cooler than the left. Pulsations could not be felt in the right arm or in the right side of the neck and the face. There was, however, no evidence of cerebral damage, and it was obvious that the circulation of the arm was adequate to maintain life.

Postoperative Course.—This was remarkably smooth. The patient was placed in an oxygen tent for several days. The circulation to the right arm remained adequate. Aspiration of the chest was not necessary. Immediately after operation the child's color improved. It was seen on the fourth postoperative day when the administration of oxygen was discontinued that the cyanosis of the lips had disappeared. The cyanosis of the fingertips decreased more slowly. The administration of penicillin was started the day before the operation and was continued for three weeks postoperatively. Dicumarol was given by mouth, beginning on the third postoperative day. The usual daily administration was 25 mg. Prothrombin determinations were performed daily, and the drug was continued for three weeks.

Although a thrill was palpable at the site of the anastomosis after the arterial clamps had been released, no murmur was audible immediately after the chest had been closed. By the first evening a faint murmur was audible, which gradually increased in intensity. By the fourth postoperative day a continuous murmur was audible over the site of the anastomosis and posteriorly throughout both lungs.

The child's compensation has remained excellent. In contrast to a preoperative arterial pressure of 85 systolic and 65 diastolic, the arterial pressure postoperatively was usually 106 systolic and 52 diastolic. The heart increased somewhat in size during the first ten days after operation, but there did not appear to be a further increase in the subsequent two weeks. Roentgenograms of the heart both before and after operation are shown in figure 10.

Arterial punctures were performed on the 9th and 24th postoperative days. The results of the analyses are given in table 2. On comparing the preoperative studies with those performed twenty-four days after operation, samples of venous blood showed that the red blood cell count decreased from 10,000,000 to 6,000,000, the hemoglobin from 26 to 20 Gm. and the hematocrit reading from 81 to 53 (Wintrobe).

The patient had had a preoperative daily elevation of temperature to 100 F., and this continued for three weeks after operation. For this reason he was not allowed out of bed

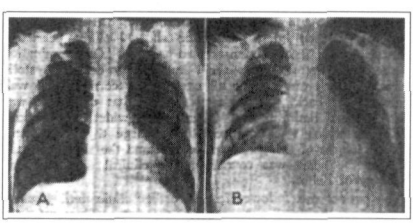

Fig. 10 (case 3).—Heart *A*, before operation and *B*, two weeks after operation.

despite his vigorous protests until three and a half weeks after operation. When permitted to do so, the child walked 40 feet with ease. He was then allowed to be up for several hours each day and has walked and played in his room. He did not develop either cyanosis or dyspnea on this activity. The patient was discharged from the hospital on the thirty-eighth postoperative day.

COMMENT

Each of these 3 patients suffered from such a severe degree of pulmonary stenosis that there was inadequate circulation to the lungs. Although the three operations differed in detail, in each instance the operation greatly increased the volume of blood which reached the lungs.

In the first case the end of the left subclavian artery was anastomosed to the side of the left pulmonary artery. As the baby was small and weak, extensive laboratory studies were not performed. Before operation the baby had been steadily losing ground. She had ceased to be able to sit alone; she had refused her feedings and had lost weight. The red blood cell count had declined from 7,000,000 to 5,000,000; consequently the cyanosis had diminished considerably. After operation her clinical improvement was remarkable. The appetite improved, she gained weight and she is now starting to learn to walk.

The second patient had a right aortic arch; hence it was possible to anastomose the innominate artery to the left pulmonary artery. The patient was deeply cyanotic and severely incapacitated and could not walk 30 feet without panting. Two and a half weeks after operation she walked 60 feet, rested a short time and walked 60 feet back to her room and sat down quietly. The seriousness of her condition and the extent of the improvement are shown by the changes in the oxygen saturation of the arterial blood, which was 36.3 per cent before operation and which rose to 82.8 per cent three weeks subsequently. The red blood cell count dropped from 7,500,000 to 6,000,000, the hemoglobin from 24 Gm. to 17.5 Gm. and the hematocrit reading from 71 to 55.

The success of the second operation led us to perform the same operation in the third case. Since the aorta was in the normal position, in order to use the innominate artery the operation was performed on the right side. The end of the innominate artery was anastomosed to the side of the right pulmonary artery. The patient was younger, and improvement was even more dramatic. Before operation he was intensely cyanotic, the lips were a dark purple, and the child was unable to take even a few steps. The day after operation he lay in an oxygen tent with cherry red lips. When taken out of the tent his color remained good. His disposition has changed from that of a miserable whining child to a happy smiling boy. We were slow to permit him to walk because of a persistent low grade fever, but at the end of the third postoperative week he could walk 40 feet without panting and without becoming cyanotic. The oxygen saturation of the arterial blood rose from 35.5 to 79.7 per cent in nine days, and it reached a saturation of 83.8 per cent twenty-four days after operation. The red blood cell count fell from 10,000,000 to 6,000,000; the hemoglobin decreased from 26 Gm. to 20 Gm. and the hematocrit reading from 81 to 53.

There are a number of features of the operative procedure which merit discussion. We were fearful that an intensely cyanotic child would not tolerate a long operative procedure in which it was necessary to open the pleural cavity and to occlude temporarily one of the pulmonary arteries. For this reason our first clinical attempt to increase the circulation to the lungs was postponed almost a year after it was decided that the procedure was a sound one, with the hope that some method of administering oxygen in addition to inhalation might prove satisfactory. This seemed particularly important since it was obvious that a new and untried procedure should be performed first on patients with a severe degree of anoxemia whose outlook without aid of some sort was hopeless. Although the use of intravenous oxygen has been reported by Ziegler [12] and may prove to be of benefit in this operation, it was impossible during wartime to procure the necessary equipment. Therefore this method could not be studied.

From our limited experience it appears that this type of patient can tolerate the use of inhalation agents for general anesthesia. We have been fortunate in this respect in that the anesthetic agents were chosen and administered expertly by Dr. Austin Lamont and Dr. Merel Harmel.[13] The first of these 3 patients was only 14 months of age and weighed less than 9 pounds. Ether by the open drip method was used during the major part of the procedure for the reason that a sufficiently small closed system was not available. In the anesthetization of the second and third patients, cyclopropane with a high concentration of oxygen was employed. Fortunately the administration of oxygen apparently increased the oxygen content of the arterial blood and cyanosis was definitely lessened. Although in only 1 patient was there any serious hemorrhage, the precaution was taken of having both blood and plasma readily available. Indeed, a slow continuous drip of plasma is advisable so that at a moment's notice if necessary the patient can be given large quantities of plasma. With these precautions no great difficulty was encountered in spite of the fact that two of the three operations required three hours.

The next question which arose was whether a patient who was already suffering from a severe degree of anoxemia would tolerate the occlusion of one of the main pulmonary arteries for the period during which the anastomosis was being performed. These periods of occlusion were approximately thirty, sixty and ninety minutes in the three operations. It is a remarkable fact that the cyanosis did not appear to be greatly increased during the occlusion period. It may be that the decreased flow of blood to the lungs caused by the congenital deformity rendered it possible for the opposite artery and lung to utilize this reduced volume almost as effectively as could the two lungs. Be that as it may, the 3 children tolerated occlusion of the left or the right main pulmonary artery for periods ranging from approximately thirty to ninety minutes.

Another question which arose was whether ligation and division of the left subclavian artery or the innominate artery would result in serious impairment of the circulation to the arm and the brain. In most instances heretofore these vessels have been occluded because of preexisting disease such as aneurysm, and it is possible under such circumstances that there has been a prolonged stimulus for the formation of collateral arterial pathways. It was gratifying, therefore, to note in our patients that there was little evidence of impairment of circulation to the parts deprived of their major arterial pathway. It is true that the pulse was absent for some time postoperatively and the part was slightly cooler than that of the opposite part of the body, but immediately after operation it was evident that the circulation was adequate to maintain life of the part. It may prove desirable to perform an upper dorsal sympathectomy at the time of operation. This would not add to the gravity of the operative procedure, since one has an excellent exposure of this region in perform-

12. Ziegler, E. E.: Intravenous Administration of Oxygen, J. Lab. & Clin. Med. **27**: 223-232 (Nov.) 1941.
13. Drs. Lamont and Harmel will deal with this subject in a subsequent communication.

ing the arterial anastomosis. In future cases the circulation of the arm will be studied more carefully.

The operation has not been attempted before on patients and there are many operative as well as clinical features which are still under investigation. The first of these is concerned with the type of anastomosis which is to be performed. This will undoubtedly depend on many factors, especially the age of the patient and the degree of anoxemia. As stated previously, in our patients the anastomosis was performed between the end of the subclavian artery or innominate artery and the side of the left or right pulmonary artery. This type of anastomosis appears to be sound in that it allows the blood to flow from the systemic circulation to both lungs. The fact that the continuous murmur which results from the operation is readily audible on both sides of the chest indicates that the anastomosis does direct blood to both lungs. It was this type of anastomosis which was used by Eppinger, Burwell and Gross [8] in their studies on the cardiac output of dogs with an artificial ductus arteriosus.

The easiest of the end to side arterial anastomoses in this region is that between the end of the left subclavian artery and the side of the left pulmonary artery. On the other hand, the subclavian artery is so small in an infant that the chances of the occurrence of thrombosis at the anastomotic site are great. This is particularly true if the patient has extreme polycythemia. Even though the anastomosis remains patent, the size of the vessel is a limiting factor in the flow of blood to the lungs which may not be sufficient to overcome the high degree of anoxemia from which some of these patients suffer. In an older patient with only a moderate degree of cyanosis the subclavian artery would appear to be the ideal vessel. The left common carotid is somewhat larger than the left subclavian artery, and its employment under some circumstances seems to be warranted. When dealing with the degree of anoxemia which was present in our patients, the innominate artery is much to be preferred to the left subclavian artery or the left common carotid artery. The performance of the anastomosis is not very difficult when the left pulmonary artery can be used. The anastomosis of the innominate artery to the left pulmonary artery is possible only in patients with a right aortic arch and hence an innominate artery on the left. With the innominate artery in its normal position the anastomosis of this vessel to the right pulmonary artery is more difficult because so much of the latter artery lies behind the aorta and the superior vena cava. Improvements in the designs of instruments will facilitate this procedure.

It is important to bear in mind that the degree of impairment in the flow of blood to the lungs varies from patient to patient, and the selection of the vessel to be used depends on the extent of the need of the patient for an increase in the circulation to the lungs. Experimental observations and clinical trial and error will undoubtedly shed additional light on this subject. It is obvious that the vessel chosen and the size of the anastomosis itself should not be larger than is necessary for the relief of anoxemia because of the danger associated with excessive shunting of blood to the lungs.

There are other methods in addition to union of an end of a systemic artery to the side of a pulmonary artery by which an anastomosis between the two circulations may be made. Included among these are (1) anastomosis of the divided proximal end of one of the vessels which arise from the aortic arch (innominate, left common carotid, left subclavian) to the divided distal end of one of the two pulmonary arteries, (2) anastomosis of the divided proximal end of the subclavian artery or the common carotid artery to the divided proximal end of the pulmonary artery to an upper lobe of one of the lungs, (3) anastomosis of the side of the aorta to the side of the left pulmonary artery and (4) anastomosis of the side of the aorta to the side of the left pulmonary artery. These will be considered in the order in which they are enumerated.

The results of the use of the first method, in which the divided proximal end of the left subclavian artery is anastomosed to the divided distal end of the left main pulmonary artery, were reported in 1939 by Levy and Blalock.[7] It was stated that "dogs which have been observed for several months following this procedure appear entirely normal. The left lung was aerated and the respiratory movements were unaltered. The systemic arterial blood pressure was not affected by this operation. The blood pressure in the pulmonary artery only a short distance beyond the anastomosis was less than half of that in the systemic arteries. This was due to the relatively low peripheral resistance in the pulmonary bed. Since only arterial blood entered the left lung, the quantity of oxygen consumed by this lung was very small. However, when anoxemia was caused, a larger quantity of oxygen was taken up by the incompletely oxygenated arterial blood. The left lung appeared pinker than the right on gross examination during life. Microscopic examination revealed no noteworthy alteration in either the left pulmonary artery or lung." Some of these animals have now been observed over periods ranging up to six years. The only disturbing finding has been that a few of the animals at autopsy have shown a thickening of the left pulmonary artery. It was noted by Dr. Arnold Rich that this was found only in instances in which the anastomotic site was partially occluded as a result of thrombosis. The discrepancy in the size of the left subclavian artery and that of the left pulmonary artery may have accounted in part for this finding. Furthermore, this discrepancy in size may be responsible in part for the sudden diminution in the arterial pressure just beyond the point of anastomosis. At any rate, it is improbable that the anastomosis of the subclavian artery to the end of the left pulmonary artery would be the procedure of choice in the treatment of pulmonic stenosis. If this type of anastomosis should be performed, the innominate artery would be a better choice than the subclavian because it is more nearly the size of the pulmonary artery. It may be found that an end to end anastomosis is more apt to remain patent than an end to side one; certainly it is technically easier to perform. If, in the process of performing an anastomosis between the end of the innominate artery and the side of one of the pulmonary arteries, the latter vessel should be torn beyond repair, it should be borne in mind that an anastomosis may still be performed between the end of the innominate and the distal end of the pulmonary artery. Experimental studies are being carried out on the relative virtues of end to end and end to side anastomoses.

A second alternative method consists in anastomosing the proximal end of the divided subclavian or carotid artery to the proximal end of the divided pulmonary artery to one of the upper lobes. Since it is technically easier to perform an end to end than an end to side anastomosis, one may consider the advisability of using

this procedure for a patient with only a slight degree of cyanosis. The proximal end of the pulmonary artery is specified because this would conceivably allow blood to gain access to all the lobes except the one supplied by the artery which was used for the anastomosis. This procedure has been performed in the laboratory and is not difficult.

The third possible operative procedure is concerned with an anastomosis of the side of the aorta to the side of the left pulmonary artery. That such a procedure is possible in dogs has been shown by Leeds [9] in his studies on patent ductus arteriosus. We considered the use of this method in our patients but were discouraged by the experience of Blalock and Park [10] in studies on experimental coarctation of the aorta. In these experiments the aorta was divided just distal to the ligamentum arteriosum, the two ends of the aorta were closed, the left subclavian artery was divided at some distance from the arch of the aorta, and the proximal end of the divided subclavian artery was anastomosed to the side of the distal end of the aorta just below the point at which it had been divided. Thus the subclavian artery was used for the conduction of blood beyond the point of division of the aorta. The discouraging feature of these experiments was that in approximately half of the animals the hind legs were paralyzed at the completion of the operative procedure. In 1 dog in which we occluded the aorta for forty minutes for the purpose of making an anastomosis between the side of the aorta and the side of the left pulmonary artery the hind legs became paralyzed. It is impossible to make an accurate anastomosis between the aorta and the left pulmonary artery without interrupting temporarily the circulation through the two vessels. We were fearful of causing a paralysis of the lower extremities and hence did not use this method with our patients. Another difficulty associated with the use of the aorta is that its walls are thick and rather friable and it is difficult to obtain an accurate approximation of the intimal surfaces.

The fourth method to be considered is that of an anastomosis of the aorta and the main pulmonary artery. It is obvious that occlusion of these vessels for the length of time that is required for an open suture anastomosis would result in death. If such a union was to be secured, it would have to be done by some other method. Fortunately the first portions of the medial walls of the aorta and the pulmonary artery are intimately adherent to each other. The ascending aorta and the main pulmonary artery are contained within the pericardial cavity and are enclosed in a tube of serous pericardium common to the two vessels. We have been able to produce a fistula between the two vessels in dogs by inflicting a stab wound in this region. The knife blade was introduced through the opposite free wall of the pulmonary artery, the walls of the pulmonary artery and aorta which were in intimate contact were pierced, the knife was withdrawn, and the opening in the free side of the pulmonary artery was closed by sutures. The establishment of the fistula required only a few seconds. This method is mentioned because it may be necessary to use the major blood vessels and to employ considerable speed if newborn infants with pulmonary stenosis or atresia are to be saved. It would not be at all surprising if this experimental method should prove to be a useful one in patients.

It remains to be proved whether a communication between the two circulations should be brought about by direct anastomoses between blood vessels such as we have employed or by the use of tubes such as those devised for other purposes by Blakemore, Lord and Stefko.[14] It is our impression that the suture method is preferable when it can be accomplished without undue tension. This method obviates the necessity for leaving a large foreign body in the tissues; furthermore, there is at least a possibility that the opening will increase in size with the growth of the child. Studies on the latter point are in progress. These comments are in no sense a criticism of the Blakemore method, which is of great value in those instances in which part of a blood vessel has been destroyed and the ends cannot be united by direct suture.

One of the possible complications which causes concern is the danger of thrombosis at the anastomotic site. The improvement of our 3 patients indicates that thrombosis has not occurred. Furthermore, in cases 2 and 3 loud continuous murmurs developed after operation. As mentioned previously, partial occlusion of the anastomotic site has been found in some of the dogs in which such anastomoses were performed. Partial occlusion of the opening and emboli in the lungs were found at autopsy in 1 animal in which the end of the subclavian artery had been anastomosed to the side of the left pulmonary artery. This experiment was complicated by the previous creation of bilateral pulmonary arteriovenous fistulas. The sizes of the vessels used and the size of the communication between the two vessels are, of course, of prime importance in the determination of whether or not the opening will remain patent. This consideration is another point in favor of using a large vessel such as the innominate artery. Because of the difference in pressure on the two sides of the anastomotic site between the systemic and pulmonary circulations, it would be more likely that such an anastomosis would remain open than communications of similar size between two systemic arteries or two systemic veins.

As previously stated, most patients with the type of malformation of the heart under consideration have a decided polycythemia and an increased viscosity of the blood. This condition undoubtedly increases the danger of thrombosis. Indeed, cerebral thromboses are of not infrequent occurrence in these patients. Therefore the question arose as to whether these patients should receive heparin shortly after the termination of the operation. After much deliberation it was decided that the possible dangers were greater than the possible advantages. This opinion, however, is subject to change. By way of compromise, it was decided to give dicumarol during the period of convalescence. Therefore, beginning respectively on the fourth and third postoperative days the second and third patients were given dicumarol in small quantities. Prothrombin determinations were made daily and the dose of dicumarol was regulated so as to keep the clotting time approximately double that of the normal control. This medication was continued for a period of approximately three weeks. It is impossible to state whether this therapy has been of importance in the maintenance of the patency of the fistulas.

In order to understand the changes produced by the operation and its application to other malformations, it is essential to understand the nature of this malformation and the course of the circulation. The four features which constitute the tetralogy of Fallot are pulmonary stenosis, dextroposition of the aorta, an inter-

14. Blakemore, A. H.; Lord, J. W., Jr., and Stefko, P. L.: Restoration of Blood Flow in Damaged Arteries: Further Studies on Nonsuture Method of Blood Vessel Anastomosis, Ann. Surg. 117: 481-497, 1943.

ventricular septal defect and right ventricular hypertrophy. The pulmonary stenosis consists in a narrowing of the pulmonary orifice, and it is usual to find that the constriction also involves the pulmonary conus of the right ventricle. Dextroposition of the aorta means that the aorta rises from the left ventricle and partially overrides the right ventricle. Whenever this occurs, the aortic septum cannot meet the ventricular septum; consequently there is a high ventricular septal defect. Such is the nature of an interventricular septal defect in the tetralogy of Fallot. The malformation renders it difficult for the blood to be expelled from the right ventricle; hence there is hypertrophy of that chamber. The structure of the heart and the course of the circulation are diagrammatically shown in figure 11.

The degree of incapacity in a tetralogy of Fallot depends on the severity of the pulmonary stenosis and the degree of the overriding of the aorta. It is well known in cases in which the pulmonary stenosis is not extreme that the malformation is compatible with relative longevity. However, with extreme degrees of pulmonary stenosis and greatly diminished circulation to the lungs, the condition causes severe incapacity and death occurs at an early age.

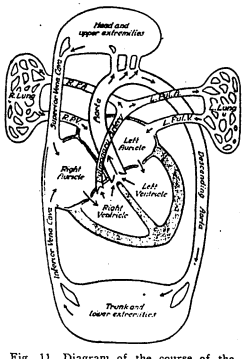

Fig. 11. Diagram of the course of the circulation in the tetralogy of Fallot. In this malformation there is pulmonary stenosis, the aorta is dextroposed and hence receives blood from both ventricles, the ductus arteriosus undergoes normal obliteration and the foramen ovale is closed. The blood from the right auricle flows into the right ventricle; hence part of the blood is pumped through the stenosed pulmonary orifice into the pulmonary artery and part of the blood is pumped directly into the aorta. Only that portion of the blood from the right ventricle which is pumped into the pulmonary artery goes to the lungs for aeration and is returned to the left auricle and the left ventricle. All of the blood from the left ventricle and some of the blood from the right ventricle is pumped out into the aorta to the systemic circulation and is returned by the superior vena cava and the inferior vena cava to the right auricle. There the cycle starts again.

The anastomosis of the innominate artery to the pulmonary artery directs a large volume of blood from the systemic circulation into the pulmonary circulation. By this means the volume of blood which reaches the lungs for aeration is increased: it follows that a greater volume of oxygenated blood is returned by the pulmonary veins to the left auricle and the left ventricle; consequently a greater volume of oxygenated blood is pumped out into the systemic circulation. As some blood from the aorta is diverted to the pulmonary circulation, the volume of blood to the systemic circulation is decreased and less blood is returned to the right auricle and the right ventricle. Thus the volume of blood which is returned to the right ventricle is lessened and that which is returned to the left side of the heart is increased. The alteration in the course of the circulation as influenced by the operation is shown in figure. 12.

In short, the operation enables some blood to bypass the obstruction to the pulmonary circulation. Hence the operation should be of value in all malformations in which the primary difficulty is due to lack of adequate circulation of the blood to the lungs; that is, in all cases of the tetralogy of Fallot and complete pulmonary atresia, in cases in which the right ventricle is absent or defective in its development, in cases of truncus arteriosus with bronchial arteries, or even a single ventricle with a rudimentary outlet chamber in which the pulmonary artery is diminutive in size.

Complete pulmonary atresia is, of course, compatible with life only as long as the ductus arteriosus remains open unless the bronchial arteries dilate and establish sufficient collateral circulation for the maintenance of life. This, we believe, happened in case 2, as at operation large aberrant vessels were found in the region of the hilus of the left lung. However, in the great majority of cases of pulmonary atresia the closure of the ductus arteriosus is so rapid that adequate collateral circulation does not develop and consequently the condition is fatal in early infancy. In all such cases the operation, if performed early, may be life saving. The same is true in cases of a defective development of the right ventricle in which all of the blood from the right auricle is directed to the left auricle and hence to the left ventricle and out by way of the aorta, and the only circulation to the lungs is by way of the ductus arteriosus.[15] The operation should be equally valuable in cases of truncus arteriosus with bronchial arteries because the bronchial arteries never become sufficiently large to provide adequate circulation to the lungs.

In every instance there is, of course, an admixture of venous and arterial blood. It would be impossible, therefore, to bring the oxygen saturation of the arterial blood to normal; nevertheless, it is conceivably possible to bring the oxygen saturation of the arterial blood sufficiently high so that there would be no "visible" cyanosis. Certainly in the 2 older children there has been an increase in the oxygen content of the arterial blood, a decrease in the oxygen capacity, an increase in the oxygen saturation of the arterial blood, a decrease in the red blood cell count, a diminution in the hemoglobin and the hematocrit reading, a striking decrease in the patients' disability and a great improvement in the patients' ability to exercise.

In cases of the tetralogy of Fallot the heart is either normal in size or relatively small. Following the creation of an artificial ductus, the increased volume of blood which reaches the pulmonary circulation undoubtedly increases the work of the left side of the heart. In our patients the heart has definitely increased in size but compensation thus far has remained excellent. Sir Thomas Lewis[16] has emphasized that in cases of coarctation of the aorta prolonged overwork does not cause cardiac failure. Palmer[17] in his studies on cardiac enlargement showed that, in essential hypertension, cardiac enlargement occurs with the gradual rise in blood pressure and that progressive enlargement does not easily occur after the blood pressure level has become stabilized. Therefore it is our hope and expectation that in this operation, although the heart immediately increases in size in response to the altered blood flow, the condition will not lead to progressive cardiac enlargement. It is encouraging that in both cases 2 and 3, although the heart increased in size in the first ten days, there was no further increase in the second ten days.

15. Taussig, H. B.: The Clinical and Pathological Findings in Congenital Malformations of the Heart Due to Defective Development of the Right Ventricle Associated with Tricuspid Atresia or Hypoplasia, Bull. Johns Hopkins Hosp. **59**: 435-443, 1936.

16. Lewis, T.: Material Relating to Coarctation of the Aorta of the Adult Type, Heart **16**: 205-261, 1933.

17. Palmer, J. H.: The Development of Cardiac Enlargement in Disease of the Heart: A Radiological Study, Medical Research Council Special Report Series, No. 222, 1937.

It is important to emphasize that the operation is not of value to all patients with persistent cyanosis. It is of value only in malformations in which the primary difficulty is lack of circulation to the lungs. The operation would be of no use in cases of complete transposition of the great vessels or in the so-called "tetralogy of Fallot of the Eisenmenger type" and probably not in aortic atresia.

In complete transposition of the great vessels the pulmonary artery arises from the left ventricle and the aorta from the right ventricle. The blood from the left ventricle is pumped out through the pulmonary artery to the lungs and is returned by the pulmonary veins to the left auricle and thence to the left ventricle. The blood from the right side of the heart is pumped out into the aorta to the systemic circulation and is returned by the superior vena cava and the inferior vena cava to the right auricle and the right ventricle. The primary difficulty in this malformation is not in the volume of blood which reaches the lungs but in the mechanism by which the blood which has been oxygenated in the lungs can reach the systemic circulation.

In the Eisenmenger complex cyanosis appears to be due to secondary changes in the alveolar wall or in the pulmonary vascular bed of such a nature as to hinder the aeration of the blood as it passes through the lungs; it is even possible that the high pressure in the lesser circulation may increase the right to left shunt and thereby increase the volume of reduced hemoglobin in the arterial blood. In any event, in this malformation there is no lack of circulation to the lungs and, furthermore, only rarely, if ever, is there deep cyanosis in early childhood.

In aortic atresia[18] not only is there difficulty in pumping blood to the systemic circulation but also the blood which does reach the systemic circulation is pumped through the ductus arteriosus before it has been to the lungs for aeration. Under such circumstances the creation of an additional ductus arteriosus would act to direct a larger volume of blood to the body; but it must be borne in mind that this blood has the same oxygen content as that directed to the lungs.

It is worthy of note in almost all patients with much polycythemia that all of the blood which circulates through the lungs is no longer fully oxygenated. Whether the size of the capillary bed in the lungs varies with the plasma volume and not with the number of red blood cells is not known, but there is clear evidence to show that even in patients in whom the primary difficulty is lack of circulation to the lungs the oxygen saturation of the arterial blood can be appreciably raised by the prolonged inhalation of a high concentration of oxygen. The potency of this factor was demonstrated by the great improvement in the peripheral cyanosis during operation when the patients were receiving oxygen. The importance of the volume of blood which reaches the lungs for aeration is demonstrated in our patients by the extent of the rise in the oxygen saturation of the arterial blood which resulted from the operation; in 1 instance it rose from 36.3 to 82.8 per cent and in the other from 35.5 to 83.8 per cent.

It may be that, with prolonged meager flow of blood to the lungs, secondary changes occur so that the pulmonary capillary bed is no longer capable of complete expansion and restoration to normal. Our 6 year old child showed prompter improvement than did the 12 year old girl. Hence the operation may prove less beneficial to older persons than to young children. For this reason the ideal age for operation appears to be after the systemic pressure has risen sufficiently high to permit the continuous flow of blood from the aorta to the pulmonary artery and before the condition has persisted long enough to cause irreversible changes in the lungs. We believe that the optimal age of patients is probably between 4 and 6 years; however, in all cases in which the closure of the ductus arteriosus renders the malformation incompatible with life the operation must be performed in early infancy.

Since the operation should be of value to all patients in whom the primary difficulty is lack of circulation to the lungs, it behooves the clinician to recognize this condition.[19] The two outstanding features, both of which should be present, are (1) roentgenographic evidence that the pulmonary artery is diminutive in size and (2) clinical and roentgenographic evidence of absence of congestion in the lung fields.

The size of the normal pulmonary artery is not difficult to determine by roentgenography. The striking feature in the roentgenogram is the absence of the fulness of the normal pulmonary conus. The shadow at the base of the heart to the left of the sternum is concave and not convex. A concave shadow in this region in patients with persistent cyanosis always means that the pulmonary artery is misplaced, absent or diminutive in size.[2] When the pulmonary artery is absent or diminutive in size, there is the additional finding in the left anterior oblique position of an abnormally clear pulmonary window.[2]

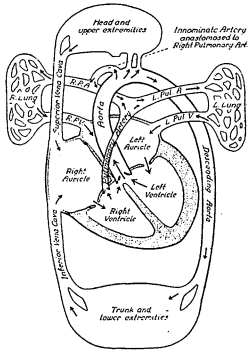

Fig. 12.—Diagram of the course of the circulation in the tetralogy of Fallot after the anastomosis of the innominate artery to the pulmonary artery. Under these circumstances the blood from the right auricle flows into the right ventricle and, as before, part of the blood from the right ventricle is pumped directly into the aorta. Now, in addition to the blood which is pumped through the pulmonary orifice into the pulmonary artery, some of the blood from the aorta is diverted through the anastomosis to the lungs. Thus the volume of blood which reaches the lungs is increased and the volume of oxygenated blood which is returned to the left auricle and the left ventricle is proportionately increased. All of the blood from the left ventricle and also some blood from the right ventricle is pumped into the aorta. Some of the blood from the aorta is directed to the lungs, and the remainder goes to the systemic circulation and is returned by the superior vena cava and the inferior vena cava to the right auricle. Thus the left ventricle receives more blood than before operation and the right side of the heart receives less. The operation has bypassed the obstruction in the circulation of the blood to the lungs.

Absence of clinical and x-ray evidence of congestion in the lungs is highly important in reaching a decision. When circulation to the lungs is inadequate, the diminished blood flow to the lungs lessens the chances of congestion in the lungs and congestion rarely occurs.[2] When congestion does occur, it suggests that the circulation to the lungs is adequate or excessive. The operation should never be attempted when x-ray exam-

18. Taussig, H. B.: Clinical and Pathological Findings in Aortic Atresia or Marked Hypoplasia of the Aorta at Its Base, Bull. Johns Hopkins Hospital, to be published.

19. The following discussion is based mainly on original unreported observations which are dealt with in detail in chapters II and III of Taussig's forthcoming book on "The Clinical Analysis of Congenital Malformations of the Heart," to be published by the Commonwealth Fund.

ination shows a prominent pulmonary conus or when there are pulsations at the hili of the lungs. These pulsations should be looked for by careful fluoroscopic examination after one's eyes are fully accommodated.

Virtually the only malformation in which there is absence of the normal shadow cast by the pulmonary artery in the presence of adequate circulation to the lungs is complete transposition of the great vessels. In this condition the pulmonary artery lies behind the aorta; therefore, in the anteroposterior view there is a narrow aortic shadow and a concave curve at the base of the heart to the left of the sternum. In the left anterior oblique position the two vessels lie side by side; hence the shadow cast by the great vessels increases in width [20] and the pulmonary window is not abnormally clear. The condition does not cause pulsation at the hili of the lungs but frequently leads to congestion in the lung fields. These observations, together with evidence of relatively rapid progressive cardiac enlargement,[2] should aid in the establishment of the correct diagnosis.

The operation should be performed on the right or left side, depending on which vessel is to be used and on which side the aorta descends. Furthermore, it is important to bear in mind that the occurrence of a right aortic arch is by no means rare in congenital malformations of the heart which cause persistent cyanosis. Bedford and Parkinson [21] have shown that the determination of the course of the aorta is not difficult, provided fluoroscopy is carefully performed and the esophagus delineated with a barium opaque mixture. Normally the aortic knob is visible on the left, the esophagus lies in the midline and is indented by the aorta on the left margin, and in the right anterior oblique position the esophagus is seen to be slightly displaced backward by the aorta. In cases of a right aortic arch the aortic knob frequently is hidden within the shadow cast by the superior vena cava. In the anteroposterior view the esophagus is indented on the right and is displaced backward in the left anterior oblique position.

It remains to be seen whether these patients will develop heart failure. Even if this occurs, the intervening period appears to be one of great clinical improvement. It may well be that, if more patients with congenital malformations of the heart survive, more will develop subacute bacterial endocarditis. Certain it is that there is nothing in persistent cyanosis which renders an individual immune from subacute bacterial endocarditis. The condition is less frequently encountered in cyanotic persons only because a comparatively small number of patients survive long enough to be liable to contract the disease. The fear of subacute bacterial endocarditis in the future is no justification for allowing a patient to die of anoxemia in the present. Even the possibility of future cardiac failure does not weigh heavily against present extreme incapacity and the danger of early death from anoxemia or cerebral thrombosis.

SUMMARY

An operation for increasing the flow of blood through the lungs and thereby reducing the cyanosis in patients with congenital malformations of the heart consists in making an anastomosis between a branch of the aorta and one of the pulmonary arteries; in other words, the creation of an artificial ductus arteriosus. Thus far the procedure has been carried out on only 3 children, each of whom had a severe degree of anoxemia. Clinical evidence of improvement has been striking and includes a pronounced decrease in the intensity of the cyanosis, a decrease in dyspnea and an increase in tolerance to exercise. In the 2 cases in which such laboratory studies were performed there has been a decline in the red blood cell count, in the hemoglobin and in the hematocrit reading, an increase in the oxygen content of the arterial blood, a fall in the oxygen capacity, and most significantly a decided rise in the oxygen saturation of the arterial blood.

The types of abnormalities which should be benefited by this operation are the tetralogy of Fallot, pulmonary atresia with or without dextroposition of the aorta and with or without defective development of the right ventricle, a truncus arteriosus with bronchial arteries, and a single ventricle with a rudimentary outlet chamber in which the pulmonary artery is diminutive in size. The operation is indicated only when there is clinical and radiologic evidence of a decrease in the pulmonary blood flow. The operation is not indicated in cases of complete transposition of the great vessels or in the so-called "tetralogy of Fallot of the Eisenmenger type," and probably not in aortic atresia. It must be emphasized that the operation should not be performed when studies reveal a prominent pulmonary conus or pulsations at the hili of the lungs.

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20. Taussig, H. B.: Complete Transposition of the Great Vessels, Am. Heart J. **16**: 728-733, 1938.
21. Bedford, D. E., and Parkinson, J.: Right-Sided Aortic Arch, Brit. J. Radiol. **9**: 776-798, 1936.

-4-

ANESTHESIA IN THE SURGICAL TREATMENT OF CONGENITAL PULMONIC STENOSIS

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ANESTHESIA IN THE SURGICAL TREATMENT OF CONGENITAL PULMONIC STENOSIS * †

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IT is felt that anesthetists confronted with a similar problem might derive some comfort from an account of our experiences in administering anesthesia to 100 patients operated upon by Dr. Alfred Blalock for the relief of congenital pulmonary stenosis or atresia. One hundred and three anesthesias were given to the 100 patients. In 95 instances an anastomosis of the pulmonary artery was performed (twice in one patient—Case 1); in 7 instances the vessels were explored but no anastomosis was performed (in one, Case 33, an anastomosis was performed later); in one instance (Case 45) the operation was canceled owing to difficulties with anesthesia but the patient later underwent a successful operation. Twenty-three of the 100 patients died. The youngest patient was ten weeks old, the oldest twenty years.

Since Blalock and Taussig (1) have already discussed the operation and the patients and their abnormalities, we shall try to limit this description to those factors which influence the anesthesia and which are influenced by the anesthesia.

The condition for which these patients undergo operation is, essentially, an insufficient flow of blood through the lungs due to pulmonary stenosis or atresia associated with the other stigmata of the tetralogy of Fallot, with other congenital abnormalities, and with their sequelae. In most of the patients who have come for operation a compensatory polycythemia has developed, with often as much as twice the normal number of red blood cells and quantity of hemoglobin. There are marked changes in the oxygen and carbon dioxide content of the arte-

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rial blood. A typical analysis (Case 30) might show an oxygen content of 13.7 volumes per cent, an oxygen capacity of 29.0 volumes per cent, an oxygen saturation of 47.2 per cent, and a carbon dioxide content of 30.9 volumes per cent. The viscosity of the blood is considerably increased. This is believed to be one of the factors producing the relatively high incidence of cerebral thrombosis in these patients. Many of these patients have multiple organizing, organized and recanalized thrombi in the pulmonary arterial tree (2), a condition which, of course, further restricts the flow of blood to the pulmonary alveoli. Except for right axis deviation and, usually, prominent P waves, the majority show no evidence of intrinsic disease of the myocardium.

It is obvious, however, that most of these patients have a small cardiac reserve. In fact, 4 patients died while awaiting operation; 3 in the hospital and 1 at home. In 2 of these the diagnosis was verified at necropsy; in 2 necropsy was not done. Several patients died en route to the hospital. Of these, one can only say that they were cyanotic and were thought by their doctors to have congenital malformation of the heart. The physical activity of these patients is usually extremely limited—many of them collapse after walking 20 yards or so.* Some were children four or five years old who never had been vigorous enough to learn to walk. Their ability to meet an increased demand for oxygen is so reduced that a tantrum or even slight exertion almost always causes pronounced dyspnea and cyanosis and may be sufficient to produce unconsciousness and sometimes convulsions. The care and attention which must necessarily be bestowed on those who survive infancy seems to make many of these children exacting, impatient, and intolerant of any treatment outside their normal experience.

PREOPERATIVE CONSIDERATIONS

The psychic factors just mentioned make it doubly important for the anesthetist to try to gain the patient's confidence before the induction of anesthesia. This task is facilitated by ample notice of the intention to operate and by the fact that the anesthetist's preoperative visits need not be associated with unpleasant experiences for the patient. On one preoperative visit an anesthesia face mask may profitably be employed as a toy so that the patient will not regard it as entirely foreign when confronted with the mask in the anesthesia room.

The preanesthetic medication has usually been morphine and atropine, given ninety minutes before the beginning of anesthesia, although on occasion nembutal instead of morphine has been used, or scopolamine instead of atropine. We like to have the patients so depressed that, if undisturbed, they will fall asleep. Only twice has it been felt that respiratory depression due to morphine might have delayed the

* According to the anesthesia code of The American Society of Anesthesiologists, the physical status of all of these patients would be classed as Group 3 and many of them would be in Group 4. Similarly, all of them would be in Group 3 and many of them in Group 4 as regards the functional capacity of the heart.

induction of anesthesia. In some of the less cyanotic patients the cyanosis on arrival in the anesthesia room has appeared to be less than on the ward, an affect which may be the result of the decreased demand for oxygen owing to depression of psychic and metabolic activity.

The unfortunate results of fear and excitement in these patients soon led us to abandon the practice of inserting a venous cannula into a conscious patient just before anesthesia. Venous cannulation and other painful or disturbing procedures are now done after the induction of anesthesia.

SURGICAL CONSIDERATIONS

The operation consists in making what amounts to an artificial ductus arteriosus by anastomosing one of the arteries arising from the arch of the aorta to one of the main divisions of the pulmonary artery. Usually the central end of the systemic artery is anastomosed to the side of the pulmonary artery so that both lungs will receive an increased flow of blood. On ten occasions anatomical relationships have made it necessary to perform an end-to-end anastomosis, with the result that the increased flow of blood is directed to only the one lung.

In brief, the operative procedure involves: (1) opening one pleural cavity and the mediastinal cavity; (2) exploration (sometimes prolonged and often rather vigorous) of the great vessels and the structures nearby; (3) ligation and division of either the innominate, the subclavian, or the carotid artery; (4) occlusion of the pulmonary artery to the exposed lung for the length of time required to perform the anastomosis; (5) opening the anastomosis and thus increasing the flow in the pulmonary vessels and the work of the left side of the heart.

It is obvious that at best an already precarious situation is not improved by collapsing a considerable part of one lung, by diminishing the blood supply to this lung for a period of twenty to ninety minutes, or by diminishing the supply of blood to the brain when the innominate or carotid artery is selected for anastomosis. Even when the subclavian is selected, it is sometimes necessary to occlude the innominate or carotid artery while the anastomosis is being performed. Most of these patients seem to tolerate the partial collapse of one lung fairly well. Serious trouble, if it comes, more often starts when the anastomosis is begun, although not infrequently the exploration, or even just the opening of the pleural cavity, has been sufficient to weaken the action of the heart. The complications which have occurred will be discussed in more detail later in this paper.

The very delicate job of making the anastomosis is facilitated by a relative lack of movement in the operative field. Although the anastomosis has been successfully completed on those occasions when we have been unable to provide it, we feel that most surgeons will require a quiet operative field. It has been noticeable, however, that as the surgeon's skill increases, he is less handicapped by moderate movement of the mediastinum.

CHOICE OF ANESTHETIC AGENT AND TECHNIC

One cannot be dogmatic in regard to these matters because the factors involved vary so much from one institution to another. In addition, since we were fortunate enough to have a fair degree of success with our first choices, we have not been inclined to experiment with other agents and technics.

For induction, cyclopropane is usually chosen because it permits a rapid smooth induction and a high oxygen tension. Vinethene and nitrous oxide have also been successfully used.

For maintenance with the closed to-and-fro absorption technic, cyclopropane has been used alone 56 times and ether alone 15 times. With 32 patients a moderate amount of ether has been added to the cyclopropane throughout the greater part of the procedure. Since we find it very much easier to provide a quiet operative field with cyclopropane, we are more likely to use that agent. In the majority of the earlier cases with cyclopropane the technic of "controlled respiration" was used; lately this technic has been used less frequently. We have rarely been successful in obtaining true control of respiration when using ether, but we can usually produce satisfactory operating conditions with ether by applying positive pressure to the breathing bag a half a second or so before the patient is going to inspire. With this technic the movements of the diaphragm are not inhibited, but apparently the fact that the lung is expanded just before the diaphragm descends serves to reduce greatly the usual mediastinal movement. On 19 occasions when it has been difficult to control the movement of the mediastinum, morphine has been administered intravenously in doses of 1 or 2 mg.* We prefer this method to that of using larger quantities of a general anesthetic agent. On one occasion the phrenic nerve was accidentally crushed, with the result that it was extremely easy to keep the operative field quiet. We have not resorted to procaine block of the phrenic nerve, but it might be a useful procedure in some of these cases.

We have found that the maintenance of positive pressure in the respiratory tract during both expiration and inspiration does not produce a sufficiently quiet field. The use of "controlled respiration" or of pressure on the breathing bag during the inspiratory phase of respiration better serves to maintain adequate tidal exchange and to relieve the patient of some of the muscular effort of breathing, factors which are of some importance. Whenever possible, therefore, intermittent positive pressure is used during the time the thoracic cavity is open, even though the mediastinal movement may not require it; in only 4 anesthesias was this not done.†

Although 6 cases have been done without the insertion of an endotracheal tube, we much prefer to use a tube. We were handicapped at

* Three times with ether, 10 times with cyclopropane (in 3 of these controlled respirations were used), and 6 times when both agents were being used together.

† Controlled respiration was used in 28 anesthesias, assisted respiration in 71.

first by lack of suitable tubes for infants. A Rovenstine connector, usually curved, joins the tube to the canister adapter. Possibly special connectors or other technics might further reduce dead space, although changes in respiration, pulse, and blood pressure have provided scant evidence of accumulation of carbon dioxide. This is not to say, of course, that such accumulation does not occur and might not be responsible for some of the complications. We have never tried a circle filter for carbon dioxide absorption in these cases.

We recently tried the T-tube technic of Ayre (3) on one infant in this series. Although there is probably less chance for the accumulation of carbon dioxide with this technic, in our hands the depth of anesthesia, especially with cyclopropane, has varied considerably and we have felt that we had less control of the respiration in this patient as well as in other patients in whom we have tried the technic. Those more experienced with this technic may find it satisfactory for these patients.

The endotracheal tubes always fit tightly enough without cuff or pack so that at the pressures employed there is no appreciable leak. For all of the cases when the closed technic was used a Foregger apparatus equipped with their water manometer has been employed. The tubing to the manometer leads off directly distal to the delivery outlet on the machine. The manometer is usually set to blow off at 8 to 12 cm. of water pressure, although on occasion it has been set as high as 16 cm.* We have not ascertained what pressure this produces in the respiratory tract. The manometer is used as a safety valve and as a rough guide to pressure, but one's eyes and sensitivity of hand are, we feel, a safer guide than any mechanical device available at present.

When an endotracheal tube is not inserted we still try to use a closed method, employing as small masks as we can find and a narrow-bore Foregger elbow to the canister. In only 1 case has the closed method not been used. When forced to use a mask the problem of dead space is a constant worry. It is hoped that someone in the future will devise a circle absorber incorporating a blower to circulate the air so that there will be no dead space in the apparatus.

COURSE OF THE ANESTHESIA AND COMPLICATIONS

Although in some of the patients the induction of anesthesia has been unusually slow or has required what seems to be an unusually large amount of anesthetic agent, in most of the children the induction proceeds at normal speed.

There is no hesitation in postponing the operation if there are any serious complications during the induction or if the patient does not react normally to the anesthetic agent. One patient, not included in this series of 100 patients (Unit No. A–44805), a boy one year old, ex-

* Average of 85 cases was 11 cm.

hibited what appeared to be acute bronchiolar constriction after a few minutes of cyclopropane. The operation was not attempted. A week later, shortly after the beginning of vinethene-ether anesthesia, this patient again showed signs of respiratory obstruction below the glottis. Although the obstruction was less severe than with cyclopropane, the operation was canceled. It is planned to try again with ether. Although we know of no deaths which have been attributed to the bronchiolar constrictive effect of cyclopropane, we fear that such a complication may prove serious in these patients. Two other patients whose operations were postponed are described.

Case 45.—This patient, an exceedingly apprehensive girl of 7 years, had a dextrocardia as well as stenosis of the pulmonary artery. The preanesthetic medication of morphine and atropine had a satisfactory effect. After cyclopropane had been administered for about one minute the patient stopped breathing, with the chest held in the inspiratory position. After a minute or two of artificial respiration the patient's trachea was easily intubated. The breathing was still abnormal. After some minutes it was discovered that the endotracheal tube was kinked in the pharynx. The patient was given ether, the cyclopropane was discontinued, and the tube removed. Throughout the whole procedure the respiration continued to be irregular, slightly gasping in character, and there was a tendency to inspiratory spasm.

Thirty minutes after the beginning of the anesthesia the trachea was reintubated. Within five minutes the pulse rose to 210 and then to 250, and was quite regular in rhythm. She was thought to have auricular flutter. The administration of ether was discontinued and the operation canceled. No incision had been made. The rapid cardiac rate continued for thirty minutes. Then, for no apparent reason, the respirations became almost normal and the heart rate slowed to 120, which had been the rate before anesthesia. The patient recovered consciousness.

Two and a half months later a successful anastomosis was performed. Nitrous oxide was used for induction and ether for maintenance. The anesthesia time was three hours. During the exploration of the great vessels the respiration was irregular and the pulse weak and very rapid. A rest of four minutes during this forty minute exploration appeared to be beneficial. Between the end of the exploration and the beginning of the anastomosis there was a period of ten minutes when the heart action was almost normal. But the pulse again became weak when traction was applied to the pulmonary artery during the anastomosis. Electrocardiograms taken throughout the procedure showed a variety of abnormalties, including auricular flutter which lasted twenty minutes.*

The postoperative course was uncomplicated save for slight hemothorax and pneumothorax requiring one thoracentesis.

Case 33.—This patient, aged 2 years, successfully survived two operative procedures. Unlike most of the other patients, he had hypochromic microcytic ane-

* Lead II was used. Early in induction there was a shift of the pace maker and inversion of the P waves. During exploration of the great vessels a two to one block occurred and there was auricular flutter at a rate of 180. During anastomosis there was a marked increase in the height of the P waves, the QRS complex was notched, and there was evidence of intraventricular block. After the anastomosis was opened the P waves reverted to normal size, and there was a marked lowering of the voltage which was still present at the end of operation.

mia and only 10 Gm. of hemoglobin. The first attempt at anastomosis was abandoned thirty minutes after incision because soon after the pleural cavity was opened the heart action became very weak and was not appreciably improved by the administration of coramine. The anesthetic agent used was cyclopropane.

Thirteen days later an anastomosis was successfully performed. Cyclopropane was used for the induction and ether for the maintenance of anesthesia. The heart action became very weak and the rate slow, especially during traction on the great vessels. One-half cubic centimeter of coramine was administred intravenously three times, with apparently beneficial effect. The respirations, when unassisted, were gasping in character while the anastomosis was being performed. Postoperatively the child did well.

It will be noted that these patients had apparently the same complications during the second operation as had been present on the first attempt, even though a different anesthetic agent was used the second time, an observation which suggests that the cause of the complications was the anesthetic technic, the operative procedure, or the patient's condition rather than the anesthetic agent. Until considerably more is known about these patients and their reaction to anesthesia it would appear to be good judgment to postpone operation, if possible, whenever serious complications arise and persist during the first attempt.

It would probably have been better judgment to have postponed the anastomosis in the following patients.

Case 22.—This colored boy, aged 4½ years, had been having repeated attacks of convulsions and unconsciousness, but he had no hemiplegia. Nembutal and atropine were given for premedication. Cyclopropane was used for the induction of anesthesia, ether for maintenance. Before the pleural cavity was entered and about thirty minutes after the beginning of anesthesia, at a time when the anesthetic agent was chiefly ether, the pulse became weak and then could not be felt. Since we thought that the level of anesthesia was unnecessarily deep at this time, the breathing bag was emptied and refilled with oxygen. In the meantime the pleural cavity was opened and coramine injected into the heart. The heart promptly recovered and gave no further cause for alarm. It must be noted, however, that before recovery, the pulse rate and blood pressure could not be obtained for more than five minutes. The operation was an end-to-end anastomosis of the subclavian and superior pulmonary arteries on the right. The patient failed to recover consciousness and died within twenty-six hours. At necropsy there was hemothorax (650 cc. clotted blood) and massive atelectasis on the right, and partial atelectasis on the left. Some evidence of pulmonary edema was present on the left.

Even if these pulmonary complications had not occurred, death would probably have ensued because of irreversible damage to the brain caused by hypoxia, which probably was present during the period of cardiac weakness described, and which may have been aggravated by mild hypoxia during the seventy minutes required to perform the anastomosis.

Case 10.—This child, aged 4 years, had had a recent upper respiratory infection. The anesthesia was cyclopropane. After the right pleural cavity was opened the breathing became very labored, with short expiration, and so continued. The respiratory rate did not rise above 36 per minute. Both pulse and

blood pressure rose moderately during the operation. The respiration was so labored that it was thought there must be some obstruction, although none could be demonstrated in the endotracheal tube and its connections. We were not successful in quieting the movement of the mediastinum. At the end of the operation the respirations were irregular and gasping, and the pharyngeal reflexes were still obtunded. The innominate artery was used for the anastomosis.

It was thought that the rise in pulse and blood pressure and the labored respiration were probably not the result of an accumulation of carbon dioxide because (1) these changes did not occur until the patient had been anesthetized for forty-five minutes, (2) they were coincident with the opening of the pleural cavity, and (3) many patients of similar size or smaller have been anesthetized by the same technic and with the same apparatus without showing similar evidence of excess carbon dioxide.

The patient never regained consciousness. There was considerable mucus in the respiratory passages. Twelve hours after operation spasticity developed on the right side, the Babinski reflex was positive and convulsions occurred. He died fourteen hours after operation.

It was believed that during the operation there had been sufficient hypoxia of the brain to cause permanent damage, and that in addition after operation there may have been a cerebral thrombosis. At necropsy, among other things, patchy pulmonary edema, fluid in the right pleural cavity, and hyaline vegetations and valvulitis of the mitral and tricuspid valves were found. Many alveoli contained blood.

In the following two cases it was impossible to postpone the operation because the anastomosis had been started before the serious complications arose.

Case 19.—This boy, aged 5 years, weighed only 10 Kg., although he was 3 feet in height. The premedication of morphine, 2.0 mg., and atropine, 0.1 mg., given ninety minutes before anesthesia had not depressed the patient. The induction, however, was satisfactory though slow. The child's color did not seem to improve with the inhalation of oxygen. His respiratory center appeared to be unduly depressed by cyclopropane, which was used throughout. For ninety minutes (fifty minutes of operation) his condition appeared to be satisfactory. About five minutes after the pulmonary artery had been occluded the blood pressure and pulse pressure began to fall. Within twenty minutes it had fallen from 90 mm. to 65 mm. systolic and from 70 mm. to 55 mm. diastolic. At this time the heart action suddenly became weak and slow, and then stopped, along with voluntary respiratory effort. The pupils now became dilated and remained dilated.

The respirations had been assisted throughout the procedure, although controlled respirations had not been instituted. Beginning ten minutes before the heart stopped, the breathing bag had been emptied and refilled with oxygen several times. Artificial respiration with oxygen was carried out. Cardiac massage was begun but could not be very effective owing to the necessity of completing the anastomosis which had been started twenty-five minutes before the heart stopped. Coramine was injected without apparent effect. The completion of the anastomosis (subclavian, end-to-side) required another thirty minutes. Then 1.5 cc. of epinephrine was injected into the heart. The heart immediately resumed activity at 140 beats a minute, 10 or 20 beats faster than the rate during the early part of the operation. The heart action improved over the next 10

minutes and a fairly good pulse could be palpated in the neck, but no pulse could be felt at the wrist and it was impossible to obtain the blood pressure. Thirty minutes after the injection of epinephrine the patient made some irregular, gasping efforts at respiration, altogether six gasps in ten minutes. These ceased, the heart action became weaker and irregular and finally stopped.

It was assumed that the patient could not tolerate the traction on the pulmonary artery. At necropsy the diagnosis of tetralogy of Fallot was confirmed, and in addition there was patchy atelectasis on both sides.

Case 17.—This patient was aged 21 months. The anesthesia (cyclopropane) and operation proceeded satisfactorily until soon after the pleural cavity was opened, when cyanosis increased noticeably. Clamping of the innominate artery was accompanied by a sharp and sustained rise in the pulse rate. After the pulmonary artery was occluded, a little over an hour from the beginning of anesthesia, the respirations became slower and so shallow and labored that it was thought obstruction was present, although removal and inspection of the endotracheal tube revealed no upper respiratory obstruction. The respirations continued to be labored and the rate to fall. The blood pressure began to fall and the pulse rate increased. Two hours after the beginning of anesthesia the heart stopped beating and voluntary respirations ceased. There was no evidence of fibrillation of the heart. Artificial respiration and cardiac massage for less than two minutes were sufficient to restore cardiac and respiratory activity. At about this time it was discovered that the blood being used for transfusion had become laked by dilution with distilled water. The innominate artery was anastomosed to the right pulmonary artery.

The patient did not recover consciousness. The following day, in the afternoon, the respiratory movements, which had continued to be labored, appeared to resemble movements seen in respiratory obstruction. Cursory laryngoscopy revealed in the trachea just below the vocal cords a brown, crusty substance which seemed to obstruct the posterior half of the trachea. Since it was thought that the child could not long endure such labored respiration, it was decided to intubate the trachea and try to suck out the material, and to perform a tracheotomy as a precautionary measure. Some brownish material was removed from the trachea, with no improvement in the respiration. During the tracheotomy the circulation and respiration failed and resuscitative measures were unsuccessful. Death occurred thirty hours after operation.

No abnormalities of the respiratory passages could be found on bronchoscopic examination immediately after death. At necropsy the findings were: a thrombus in the anastomosis, thrombi in the left ventricle, transposition of the aorta and pulmonary arteries, pulmonary stenosis, and other congenital abnormalities, pulmonary edema and hemorrhage, purulent bronchitis with necrosis of bronchial epithelium, some atelectasis, focal necrosis of the tubular epithelium of the kidney, and so on.

The part played by the anesthesia in this case is not clear. There may have been sufficient cerebral hypoxia during the operation to cause permanent damage to the brain.

A weakening of the cardiac action appears to be the commonest serious complication with either ether or cyclopropane (fig. 1). This complication occurred 5 times with ether, 19 times with cyclopropane, and 15 times when both agents were used together. This complication was

encountered in 42 per cent of the patients in whom the operation was on the right side, and in 24 per cent of the patients in whom the operation was on the left side. In 2 instances this complication occurred before the pleural cavity was opened; in 18 instances it occurred as soon as the pleural cavity was opened, although in only 3 of these cases did the weakness persist. In 8 cases the weakness came on during the exploration of the great vessels, and in 2 of these the weakness continued. In 11 patients there was weakening of the pulse only during the anastomosis which is, we believe, the most dangerous period, especially in those patients with a greater degree of pulmonary stenosis and physical disability. Fourteen of these 39 patients subsequently died. Whenever this complication occurs, the operation is interrupted if possible, the retractor holding the ribs apart is released, and the

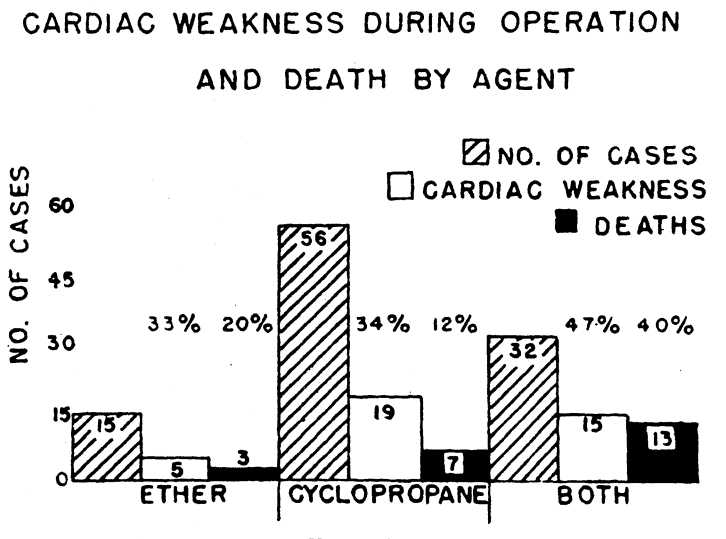

FIGURE 1

lungs are reinflated. In 2 of these patients it was thought that the traction on the pulmonary artery had been sufficient partially to occlude the pulmonary artery to the opposite lung. This complication, if it exists, could presumably be tolerated only by those patients in whom considerable collateral circulation to the lung has developed.

Coramine has been injected into the heart or superior vena cava of 11 patients; in 4 instances we felt this drug had been beneficial, in 4 instances no effect was apparent, and in 3 cases the effect was doubtful.

On the assumption that the vagus nerve may be implicated in the slowing of the heart, in 9 patients the surgeons have recently injected 0.5 per cent procaine around the exposed vagus nerve at the most distal point easily accessible to them. This injection has been made as soon

as convenient after opening the pleural cavity, but no injection is made when the heart is beating at a rate faster than the rate before induction of anesthesia. In 5 cases the injection was followed by tachycardia; in 4 cases there was no effect. Although in those cases in which injection has been done there has been no slowing of the heart, we have not yet had enough experience to say whether the procedure is beneficial. It seems likely that in the future such injections will not be made unless the heart shows definite signs of slowing. Perhaps the intravenous administration of a small amount of atropine might prove more efficacious than the injection of procaine into one vagus nerve.

The pulse rate varies considerably. In 34 patients the pulse was faster than the patient's normal rate (by at least 15 beats per minute) and slower in 16 patients. There seemed to be no significant difference according to the agent used (table 1). The blood pressure also varies in no consistent fashion; in 24 patients it was 10 mm. or more higher than the patient's normal; in 17 patients it was lower than normal (table 1). The pulse pressure is usually reduced and has frequently been as little as 10 mm. of mercury.

TABLE 1

RELATIONSHIP OF PULSE RATE AND BLOOD PRESSURE TO ANESTHETIC AGENT

	Ether	Cyclopropane	Both
Tachycardia	7	12	15
Bradycardia	2	9	5
Hypertension	4	15	5
Hypotension	5	5	7

Minor cardiac arrhythmias, usually transient, have been noted in 12 anesthesias (11 patients). Five of the patients were receiving ether, 4 cyclopropane, and 3 were receiving both agents. Although 1 of the latter and 1 of the patients receiving cyclopropane subsequently died, it was not believed that the arrhythmias had contributed to the death.

Respiratory complications during operation have not been very frequent. The respiratory rate is more likely to be increased above normal (75 cases) than decreased (16 cases). In 18 instances there was temporary obstruction to respiration, occurring 3 times before the pleural cavity was opened, 7 times during exploration, and 8 times during the anastomosis. In 5 instances (once with cyclopropane and 4 times when both agents were used together) it was thought that bronchiolar constriction might have been present. On three or four occasions the patient has held the respiratory muscles in the inspiratory or expiratory phase of respiration. Traction on the pulmonary artery has seemed to initiate the obstruction several times. In none of the 18 instances has the obstruction appeared to be in the upper respiratory passages. The side on which the operation is performed does not seem to influence the incidence of such complications.

Another complication during operation which might be related to the anesthesia is a temporary deepening of the cyanosis which has oc-

curred at various stages of the operation after opening the pleural cavity in 38 patients, 11 of whom subsequently died. The agents used in these patient were; ether, 6 times; cyclopropane, 25 times, and both agents together, 7 times. Although one is always disturbed by this phenomenon, operation has never been postponed on its account alone.

With those patients who present none of these complications the anesthesia usually proceeds smoothly and there are few changes in pulse, blood pressure and respiration. Not infrequently when the anastomosis is opened there is a fairly sharp fall in both the systolic and diastolic pressure, with an increase in pulse pressure and pulse rate. The pressure usually rises again within fifteen minutes. The tachycardia may persist for hours or days. The respiration is always at least assisted during the time the pleural cavity is open. When the surgeons begin to close the chest wall it has become customary to cease the application of positive pressure on inspiration only and to distend the breathing bag so that there is applied constantly a somewhat lower positive pressure than that used during most of the procedure. In addition, the end of a rubber catheter is left within the pleural cavity and when the closure is air tight the surgeons aspirate air from the pleural cavity by means of this catheter which is then withdrawn. In no patient has the suction catheter been left in the pleural cavity beyond the end of the operation. During the closure the high concentration of oxygen in the inspired gases is gradually reduced to that in room air, usually by the addition of nitrous oxide or, at the end, of helium. At the end of the operation the color of most of the patients on whom an anastomosis is performed is better than it was before the anesthesia was started. The majority of the patients are conscious enough to cry or even to obey simple commands before they leave the operating room. Those patients who have not recovered consciousness within two hours after operation have usually died within a day or two.

POSTOPERATIVE COURSE AND COMPLICATIONS

We believe that the immediate benefit received from a successful anastomosis is one important reason why so many of these children do so well after operation. There have been 7 cases in which the surgeons, after thorough exploration, decided not to attempt an anastomosis because of lack of suitable vessels or other reason. One of these patients (Case 28) had no serious complications during the operation. He recovered consciousness, only to die twenty hours after operation. His blood pressure fell, the pulse rate became very rapid and the respirations labored. Death may have been due to cardiac failure. The necropsy findings confirmed the diagnosis of pulmonary stenosis and were not incompatible with death due to heart failure. There was a patent interventricular septum, cardiac hypertrophy and dilatation, especially on the right, and there were thrombi in many branches of the pulmonary artery. Some of the collateral circulation had apparently been de-

stroyed at operation. Another patient (Case 66), a woman 20 years old, whose heart action had been very weak during the exploration of the great vessels, had bleeding into the pleural cavity. Thirty minutes after operation half a liter of blood was removed from the pleural cavity. The patient did not respond and her neck was stiff. She died two hours after operation. At necropsy the right pleural cavity was found to be filled with blood (about 1 liter) and the lung on this side was completely collapsed. There was also partial atelectasis of the opposite lung. The other 5 patients in this group recovered well from the operation. One of them had a successful anastomosis later.

It is obvious that a successful anastomosis when permitted to function will immediately increase the flow in the pulmonary vessels and the work of the left side of the heart. It is surprising that these changes have not more frequently caused pulmonary edema and heart failure. In only 2 cases has pulmonary edema occurred immediately. Both of these patients died quickly in spite of treatment with oxygen under pressure and phlebotomy. The first patient (Case 61) had had a recent infection of the upper respiratory tract. An unusually large amount of secretion was aspirated from the tracheobronchial tree during operation. The end of the right subclavian was anastomosed to the end of the superior branch of the pulmonary artery. At the conclusion of the operation she appeared to be recovering consciousness; she was moving about and swallowing. Pulmonary edema quickly developed and she died within forty minutes. At necropsy she was found also to have bled into the right upper lobe of the lung. The other patient (Case 83) exhibited some weakness of cardiac action during the operation. Unfortunately, the anastomosis was made by mistake to the right superior pulmonary vein. Pulmonary edema came on soon after the anastomosis was opened. The patient died fifty minutes later. At necropsy there was found, in addition, dilatation of the right auricle and a hemorrhagic infarct of the right upper lobe.

Pulmonary edema, almost always accompanied by signs of cardiac failure, has developed in a number of patients from one to twenty days after operation. The administration of digitalis has usually been of benefit. Five of these patients died, but in each of these cases the pulmonary edema appeared shortly before death and was not considered to be the sole cause of death. These patients will be discussed later.

Another possible complication resulting from the alteration in hemodynamics is bleeding from or into the lungs. One patient (Case 42) who seemed to be doing quite well suddenly coughed up a large quantity of blood on the fifth day after operation and promptly died. It was thought that she had died of an intrapulmonary hemorrhage. She had been receiving dicoumarol, and this drug, rather than the alteration in hemodynamics, may have caused the bleeding. At necropsy, an acute fibrinopurulent pericarditis with 150 cc. of fluid in the pericardial cavity, right hemothorax, the tracheobronchial tree filled with blood and

mucus, blood in the ileum and colon were found. There were also shallow ulcers of the laryngeal mucosa. A cuffed endotracheal tube had been used in this patient (and in no others), but the cuff had not been inflated. One other patient who apparently died of other causes was found at necropsy to have hemorrhagic foci in the lungs.

Sixteen patients have shown signs of interference with the flow of blood to the brain after operation. With the exception of one patient who exhibited symptoms at the end of operation, it is assumed that cerebral thrombosis has been the cause in each case. The symptoms have become apparent from seven hours to a few days after operation. Seven of the patients had symptoms within twelve hours, 3 within two days, 2 within four days, and the rest later. Six of the 16 patients died. It is difficult to correlate the occurrence of cerebral thrombosis with factors under the anesthetist's control. For example, only 3 of the 16 patients had low blood pressure during operation, 1 had hypertension, and 12 had neither. Of the 3 who had a relatively low blood pressure during operation, 2 showed signs of cerebral thrombosis within twelve hours. The age distribution of these patients is similar to that for the entire series. The incidence of convulsions before operation appears to bear no relation to cerebral thrombosis after operation. The type of surgical procedure seems to bear a fairly consistent relation to the incidence of cerebral thrombosis. Of the 16 patients, 11 had an innominate anastomosis, 1 a carotid, and in 4 the subclavian artery was used, but in 1 of these 4 the carotid was ligated and in another the carotid and innominate were occluded for thirty minutes. Fourteen of the 16, therefore, had some interference with the carotid or innominate arteries.

In an effort to avoid thrombosis, 28 of the earlier patients received dicoumarol. Four patients received both dicoumarol and heparin. The use of dicoumarol has been abandoned. Heparin is now given at the first sign of thrombosis and occasionally in the absence of any such signs. A total of 23 patients have received heparin.

Digitalis in one form or another has been administered to 22 patients in whom heart failure was thought to be developing.

The blood pressure after operation was followed fairly closely in most of these patients. Immediate and transient (one-half to two hours) hypotension has been observed in 7 patients, in whom there was no hemorrhage to account for the hypotension. Two of these patients had received ether, 1 cyclopropane, and in 4 patients both agents were used. In none of these patients did cerebral thrombosis develop later.

A recent paper by Dripps (4) suggested that a fall in blood pressure immediately after anesthesia with cyclopropane may be due in part to retention of carbon dioxide during anesthesia. We have not been able to investigate this point specifically but we have analyses (Van Slyke technic) of the arterial blood gases of 8 patients who received cyclopropane. As compared to the resting unanesthetized values, after ten or twenty minutes of anesthesia the oxygen content, oxygen saturation,

and carbon dioxide content rose and the oxygen capacity fell. From six to twenty minutes after the end of operation the oxygen content and saturation and carbon dioxide content were less than during anesthesia but still higher than before anesthesia, and the oxygen capacity was lower than during anesthesia (table 2). It is thought that the con-

TABLE 2
CHANGE FROM RESTING VALUES

	Content, vol. per cent	Oxygen Capacity, vols. per cent	Saturation, per cent	Carbon Dioxide Content, vols. per cent
After 10–20 minutes of anesthesia	+6.9	−1.2	+36	+5.4
6–12 minutes after end of operation, breathing room air	+3.4	−2.8	+23	+4.2

siderable rise in oxygen saturation which accompanies the administration of an anesthetic atmosphere rich in oxygen is an important factor in the ability of the patients to withstand operation.

Half of the patients have had evidence of the accumulation of fluid (usually bloody) in the pleural cavity after operation. Thoracenteses were performed in 33 of these 48 patients. In 4 of these patients fluid was recorded as being present also in the opposite pleural cavity. Of the 33 patients who had thoracenteses, 11 had air as well as fluid in the pleural cavity.

Tension pneumothorax has occurred 5 times (after each of two operations in 1 patient). Three of the five complications were followed by death. These cases have been of some concern because of the possibility that the positive pressure used during anesthesia may have produced pulmonary interstitial emphysema, pneumomediastinum, and the other sequelae studied by Macklin (5). We have tried always to use only moderate degrees of pressure, but undoubtedly when the situation has been strained we have used more pressure than we realized. It is hard not to try to overcome an apparent respiratory obstruction when the patient's respiration and circulation are failing. Such a situation presented itself in the very first of this series of cases:

Case 1.—(This is Case 1 in Blalock and Taussig's original paper (1).) This emaciated underdeveloped infant, aged 15 months, weighed 4 Kg. If not kept in an oxygen-enriched atmosphere she would become unresponsive. It was our inexperienced opinion that she would not survive any extensive operative procedure, especially an untried operation of this sort.

The anesthetic was open ether. At that time we felt that the closed methods of anesthesia were unsuitable for infants, an illusion which was dispelled by Miss Elizabeth Lank of the Children's Hospital, Boston. When the left pulmonary and subclavian arteries were clamped, the pulse slowed and became almost imperceptible, the respirations became slower and shallower, and the patient's normal

cyanosis deepened. For a time the patient appeared to have an obstructed airway and an attempt was made to force oxygen into the lungs.

The postoperative course was unsatisfactory. Pneumothorax was apparent on the left side about thirty hours after operation, on the right about sixty hours after operation. A number of thoracenteses on the left and one on the right seemed to bring the situation under control. After an interval of three days without thoracentesis, bilateral tension pneumothorax was observed. It responded gradually to treatment by suction. The patient was discharged improved, and the improvement was maintained for a few months.

Eight months after the first operation, an anastomosis was done on the opposite (the right) side. The patient at this time weighed 5.2 Kg. The anesthetic was cyclopropane by the to-and-fro absorption method. The pulse rate during most of this operation was around 160, whereas it averaged 100 during the first operation. During the procedure a small hole was made in the visceral pleura. The patient's condition at the end of operation seemed fairly satisfactory.

Nine hours after operation subcutaneous emphysema was noticed. On the following day, before any thoracentesis had been performed, signs of tension pneumothorax were apparent on the right. The removal of the entrapped air revived her, but in spite of repeated thoracenteses the patient had more and more difficulty in breathing. She became unresponsive the day after operation and she died on the fifth day.

In another of these patients (Case 39) bilateral hemothorax developed twenty hours after operation and pneumothorax on the side of operation. Tension pneumothorax was noted on this side sometime after the first thoracentesis. A roentgenogram taken about this time showed subcutaneous and mediastinal emphysema as well as pneumothorax. In spite of treatment the patient fell into a coma and died eight hours later, about thirty hours after operation. There was some pulmonary edema at the end. At necropsy there was a question of a perforation in the left upper lobe. Some atelectasis was present on the left. There was also a thrombus in the anastomosis.

In a somewhat similar case (Case 9) fluid accumulated on both sides twelve hours after operation. The fluid was removed by thoracenteses. Eight hours later fluid had reaccumulated on both sides and, in addition, air under tension was found on the side opposite the operative site. The patient did not respond to treatment and died four hours later, twenty-four hours after operation. At necropsy, bloody fluid was found in both pleural cavities; patchy atelectasis bilaterally, and some pulmonary edema, mostly on the right, were present. There were needle punctures of the left lower lobe, and a small thrombus in the anastomosis.

Tension pneumothorax developed in one patient (Case 76) on the operative side following treatment for hemothorax and pneumothorax. Although he also had many other complications, he survived. In this patient and in one other the symptoms of tension pneumothorax seemed to coincide with the formation of a cerebral thrombosis.

In all of these instances there was the possibility that the preceding thoracentesis or surgical trauma at operation had caused the tension pneumothorax.

Four other patients had signs suggestive of pulmonary interstitial emphysema and its sequelae. In Cases 46 and 97 there was subcutane-

ous emphysema, in the former case associated with a sudden increase of pulse rate. In Case 44 five days after operation pneumothorax developed on the side opposite the surgical incision. Air in the mediastinum and what was called a pleuropericardial friction rub were present. Case 53 showed a pericardial friction rub on the second day after operation. In this patient the pericardium had been opened at operation. We suspect that if lateral roentgenograms had been taken routinely pneumomediastinum would have been diagnosed more frequently.

It is true that pulmonary interstitial emphysema may occur in an apparently normal person on the slightest provocation (6), and that the positive pressures used during anesthesia were considerably lower than those produced by coughing. It should also be noted that in almost every one of these operations the surgeon has found it necessary to incise the mediastinal pleura. In addition, Macklin stated that pulmonary interstitial emphysema may follow the rupture of an alveolus and the establishment of a pressure gradient from alveolus to vascular sheath, and that this may be accomplished either by overinflation of an alveolus without a corresponding increase in the vascular lumen or by a narrowing of the vessel's caliber without a corresponding diminution of the outer vascular sheath. This latter condition might well be present in these patients with pulmonary stenosis, for we know (2) that the lumen of many of the pulmonary arterial vessels is diminished by the formation and recanalization of thrombi. Nevertheless, it is difficult to escape the conclusion that the positive pressure used by the anesthetist may have been at least partly responsible for the development of this distressing complication. Whatever the final answer, we shall continue to use positive pressure, as little as possible, but we shall still use it because we feel that the danger of developing pulmonic interstitial emphysema after operation is less than the danger of having the patient die during operation because of insufficient tidal exchange.

Six patients were thought to have signs of pneumonia after operation in spite of the fact that almost all of these patients received penicillin before and after operation. In only one instance did this prove to be a serious complication and this was the only case of pneumonia that developed in any of the 18 patients who had had recent infections of the upper respiratory tract. These children seem to have very stubborn upper respiratory tract infections. The operation has been performed several times on patients with active infections of the upper respiratory tract because it was feared that the patients might die if the operation was longer postponed.

DEATHS

Twenty-three of the 100 patients died. The mortality rate was lower in those patients between 6 and 10 years of age (fig. 2). Two of the 3 patients more than 15 years old died. The duration of the operation appeared to have no influence on the mortality rate. A larger pro-

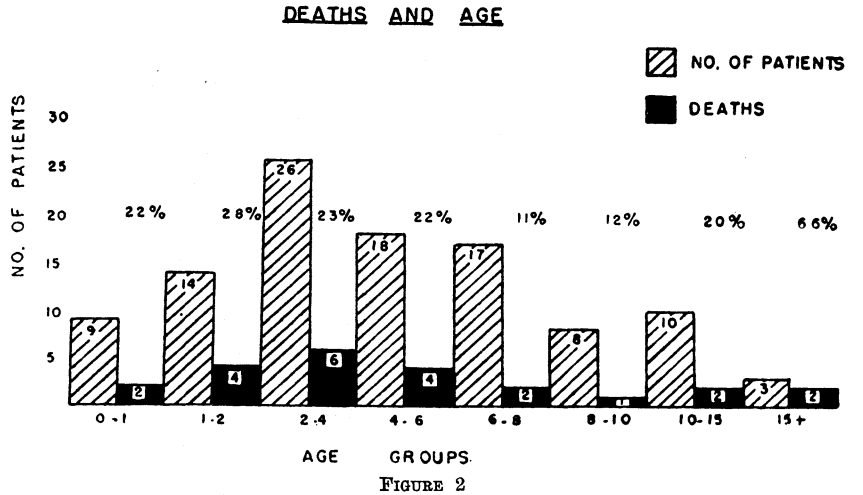

FIGURE 2

portion of the patients died when the innominate artery was selected for anastomosis (fig. 3). Fewer patients died when cyclopropane alone was used (fig. 1). If those patients who received ether and cyclopropane together are grouped with those who received cyclopropane alone, the combined mortality rate is not significantly different from the mortality rate in those patients who received ether alone for the maintenance of anesthesia.

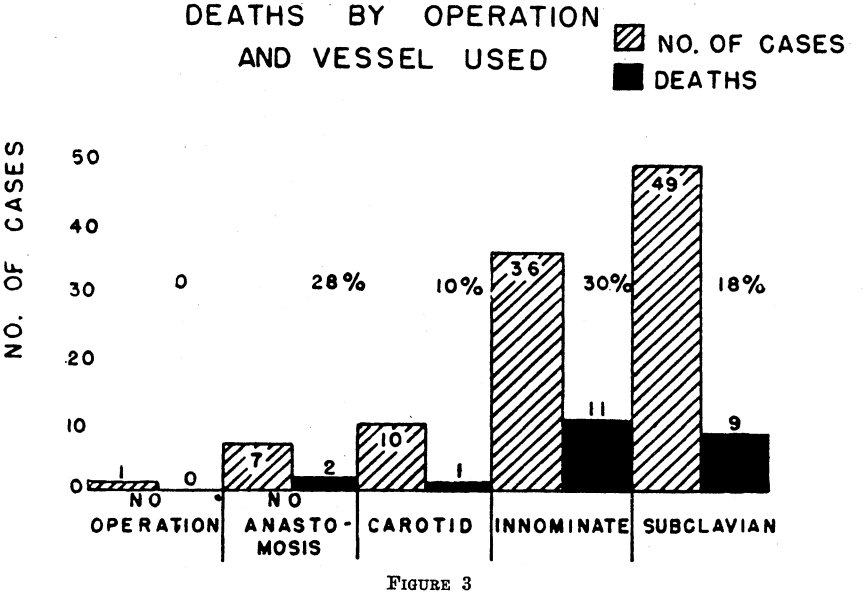

FIGURE 3

The patients who died have been roughly divided into six groups:

Immediate.—Five patients died during or immediately after operation. Two patients in whom pulmonary edema developed have already been described (Cases 61 and 83). Three patients died apparently of heart failure. One of these has already been described (Case 19). Another similar case (96), an 8 year old girl, died when the anastomosis was almost completed. The respirations had been somewhat gasping in character and 2 mg. of morphine had been injected intravenously forty minutes before the heart stopped. Very little was found at necropsy. The last patient in this group, Case 90, 10 weeks old, was in very poor condition. The pulse became very weak as soon as the pleural cavity was opened. According to the surgeon the operation was extremely difficult and the procedure hopeless. The heart stopped soon after the anastomosis was opened. At necropsy there were subpleural hemorrhages in the right lung and the right ventricle was seen to open into the aorta. It must be assumed that in each of these 3 cases the anesthetist was at fault, though it is difficult to know just what mistake was made or how much that mistake may have contributed to the fatal outcome.

Cerebral.—In 4 patients diminished circulation to the brain appeared to be the cause of death. Case 7, an 18 year old girl, who had a left innominate anastomosis, suffered right hemiplegia twenty hours after operation and lost consciousness. She later had some pulmonary edema which did not respond well to treatment. She died about forty-six hours after operation. Another, Case 10, has already been described. This 4 year old child died fourteen hours after operation. Case 73, a 2 year old who had had a recent upper respiratory infection, died fifty hours after operation. The innominate artery had been used for anastomosis. At necropsy there was a thrombus in the anastomosis and in the right internal carotid artery, with necrosis of the right hemisphere of the brain. Case 89, 2 years old, had had a recent infection of the upper respiratory tract. During the anastomosis of the innominate artery the heart was weak and the respiration gasping. The patient had spastic hemiplegia on the left and died within eight hours. At necropsy, among other conditions, there was a thick mucopurulent exudate in the larynx, trachea, and bronchi, and multiple small infarcts or hemorrhages of the right lung. The brain was not examined.

Pneumothorax.—The 3 patients (Cases 1, 9, and 39) who died following the development of tension pneumothorax have been described and discussed.

Hemorrhage.—Four patients died apparently of excessive bleeding after operation. Cases 22, 42, and 66 have been discussed. The other, Case 36, died seven days after operation. The pulse and temperature had remained elevated. At necropsy there was 200 cc. of blood in the right thorax and the lung was partially collapsed; there was fluid on the left, some edema of the lung, and slight lobular pneumonia. Hem-

orrhage had occurred into the subcutaneous and mediastinal tissues on the right side.

Cardiac Failure.—The cause of death in 2 cases probably was heart failure. One, Case 28, has already been described. The other, Case 35, 6 years old, died suddenly twenty-three days after operation. He had had tachycardia and an enlarging liver. A few days after operation he had transient hemiplegia. At necropsy he was found to have a single ventricle, dilatation of the right auricle, chronic passive congestion, moderate bilateral atelectasis, and hydrothorax (about 700 cc. on each side).

Miscellaneous.—One patient, Case 95, a 5 year old boy in very poor condition, died twenty days after operation, probably of anoxemia. He had a left subclavian end-to-end anastomosis, a very difficult operation. At necropsy he was found to have a two-chambered heart and an old thrombus in the anastomosis.

One patient, Case 56, 2 years old, had had a recent infection of the upper respiratory tract. Thirty hours after operation pulmonary edema developed and in spite of treatment the patient died. At necropsy both lungs were heavy, wet, and soggy. There was an extensive fresh lobular pneumonia with a suggestion of rheumatic pneumonitis. Another patient, Case 63, 4 years old, had also had a recent upper respiratory infection. She was slightly spastic on the right side and after operation the spasticity seemed to be increased. She had a good deal of bloody mucus in the respiratory passages. She died rather suddenly eleven hours after operation. At necropsy a thrombus was found partially blocking the anastomosis. There was congestion of the lower lobe of the lung on the side opposite the operation, and some small emphysematous blebs in the right lung. In these last 2 cases it must be assumed that the anesthetist may have done something which contributed to the outcome.

Case 17, the 20 month old child who received laked blood, has already been described.

The last of the twenty-three deaths, Case 85, was that of a girl 2½ years old who had had a recent upper respiratory infection. She weighed 25 pounds. It was noted that the secretions from the tracheobronchial tree were mucopurulent in character. The operation was on the right. She had some bleeding after operation and was given a transfusion. During the eighteen or nineteen hours that she lived after operation she was given 128 mg. of nembutal, 12 mg. of codeine, and 4 mg. of morphine. About fifty minutes after the last dose (2.0 mg.) of morphine her respirations began to slow. She died two hours after the last dose of morphine. At necropsy, a mucous plug was found in the left main bronchus with moderate atelectasis of the left lung and congestion and edema of the right lung. There was a rudimentary right ventricle, complete atresia of the tricuspid valve, and a small, patent ductus arteriosus.

It is difficult to assess the responsibility of the anesthetist in respect to these deaths. He may have been partly responsible for three of the immediate deaths—Cases 19, 90, 96; for the 3 patients with tension pneumothorax—Cases 1, 9, 39; and for Cases 10, 22, 56 and 63. But in each of these 10 patients there were other factors which might as reasonably be held responsible for the death. We do not wish to minimize the importance of the errors we have made in anesthetizing these patients, but at the same time we feel that the hazards inherent in the physical condition of the patients and in the delicate operation have been of greater influence than the anesthetic factors.

FLUID REPLACEMENT THERAPY

One or two early attempts to reduce the viscosity of the blood before operation by withdrawing whole blood and replacing it with plasma were not successful and have not been repeated. It is believed that these patients withstand operation better if their hemoglobin is not depleted. One patient died before operation, presumably of heart failure after a reaction to injected plasma. Whenever plasma was given thereafter it was cross-matched.

Before the operation is begun a needle or cannula is placed in a vein in the ankle. A slow drip of glucose or saline solution, or both, is permitted to run in; glucose is preferred. Plasma is substituted when the operation is started, although in the first 50 cases or so the administration of plasma was postponed until the anastomosis was begun. Usually there is very little loss of blood. In the earlier cases if an unusual amount of hemorrhage occurred the plasma drip was accelerated, but recently the tendency has been to give whole blood instead of plasma in case of hemorrhage. These patients have such a small cardiac reserve that care must be taken not to overload the circulation.

If there had been no undue loss of blood during the operation, many of the earlier patients with polycythemia were bled at the end of the procedure in an effort to reduce the viscosity of the blood and thereby the danger of the formation of a thrombus in the anastomosis or in a cerebral vessel. This practice has now been almost wholly abandoned.

Since in this institution the anesthetist has no responsibility for fluid therapy on the wards, the question of postoperative fluid therapy will be dealt with more fully in papers by Drs. Taussig and Blalock.

The following miscellaneous data are added for sake of completeness:

1. *Side of Operation*

Right	73
Left	29

2. *Type of Anastomosis*

End-to-end	10
End-to-side	85

3. *Duration of Operation*—95 anastomoses

	Average	Longest	Shortest
From beginning of anesthesia to closure of incision	2 hr. 40 min.	3 hr. 40 min.	1 hr. 40 min.
From opening of pleural cavity to closure of incision	2 hr.	3 hr.	1 hr. 15 min.

4. *Days from Operation to Discharge from Hospital*

Average of 72 Patients	Longest	Shortest
27	58	14

SUMMARY

Anesthesia has been given to 100 patients operated on by Dr. Alfred Blalock for the surgical treatment of congenital pulmonary stenosis or atresia. An account is given of the anesthetic management of these patients, of the operative and postoperative complications, and of the deaths which have occurred. It is concluded that these patients tolerate the anesthetic and surgical procedures surprisingly well.

We wish to record our gratitude to Drs. Blalock and Taussig and their colleagues for their help in preparing this paper. It has been a privilege to be associated with them in the treatment of these patients.

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-5-

ANESTHETIC PROBLEMS IN CARDIAC SURGERY IN CHILDREN

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ANESTHETIC PROBLEMS IN CARDIAC SURGERY IN CHILDREN *

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IN the space of a few years, cardiac surgery in children has changed from the rare operation performed in one or two clinics in the United States to a relatively frequent operation undertaken in many medical centers throughout the world. Several different cardiac malformations are now corrected or improved by judicious surgical procedures. The most common of these are: division of a patent ductus arteriosus; anastomosis of the pulmonary artery to the aorta or to one of its branches in patients with the tetralogy of Fallot, and excision of an aortic coarctation. All three conditions present many anesthetic problems in common. The patient with a tetralogy of Fallot, however, is usually by far the poorest risk, and presents a few anesthetic problems unique to this condition.

Harmel and Lamont (1), in September 1946, published an excellent report on their first 100 cases in which anesthesias were administered for the Blalock operation for treatment of patients with congenital pulmonary stenosis or atresia. Many of the anesthetic problems which arise during or following this procedure also occur when the Potts-Smith operation is employed. Because of this similarity, we were able, at Children's Memorial Hospital in Chicago, to anticipate many of the problems that are encountered with these operations.

It has been my good fortune to be connected with the group which introduced the Potts-Smith technic of aortic-pulmonary anastomosis for the relief of hypoxemia in pulmonary stenosis or atresia, and to have administered the anesthesia to more than 200 children undergoing cardiac surgery, the majority being for the tetralogy of Fallot. We have thus been able to observe the anesthetic problems of cardiac surgery in children, and have received helpful suggestions from visiting anesthesiologists and surgeons from almost every country in Europe, as well as from Australia and the Americas. As a result of these stimulating discussions the technic which we now use varies somewhat from that which we used in 1946, but it has been an evolution rather than a revolution. We have had no experience in these

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cases with the use of the nitrous oxide-pentothal-curare sequence employed by the Minneapolis group, the ether technic used at the Mayo Clinic, the Ayres tube, or high spinal. That so many technics have proved satisfactory is a healthy condition.

I will here present only that technic which has been satisfactory in our hands at Children's Memorial Hospital in Chicago, and which has been used for all types of cardiac surgery at this hospital.

Since September 1946, when Dr. Willis J. Potts and Dr. Sidney Smith (2) introduced a new surgical procedure for the relief of hypoxemia due to pulmonary stenosis or atresia, 142 operations have been performed on 140 children for the relief of cyanosis. Without surgical relief the outlook for these children would have been hopeless. Because of this fact, no child was denied surgical exploration because he was considered a poor risk. A number of children in critical condition, with physical findings varying somewhat from the classical tetralogy of Fallot, have had exploratory operations. Anastomosis was possible in several of these cases.

PREOPERATIVE CONSIDERATIONS

The extreme hypoxia of these children, even while at rest, makes them difficult problems preoperatively. Excitement, crying, or fear may produce unconsciousness or convulsions, owing to the child's inability to adjust to an increased demand for oxygen, because of the low cardiac reserve. This low reserve and the psychic factors so common in cardiac children make depression of metabolic activity and psychic sedation the most important considerations of preoperative medication.

Early in this series, we used relatively small doses of premedication. Children under 3 years of age were given small doses of atropine and nembutal, or atropine alone. Morphine and atropine, or morphine and scopolamine, were used in children 3 years of age or older. Later, following the suggestion of Dr. Taussig that even small infants tolerate morphine well and that she used it frequently for considerable periods of time in preparing these patients for surgery, we began using relatively large doses of morphine and atropine, or morphine and scopolamine, on all cases, even infants a few weeks old. A 2 or 3 months old infant, weighing only 7 or 8 pounds, is given morphine, 1/48 grain, and atropine, 1/300 grain. As the age increases, the amount of morphine and atropine is increased, so that a 4 year old child receives morphine, 1/8 grain, and atropine, 1/200 grain. For children 5 years of age to puberty, morphine, 1/8 grain, and scopolamine, 1/200 grain, is usually administered. Age and not weight is the determining factor of the size of the dose. The patients should be sufficiently depressed that, if undisturbed, they will be drowsy or asleep when they reach surgery. In most patients, the degree of cyanosis has appeared to be less after sedation than before.

No operation has been canceled or delayed because of excessive depression.

A cannula is always inserted into the saphenous vein at the ankle for the continuous administration of fluids and emergency therapy. This is done after the induction of anesthesia to keep painful or distressing stimuli to a minimum.

CHOICE OF AGENTS AND TECHNIC

Before making a choice of anesthetic agents or technics to be used for an operative procedure, one must consider the requirements of both the patient and the surgeon. All other considerations must be secondary to these.

For the patient, an agent and technic is desired that (1) permit a rapid and smooth induction with a high oxygen tension; (2) permit minute-to-minute control of the depth of anesthesia; (3) insure an adequate airway, so that the lung may be collapsed or expanded instantly; (4) remove excess carbon dioxide; (5) disturb the physiology as little as possible, and (6) permit a rapid return to consciousness without unpleasant side reactions.

The surgeon needs a quiet operative field, undisturbed by respiratory movements. This is almost essential for the Potts-Smith technic of pulmonic-aortic anastomosis, and it is highly desirable in other surgical procedures on the heart and great vessels.

At Children's Memorial Hospital, cyclopropane has been used as the principal agent for all cardiac surgical procedures, even in the presence of arrhythmias. It is administered by the to-and-fro absorption technic, with controlled respiration. Special face masks and soda lime canisters have been designed for small infants to eliminate the dead air space. The Foregger infant or child-size masks have been satisfactory for the larger children.

Intubation of children, and especially of infants, may be followed by a number of complications ranging in severity from cough to laryngeal edema necessitating tracheotomy. The advantages of the endotracheal technic for open chest operations are well known, especially when the patient is in the lateral position. Cases 2 and 7 were not intubated before the operation was started, but complications occurring after the pleural space was opened necessitated prompt intubation. Since then all children have been intubated before being turned on their sides. Endotracheal tubes without cuffs have been used for all the smaller children. An attempt is made to choose a tube that will fit tightly enough that there will be no appreciable leak, and yet small enough that pressure will not cause damage to the cords. A small amount of ether added to the anesthetic atmosphere before intubation relaxes the cords and gives time to select a tube with the optimum diameter. Gentleness, experience, and the careful selection

of a smooth tube of proper size will reduce the incidence of complications following intubation.

In order to facilitate the anastomosis and to lessen the danger of tearing the frequently thin-walled pulmonary artery, an attempt is made to control completely the respiratory movements. Attempts at respiration, however, are sometimes noticed when the pulmonary artery is temporarily occluded. Since all respiratory efforts by the patient stop as soon as the new ductus is opened and the blood becomes better oxygenated, we believe that these respiratory efforts are due to both hypoxia and carbon dioxide excess. Hence, these respiratory efforts are of great prognostic significance and constitute a warning of dangerous asphyxia. We, therefore, hesitate to mask this sign by the use of curare preparations unless absolutely necessary to permit completion of the anastomosis.

Next to anoxia, the most frequent serious complication is a cerebral accident. Since the red blood count of these children is usually between 7,000,000 and 11,000,000, the increased viscosity of the blood makes cerebral thrombosis an ever-present hazard. Thus bradycardia or hypotension or both are not well tolerated and must be treated promptly. Atropine in solution is always instantly available for intravenous administration and is used to stimulate the heart action. As little as 1/1000 grain of atropine administered intravenously will usually have a striking effect on both the heart rate and the blood pressure, and the heart, which is under direct observation, appears to have a more vigorous beat. Acute bradycardia, or arrhythmia initiated by vagal reflexes, has not occurred frequently but, when it does take place, it has been treated by administering 100 per cent oxygen, local cocainization of the hilar area with 5 per cent cocaine, and the intravenous administration of atropine. Routine cocainization has not been used.

HYPOXIA

At Children's Memorial Hospital, animal experiments designed to oxygenate the blood independent of the lungs proved uniformly unsuccessful, and a different approach was considered. In a paper read before the joint meeting of the American Society of Anesthesiologists and the Chicago Society of Anesthesiologists, in May 1948, I stated, "Reduction of cellular metabolism would seem to be a more physiologic solution to this unsolved problem. The effect of elevated body temperature on the metabolism must not be overlooked."

Hyperthermia in children during or following operation has long been recognized as a serious complication, and very few hospitals can report no mortality from this cause. Knight (3) suggested the use of chilled gases to help prevent this serious complication. At Children's Memorial Hospital, surgeons, internists and anesthesiologists have for some time been acutely aware of the danger of hyperthermia in infants and children. More than a year ago, with John A. Bigler, Medi-

cal Director and Assistant Chief of Staff of Children's Memorial Hospital, I began a study of this condition. Bigler and States of the Central Scientific Laboratory constructed an explosion-proof apparatus for the continuous recording of rectal temperatures in children. With the aid of this apparatus we were able to observe and record accurately the temperature variations from minute to minute during the operation. The results of this temperature study in all types of operations on children will form the basis of another report, but I cannot discuss our present technic in cardiac surgery without saying a few words about our experiences in thermal control.

Until the spring of 1948, we were concerned chiefly with the cause and prevention of hyperthermia. The advisability of producing hypothermia for the purpose of decreasing the oxygen demand during operations on "blue babies" was discussed. Perusal of the voluminous medical literature on "cold therapy," "the effects of cold," and "local refrigeration anesthesia" led us to believe that hypothermia may be produced safely in adults, but we were unable to find any reports of the deliberate production of hypothermia in critically ill children. In fact, the literature abounds in reports on the conservation of body temperature in children undergoing surgical procedures. Because of the acute need of increasing the arterial oxygen, or of lowering the oxygen demand, in patients with critical hypoxemia, however, we decided to resort to hypothermia.

Case 110.—Thomas O., aged 3 months, 25 days, was admitted to the hospital in May 1948, with marked cyanosis. He had begun to have spells of cyanosis at the age of two months. During these attacks, which lasted for about thirty minutes, he became semicomatose and blue-black in color. As is true of most of the extremely severe cases with a diagnosis of tetralogy of Fallot, this infant on roentgenologic examination had an exaggerated boot-shaped heart and clear lung fields, showing that a very small amount of blood was reaching the lung for aeration.

It was the unanimous opinion of the cardiologists, surgeons and anesthesiologist that the infant would probably die on the operating table. It was obvious that he would not live without operation; therefore, it was decided to attempt an anastomosis.

Morphine sulfate, 1/60 grain, and atropine, 1/300 grain, were administered one hour before the operation. Cyclopropane was administered by the to-and-fro technic, and the infant was surrounded with icebags. His temperature was lowered until it registered 96° rectally. Very little cyclopropane was needed for maintenance of anesthesia. In fact, for more than ninety minutes, the cyclopropane valve was shut off. Upon completion of an anastomosis between the aorta and the pulmonary artery, hot water bottles were applied. When the rectal temperature reached 96.7°, the patient began to react, and cyclopropane was again administered during closure of the incision. The patient was awake when he left the operating room. Total anesthesia time was three hours.

After twenty-four hours the infant was removed from the oxygen tent. Phleboclysis was discontinued, and he was given a full formula by bottle. He was discharged on the fourteenth day after an uneventful convalescence.

Since May 1948, more than 25 children in this series have had refrigeration. This number is too small to have statistical significance. It is the opinion of the cardiologists and surgeons who have followed these cases, however, that the mortality and morbidity would have been higher had refrigeration not been used. Our unpublished report on hypothermia tends to substantiate these clinical impressions. Our primary purpose in refrigeration of "blue babies" has been to counteract the deleterious effects of hyperthermia and to reduce the oxygen demand on hypoxic children. The other beneficial effects of hypothermia during anesthesia of other children will not be discussed at this time.

OPERATIVE COMPLICATIONS

Many of the preoperative, operative and postoperative complications already mentioned are illustrated in our second case:

Case 2.—This little girl, aged 11 years and 8 months, was admitted to the hospital in September 1946. She was a small, thin child, weighing 54 pounds. Her left arm and leg were smaller than the right, and there was some spasticity resulting from a cerebral accident which had occurred in infancy. Cardiac examination showed findings consistent with congenital heart disease. The erythrocyte count was 10,190,000; the hemoglobin level was 26.5 Gm. and the hematocrit reading, 79. The oxygen saturation of the arterial blood was 38.7 per cent.

Operation: Morphine sulfate, 1/8 grain, and scopolamine hydrobromide, 1/200 grain, were administered at 7:30 a.m. for premedication. Administration of cyclopropane was begun at 8:40 a.m., with to-and-fro absorption technic. A cannula was placed in the internal saphenous vein and fluids started. The patient was then draped for surgery, and at 9:35 a.m. the incision was made. After the pleural space was opened, attempts to retract the lung resulted in the phenomenon described by Burstein and Alexander (4) as "bucking," or an exaggerated coughing effort. Bucking is most often observed when the vagal tone is high, in the lightly anesthetized patient, and when agents are being used which tend to sensitize the vagal mechanism. Attempts to retract the lung after deepening the anesthesia and after addition of ether were unsuccessful. Naso-endotracheal intubation was performed and the operation was continued. During exploration of the hilar structures, the heart suddenly slowed and stopped for a few seconds. Cardiac massage, oxygen, and cocainization of the hilar area resulted in prompt return of cardiac rhythm. Too rapid closure of the clamp on the aorta resulted in a rise in systolic pressure from 100 to 132 mm. of mercury. The clamp was released, and the blood pressure returned to 100 mm. When the clamp was closed more slowly, the systolic pressure rose to 110 mm. of mercury and remained at that level throughout the anastomosis. The operation was completed at 2:05 p.m. without further complication. The patient's condition, however, was considered to be poor at this time. Fluid replacement during the operation consisted of 100 cc. of physiologic saline solution, 200 cc. of whole blood and 300 cc. of plasma.

At 9:30 p.m., the patient responded to painful stimuli but was still unconscious. Respirations were 30, pulse 120, and rectal temperature 102.6. Her condition remained critical throughout the night, and at 1:00 p.m. on the

following day a diagnosis of cardiac failure with pulmonary edema was made. Administration of 50 per cent glucose was followed by some improvement. At 3:30 p.m. 50 per cent glucose was again administered. The patient expired at 8:00 p.m. without having regained consciousness. Postmortem examination revealed a patent anastomosis with no leakage at the site. The lungs were congested. A scar was found in the right frontoparietal region of the brain, obviously the result of the cerebral accident at the age of fourteen months. On the left side, a hemorrhagic infarct occupied the upper portion of the postcentral gyrus.

More experience on the part of the anesthesiologist and more adequate preparation in anticipation of these complications might have prevented this death. However, it should be pointed out that patients with previous cerebral accidents are poor risks. Five patients in this series had a history of cerebral accidents before operation. Two of these 5 children had cerebral accidents during or immediately following operation and died within a few hours.

Several patients less than 2 years of age in this group exhibited hypoxia of such an extreme degree that they were unable to remain conscious without oxygen. Preoperatively, it was thought that they could not survive operation. When anesthesia was started, however, their cyanosis decreased and heart action improved. We now consider the prognosis to be good when cyanosis becomes less marked after the anesthesia is started. This usually means that a pulmonary artery of sufficient size for anastomosis is present, and that the patient will withstand the surgical procedure well. On the other hand, if there is no decrease in the cyanosis after the anesthesia is started, the prognosis is grave.

Patients who show signs of pulmonary decompensation, as manifested by increased cyanosis, weakened heart action, and respiratory effort, do not regain consciousness rapidly after the operation is completed. In this series, only one patient who remained comatose for more than a few hours has recovered.

POSTOPERATIVE COMPLICATIONS

The postoperative complications of the 123 patients in this series who survived have been divided into three groups, namely: (1) those that were probably due to anesthesia; (2) those in which the anesthesia may have been an important factor, and (3) those in which anesthesia probably played no part. A further division into the refrigerated group and the unrefrigerated group has not been attempted because of the relatively small number of refrigerated cases.

Holinger and Andrews and their associates in the bronchoscopic department at Children's Memorial Hospital have convinced us that the most satisfactory treatment for children with laryngeal edema is to place them in a steam room. By a steam room we refer to a room with the humidity of a "Turkish bath" but with a maximum tempera-

ture of 75°. The usual vaporizer with a small plume of steam emitting from its spout is entirely inadequate to supply the necessary amount of moisture. At the present time, Children's Memorial Hospital is remodeling the steam rooms at a cost of more than $25,000. This is an indication of the importance placed on this type of therapy by our staff.

TABLE 1

COMPLICATIONS PROBABLY DUE TO ANESTHESIA

Complications	Incidence
Cough	12
Cough with expectoration of mucus	5
Cough with expectoration of blood tinged mucus	1
Laryngeal edema, steam room treatment	6
Laryngeal edema, tracheotomy and steam room	2
Pulmonary edema (secondary to laryngeal obstruction)	1

TABLE 2

COMPLICATIONS, ANESTHESIA A POSSIBLE FACTOR

Complications	Incidence
Cerebral anoxia, {coma lasting 4 days—1 / coma lasting 3 days—1}	2
Cerebral anoxia with temporary spasticity	2
Extrasystole (twenty-four hours)	1
Pulmonary rales, bilateral	1
Pneumonia	1
Atelectasis	2
Effusion with bronchitis	1
Tonsillitis	2

TABLE 3

COMPLICATIONS PROBABLY UNRELATED TO ANESTHESIA

Complications		Incidence
Thrombophlebitis of the saphenous vein		7
Subcutaneous emphysema		4
Pneumothorax	3*	5
Hemothorax	2*	5
Hemopneumothorax	1*	1
Effusion	3*	5
Encapsulated effusion		1
Pulmonary edema (transfusion reaction)		1
Anuria (transfusion reaction)		1
Wound infection	1*	1

*Undrained cases.

The complications that were probably caused by anesthesia are shown in table 1. Those in which anesthesia may have been a possible factor are shown in table 2, and those probably not related to anesthesia are shown in table 3.

Pneumothorax and atelectasis probably would have occurred with greater frequency had not all but the first 15 patients had closed drainage with negative pressure.

Case 108 had a transfusion reaction in the operating room. During the next twenty-four hours he had pulmonary edema, hemoglobinuria progressing to anuria, an elevated temperature and an elevated icteric index. Tracheal aspiration and oxygen under pressure were used to treat the pulmonary edema. Hypertonic glucose and digitalis were administered during the first twenty-four hours after operation. Anuria was complete. A high spinal anesthesia was followed by an immediate return of kidney function.

A left aortic arch was present in 108 patients and a right arch in 32 patients. The operation for patients with right arch is technically more difficult than that for left aortic arch. These patients recover more slowly, a good ductus murmur appears more gradually, and cyanosis is more persistent than in patients with a left aortic arch. One patient in this series had a complete situs inversus except for the aortic arch which was on the left side. Technically, she presented all the surgical problems of the usual patient with a right aortic arch. Two patients with right arches had exploratory operations on the left because of a mistaken diagnosis. In both patients a second operation was performed on the right side. One patient had complete pulmonary atresia and died following the second operation. The other patient made a good recovery after an anastomosis was made on the right side.

A study of the length of postoperative hospitalization shows the remarkable recovery made by these children. The average postoperative stay in the hospital was sixteen and a half days. The shortest period of hospitalization was nine days and the longest was twenty-eight days. All children had completely recovered from the operation and had no complications when discharged from the hospital. It should also be noted that several of these children were from foreign countries and the majority were from distant states, so that the average period of hospitalization was longer than would be necessary for children from the Chicago area.

DEATHS

Nineteen deaths occurred in 142 operations, making an over-all mortality of 13.4 per cent. In the 127 patients in whom anastomosis was completed, there were 13 deaths or a mortality of 10.1 per cent. The mortality in the 15 patients in whom no anastomosis was possible was 40 per cent (tables 4 and 5).

In view of the postmortem finding of pulmonary atresia in 5 of the 6 patients who died in the unanastomosed group (table 5), it is not surprising that anoxia was listed by the pathologist as the most frequent cause of death, occurring six times in the 19 deaths in the combined groups.

Cerebral hemorrhage or cerebral thrombosis was the next most frequent cause of death, occurring four times in the 19 deaths.

TABLE 4

DEATHS IN PATIENTS WITH ANASTOMOSIS

Age, Years	No. of Cases	No. of Deaths	Time and Cause of Death
0–1	12	2	Case 71: 8 days postop. Pneumonia. Case 128: 16 days postop. Right heart failure.
1–2	20	4	Case 12: 15 hrs. postop. Cerebral thrombosis. Case 52: 4 days postop. Cerebral hemorrhage. Case 75: 8 wks. postop. Sepsis, secondary to infected cut-down. Case 122: 16 hrs. postop. Hemorrhage. Ruptured pulmonary artery.
2–3	16	3	Case 28: 36 hrs. postop. Cerebral hemorrhage. Case 83: 7 days postop. Thrombosis, anastomotic site. Saddle embolism. Died following embolectomy. Case 127: 20 days postop. Sepsis. Multiloculated empyema of left chest.
3–4	10	0	
4–5	14	1	Case 13: End of operation. Pressure pneumothorax.
5–6	11	1	Case 78: End of operation. Anoxia.
6–7	12	0	
7–8	10	0	
8–9	5	0	
9–10	7	0	
10–11	2	1	Case 88: 18 hrs. postop. Hemorrhage, intercostal artery.
11–12	3	1	Case 2: 30 hrs. postop. Cerebral hemorrhage.
12–16	5	0	
	127	13	Mortality 10.1%

TABLE 5

DEATHS IN PATIENTS WITHOUT ANASTOMOSIS

Age, Years	No. of Cases	No. of Deaths	Time and Cause of Death
0–1	1	0	
1–2	1	0	
2–3	1	1	Case 25: End of operation. Anoxia.*
3–4	3	2	Case 15: End of operation. Anoxia.* Case 85: During operation. Anoxia.* Only blood to lungs through patent ductus, obstructed at operation.
4–5	1	0	
5–6	2	1	Case 115: 6 hrs. postop. Anoxia.
6–7	2	0	
7–8	1	1	Case 60: 3 hrs. postop. Anoxia.*
8–9	1	1	Case 41: 58 hrs. postop. Bilateral bronchopneumonia.*
9–10	0		
10–11	1	0	
11–12	0		
12–16	1	0	
	15	6	Mortality 40%

* Pulmonary atresia.

As stated earlier in this paper, the refrigerated group was considered too small to be of statistical significance. It is of interest to us, however, that none of those in the refrigerated group died of anoxemia or cerebral accident.

Of statistical importance is the mortality in relation to age, as shown in table 4. Of the 76 patients between the ages of 3 and 16 years, the mortality was only 3.8 per cent, whereas in the 48 patients under 3 years of age, the mortality was 14.5 per cent.

In most operations, the spotlight is focused on the diagnostician, the surgeon and the anesthesiologist. We would be remiss if we did not mention the resident staff when discussing these patients. Several of these children were literally kept alive before operation by the residents. After operation, the close, intelligent supervision of these patients by the residents greatly reduced both the morbidity and the mortality. In cardiac surgery, preoperative, operative and postoperative complications must be instantly recognized, and treatment instituted at once.

SUMMARY

The use of relatively large doses of morphine as preoperative sedation for children with congenital cardiac anomalies is recommended.

The anesthetic agents and technic used at Children's Memorial Hospital for cardiac surgery have been discussed.

The use of hypothermia to reduce metabolism during operation, particularly the surgical procedures on hypoxic children, has been suggested.

The operative and postoperative complications, with several illustrative cases, have been presented. The causes of death have been listed.

Hypoxemia is the most troublesome complication and the most frequent cause of death.

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-6-

GENERAL HYPOTHERMIA FOR EXPERIMENTAL INTRACARDIAC SURGERY THE USE OF ELECTROPHRENIC RESPIRATIONS, AN ARTIFICIAL PACEMAKER FOR CARDIAC STANDSTILL, AND RADIO-FREQUENCY REWARMING IN GENERAL HYPOTHERMIA

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GENERAL HYPOTHERMIA FOR EXPERIMENTAL INTRACARDIAC SURGERY*

THE USE OF ELECTROPHRENIC RESPIRATIONS, AN ARTIFICIAL PACEMAKER FOR CARDIAC STANDSTILL, AND RADIO-FREQUENCY REWARMING IN GENERAL HYPOTHERMIA

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FROM THE UNIVERSITY OF TORONTO, TORONTO

GENERAL HYPOTHERMIA is being investigated as a means of reducing the oxygen requirements of the body sufficiently to allow exclusion of the heart from the circulation, thereby permitting intracardiac surgery under direct vision.

During the last two years, an interdepartmental research team has studied oxygen transport and utilization in dogs at low body temperatures[1] and has investigated the factors governing survival in hypothermia.[2] A total of 176 dogs have been cooled. Continued improvement in our technic of cooling and re-warming has made reduction of body temperature to 20°C in dogs a relatively safe procedure. However the minimal temperature with survival has been 15°C. There are no ill effects from cooling to 20°C. Death at lower temperatures is usually due to ventricular fibrillation. Below 28°C the animal enters a state of "cold narcosis" in which an anesthetic agent is no longer necessary to maintain unconsciousness and relaxation. At 20°C the oxygen consumption, cardiac output, blood pressure and heart rate are about 15 per cent of normal. With the knowledge that hibernating mammals of similar normal anatomy can survive body temperature of 3°C,[3] we have been encouraged to seek a method of reducing temperatures in dogs below the present critical level.

COOLING WITH "ELECTROPHRENIC RESPIRATION"

The present method of cooling, using two blankets containing coils with circulating refrigerant** has already been described.[1, 2] The animals are given digoxin and procaine intravenously initially and hypothermia is then induced with the aid of intravenous pentothal and curare to control shivering. About half of the animals have been heparinized with no recognizable effects on the

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‡ Radio and Electrical Engineering Division, Canadian National Research Council.

** Therm-O-Rite Products Corporation, Buffalo, N. Y.

cooling pattern. Venesection is used for abnormal increase in venous pressure. Continuous cathode-ray electrocardiograph visualization is used.*

Recently artificial respiration, necessary at lower body temperature, has been carried out by the periodic stimulation of the exposed phrenic nerve, as described recently[4] as the "electrophrenic respiration." A stimulator† with a rotating potentiometer‡ has been used as an electrical source. This device delivers any type of electrical current in periodic bursts of desired duration or frequency. The respiratory rate is varied simply by adjusting a dial.

This technic has been used 30 times. Continuous venous pressures from the superior vena cava have been observed in each experiment. Electrophrenic respirations applied in the presence of a positive venous pressure have invariably caused a reduction, and pressures below zero cm. of water have been maintained in nearly all animals.

One phrenic nerve only is stimulated. Optimum results are obtained when the stimulating electrode is in contact with all roots of the nerve, at which time an excellent respiratory excursion is obtained which easily maintains full arterial oxygen saturation. In the dog which has normally a communication between pleural cavities these diaphragmatic movements are of no value with the chest open. At such times positive pressure respirations are instituted.

EXCLUSION OF THE HEART AND CARDIOTOMY

It has been possible at a body temperature of 20°C to exclude the heart from the circulation for periods of 15 minutes with survival. In some of the animals during the period of exclusion the heart has been opened and then sutured.

Although further physiologic studies are in progress and methods of cooling are being investigated which may allow reduction of the body temperature with safety to below 20°C, it was decided to test our hypothesis by operating at this temperature. Using sterile technic the fifth rib is removed and the chest opened. Bull dog clamps are applied to the superior and inferior venae cavae and azygos vein. This prevents all blood from entering the heart except that from the mouth of the coronary sinus, which is reduced to a slow ooze because of the low arterial pressure.

No attempt has been made to carry out intracardiac procedures or investigate special exposures. The cardiotomy performed is a token operation. Once the heart is excluded from the circulation, the pericardium is incised and after surface application of cocaine the right auricle is opened with exploration of right auricle and ventricle. Several technics have been used to attempt to eliminate or minimize air embolism. Usually during closure of the cardiac muscle the chambers are filled with heparin-saline solution. With

* Smith and Stone, Ltd., Georgetown, Ontario.

† Grass Instrument Co., Quincy, Mass., U. S. A.

‡ National Research Council, Ottawa, Canada.

completion of the cardiotomy the clamps are removed and the chest closed. Re-warming is commenced immediately.

When the clamps are applied, the heart appears empty and the auricle no longer fills in diastole. Its rate, reduced by hypothermia to 20 per minute, usually increases four or five beats per minute. Incision into the auricle is well tolerated and has never precipitated ventricular fibrillation.

In 39 dogs the heart has been excluded from the circulation in the manner described for periods of 15 minutes or more at a body temperature of 20°C. On 23 of these a cardiotomy was performed. Nineteen, or 49 per cent of the

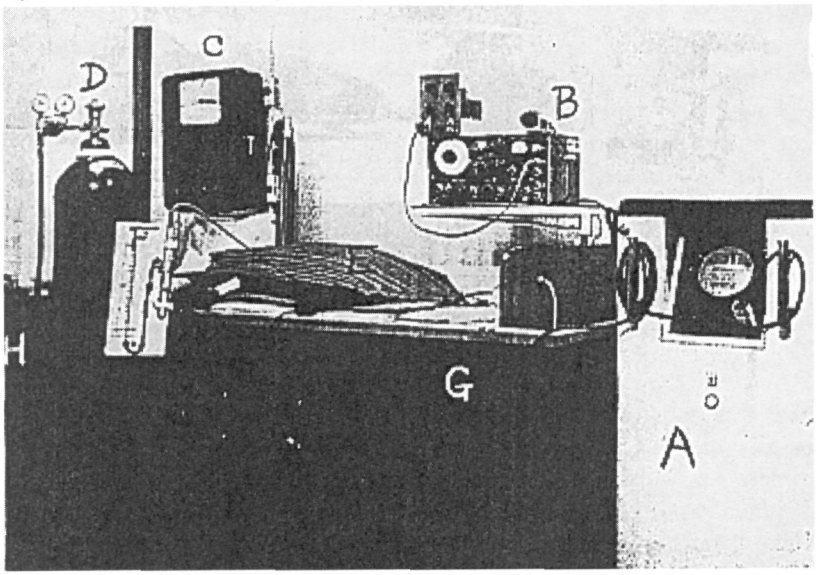

FIG. 1

A. Continuous cathode-ray electrocardiograph.
B. Electric stimulator.
C. Thermometer.
D. Oxygen tank.
E. Animal wrapped in cooling blankets containing coils of circulating refrigerant at 0°C.
F. Venous pressure and blood pressure Manometers.
G. Diathermy re-warming cabinet (lower half).
H. Refrigerating machine.

total, died either during the clamp-off period or during re-warming. Twenty, or 51 per cent of the total (including 11 with cardiotomy) were revived to normal body temperature.

Of those dying in the cold state, five experienced cardiac standstill, while the remaining 14 died from ventricular fibrillation. Six deaths occurred during the clamp-off period, six immediately after removing the clamps and seven during re-warming. Some of the deaths immediately after removal of the clamps may have been caused by removing the clamps too rapidly, with

overfilling of the heart. Most of the deaths in the re-warming period occurred around 32°C.

Of the 20 animals revived to normal body temperature and returned to their cages, six survived the procedure completely. Of these, two were sacrificed during the second week because of gross wound infection and the remaining four were used several weeks later for other cooling experiments. After an initial period of lethargy and weakness, these animals resumed apparently normal activity within a few days.

The remaining 12 with good respiratory function and normal electrocardiograph tracings at normal body temperature developed a state of shock which appeared in two to 12 hours. This was characterized by a progressive fall in blood pressure with cyanosis. Observations of blood pressure and venous pressure, together with blood oxygen and hematocrit studies and routine postmortem examinations, have not as yet given us a full understanding of this shock state.

As a rough index of their tolerance to severe cold two dogs were cooled to 20°C and were maintained at this temperature until death from ventricular fibrillation. They lived 17 and 20 hours with a persistently good electrocardiographic tracing. Their total periods of hypothermia were 27 and 28 hours.

DEFIBRILLATION

Our early attempts at defibrillation have been reported.[2] In the present series this has been attempted in ten experiments and has been successful six times. In five of these cases spontaneous heart beat returned, but the sixth remained in cardiac standstill. Those hearts with a weak ventricular fibrillation did not respond, or responded poorly to defibrillation.

The defibrillating shock is delivered to the heart through nickel-plated electrodes mounted upon an insulated handle after the method of Hooker, *et al.*,[5] Beck and Mautz,[6] using 50 to 120 volts, and frequencies of 25 to 60 cycles per second.

AN ARTIFICIAL PACEMAKER FOR CARDIAC STANDSTILL

Medical men have little fear of temporary cessation of respiration and successfully apply artificial respiration in several forms for prolonged periods. With evidence that many hearts, including those in the hypothermic state, which have ceased beating still have the power to contract following mechanical stimulation,[7] it seemed reasonable to consider the use of an artificial pacemaker to restore heart function. It was felt that, using the principle of electrophrenic respiration, periodic electrical stimulation of S-A nodal area might restore the beat. This could conceivably be carried out for prolonged periods until the organism had been restored to a state where spontaneous normal heart action was regained. As yet no report of a similar technic used in the intact animal has been found in the literature.

This is a very early report of such a procedure which has been attempted recently in four cases of cardiac standstill, in each case with restoration of heart action. The stimulator, with rotating potentiometer, has been used to deliver impulses at any desired rate. An indifferent electrode is clipped onto the chest wall and the stimulating electrode placed in the region of the S-A node. Normal appearing heart action is observed and the heart rate is varied within limits by adjusting a dial.

In two experiments the artificial pacemaker was used for ten to 15 minutes, and when it was discontinued the heart returned to standstill. In the other two animals following electrical control of the heart beat for ten and 30 minutes, normal spontaneous heart beats returned.

In one of these following cardiotomy at 20°C the heart was sutured and clamps removed. Ten minutes later in the presence of good vigorous heart action and normal venous pressure, ventricular fibrillation set in. The heart was defibrillated by the technic described, producing cardiac standstill. Electrical stimulation of the S-A nodal area was then carried out for ten minutes, testing effect of withdrawal of this at intervals until spontaneous heart action was restored. The chest was closed and the dog re-warmed to normal body temperature, only to die several hours later.

Defibrillation following cardiac massage has been used to revive animals[8] and human beings,[6] and we have used cardiac massage for periods up to ten minutes, with return of normal heart action and revival. However, the possible advantages in hypothermia where the stimulating wire could be left in place during closure of chest and re-warming are obvious. Should such a technic prove worthwhile, its extension to other clinical conditions with cardiac arrest might be considered.

RADIO-FREQUENCY REWARMING

Radio-frequency re-warming has been used successfully on hypothermic animals. Until recently, re-warming has been carried out by immersion of the animal in a water bath at a temperature of 40°C. Such a technic, although successful, has the theoretical disadvantage of re-warming superficial structures before the heart and blood stream. It was considered to have several unsatisfactory features, should hypothermia ever come to be applied to surgery on human beings.

Since 1900, short wave diathermy has been used extensively to study the production of hyperthermia from normal body temperature.[9] More recently, microwave diathermy has been used in similar investigations.[10] No reference has been found to their use in deep hypothermia. In our re-warming experiments, ordinary microwave and short wave capacitive heating diathermy technics were found unsatisfactory, due either to localized or inadequate general heating, or to electrode burns. Further investigation indicated that inductive heating was a preferable technic, providing greater facility of application, reduced danger of superficial burning, and more generalized heating. In this

type of heating, eddy currents are set up in the tissue within the influence of the electro-magnetic field of the induction coils. The heating action is caused by the conversion of the eddy currents to heat within the tissues. Since the vascular tissues produce a greater concentration of eddy currents our coils were arranged so as to parallel the main blood vessels, thus enhancing heat distribution throughout the body.

No optimum frequency was found within the usual short wave diathermy range. The rate of re-warming at 27 mc and 13 mc was about the same. However, at the lower frequency, the danger of coil burns was reduced.

A shielded radio-frequency heating cabinet was constructed along the lines of a conventional hyperthemia cabinet, with supplementary air heating to minimize heat losses by conduction. With this cabinet nine animals have been re-warmed and all successfully returned from an initial 15° to 20°C to normal body temperature. The rate of re-warming has varied between 3°C and 13°C per hour as a result of variation in experimental technic. The first two, imperfectly insulated, suffered extensive superficial burns, two others had a local reaction about the metal electrocardiographic electrodes, and five were free of any apparent ill effects.

At the present time a frequency of 14 megacycles is under study with induction coil-type applicators. This method is simpler than water immersion and allows easier access to the animal. It is felt that a satisfactory and safe technic is being developed, although an assessment of possible late ill effects is not yet possible.

DISCUSSION

At normal body temperature of 38°C a dog will survive exclusion of its heart from the circulation from five to nine minutes.[11] Although the final survival rate of 15 per cent in this study following 15 minute exclusion of the heart at low body temperature is not very impressive, 85 per cent survived the actual clamp-off period. This suggests that our basic hypothesis may be correct.

With a greater knowledge of the physiology of hypothermia it may be possible to endow non-hibernating mammals with the ability to survive even lower temperatures than those tolerated thus far. Temperatures below 20°C would further reduce the tissue oxygen requirements and would conceivably increase the length of time an animal could tolerate interruption of its circulation. Should deep hypothermia be developed as a safe surgical technic, it might be expected to extend the scope of surgery in other fields.

Reference has already been made[2] to the many problems that must be solved to understand even the elementary changes in hypothermia. One is encouraged in this study, however, by our knowledge of the tolerance to cold exhibited by hibernating animals and the reports of human survival from temperatures as low as 25°C.

SUMMARY

1. It has been possible to exclude the heart from the circulation for periods of 15 minutes in dogs at a body temperature of 20°C with survival. In most of these animals during the period of exclusion the heart has been opened and then sutured. This procedure is attended by a high mortality and the cause of death is not clearly understood.

2. Periodic electrical stimulation of the phrenic nerve has been used as a form of artificial respiration during the period of respiratory depression in the lower temperature range.

3. Electrical defibrillation of the heart has been practiced.

4. An artificial pacemaker in the form of periodic electrical stimulation of the S A node area of the heart has successfully restored heart action in cardiac standstill in the cold state.

5. Radio frequency re-warming procedures have been studied.

We would like to acknowledge the valuable technical assistance of Mr. Donald Hughes.

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DISCUSSION.—DR. WILLIAM L. RIKER: We have enjoyed this paper very much, and wish to present some of the clinical applications of hypothermia. For the past two years at the Children's Memorial Hospital in Chicago, we have been interested in reducing the temperature of patients undergoing major surgical procedures, for two reasons. In the first place, we want to control hyperpyrexia. In more than a hundred

unselected major surgical procedures the temperatures were recorded, and it was found that in 60 per cent of the patients the rectal temperature went over 100 degrees. In 20 per cent of the patients the rectal temperature exceeded 102 degrees. In some patients the rectal temperature went up exceedingly high. We had two fatalities attributed to hyperpyrexia before we began the cooling procedure.

In the second place, we felt that in the cyanotic cardiac cases, hyperthermia during operation with increase in oxygen requirement, might be disastrous, while hypothermia, on the other hand, would lower the oxygen requirement and reduce our operative risks.

[Slide] This shows the apparatus that has been used. It has been simplified somewhat recently. On the right we see an oven with a constant temperature, in which one thermocouple is kept. Here is another thermocouple which is inserted in the rectum. In the operating room there is a galvanometer which allows us to read off the rectal temperature at any time during the operation.

Here we have a water mattress, which may be filled with either cold water or warm water, and can be emptied whenever we want to change the temperatures.

In applying the cooling system in the cases of non-cyanotic patients, we have attempted only to keep the rectal temperature as near normal as is possible. We have used the cooling system only in those cases in which the temperatures rose above normal. In none of the patients, since we have been using the cooling system, has the temperature gone over 102 degrees rectally, even in the hottest part of the season in Chicago.

In the cyanotic group we have attempted to keep the patient's temperature below normal, down to 96 degrees Fahrenheit if it is at all possible. In the extremely poor risks we have even lowered the rectal temperature to 93 degrees Fahrenheit.

As to results, out of 109 cases that were not cooled (before we had the system we are now using) eight patients developed signs of severe anoxia. Four of these patients died from anoxia. Since we have been cooling the patients, only three of the 128 cyanotic heart cases operated upon have shown any degree of severe anoxia. There were only two deaths attributable to anoxia. We therefore feel that in the cyanotic cardiac cases if you can produce a hypothermia during surgical procedures it gives a much smoother anesthesia, the operative course is much easier, and it decreases the evidence of severe anoxia and mortality postoperatively.

DR. WARFIELD M. FIROR: An interesting corollary to this whole subject is an observation and experiment that was carried out in the tissue culture laboratory of the Department of Surgery at Johns Hopkins.

Until three years ago it was thought that the maintenance of a temperature of approximately 37° C. was essential to the viability of mammalian cells in tissue culture. It was shown, however, by Gey that one can maintain a variety of mammalian tissues in a viable state for periods of six weeks at a temperature as low as 28 degrees centigrade.

Certain basic biologic phenomena can be studied under this experiment. It has been observed that cell division continues at the reduced temperature, and that the process of cell growth appears to be altered, because in many instances innumerable giant cells appeared in the cultures.

The morphology of these cells did not in any way simulate the alteration of a benign to a malignant cell, but, nevertheless, this offers one tool for understanding something of the growth process of mammalian tissue.

DR. CLARENCE DENNIS: With considerable misgivings, Mr. Chairman, in the presence of pioneers like Dr. Crafoord and Dr. Bjork and Dr. Gibbon, I feel this is the proper time to say a little bit about the experimental work that our group has been doing in the laboratory at Minnesota. Our group includes also Dr. R. M. Nelson, Dr. W. P. Eder and Dr. K. E. Karlson.

The primary reason for getting up to say anything seems to me to be the observations by Dr Bigelow and his associates, in their excellent study, of the death of about two-thirds of the animals who apparently had recovered at the time of return to normal temperature. This is one of our major problems as well.

With the apparatus which we are using at the present time, which consists of a modification of Gibbon's apparatus and a considerable modification of that of Crafoord and Bjork, we have found that we can carry on oxygenation satisfactory to carry an extra corporeal cardiac and pulmonary circulation for a period of half an hour in a dog of 70 pounds. We are able to pump about 2800 cc. of blood per minute, with a saturation of over 90 per cent, for periods of about one-half hour. We can introduce about 200 cc. of oxygen per minute.

We have been successful in opening the right ventricle of the heart, closing the ventricle, carrying the dog for half an hour on the machine, and having the dog recover.

The longest period we have carried our dogs is a little over an hour, but that dog did not recover.

Hemorrhage is no longer a problem. Foaming seems no longer to be a problem. Our chief problem seems to be the late death, such as Dr. Bigelow has observed.

It occurred to us that the rise in the blood sugar level, which is consistently seen during this profusion, and the drop in the blood pH which occurs in spite of the maintenance of the normal partial pressure of carbon dioxide, and good oxygenation, should suggest that there is something wrong with the intermediary metabolism of carbohydrate. We have started out by working on some of these enzymes, with the cytochromes in particular. We find that there is an increase in the concentration of pyruvic acid and of lactic acid in the blood during the course of these profusions, and, furthermore, that in some of these animals the pyruvic acid and lactic acid level can be returned, not to, but toward, normal, by the continuous infusion of cytochrome or cytochrome oxydase into the circulating blood in the machine.

Of interest, however, is the late death of these animals. Normal pyruvic acid levels run about 1 mg. per 100 cc. At the end of the profusion we are usually under 2 mg. per 100 cc. The dogs begin to recover, and begin to whine, maybe moving around, and occasionally one has been up and around, and on drawing specimens of blood for various studies at varying periods of time afterward, we have found some dogs that have gone five or six hours when some sort of poorly understood compensation breaks, and the pyruvic acid goes to very high levels. Our highest has been 8 mg. per 100 cc. That dog died shortly afterward. The mechanism of this is under study; we have no explanation for it.

DR. W. G. BIGELOW (in closing): I was very interested in what Dr. Prior said about tissue cultures. We are starting a similar study. His observations concerning cell division at 28° C. are very interesting. I do not know whether our delayed shock is the same problem that Dr. Dennis had in his extra corporeal circulation studies. We deal with other factors, such as hypothermia and an interrupted circulation, but his references to pH are interesting.

Our professor of pathologic chemistry, Dr. J. Dauphinee, and Dr. R. Fleming, have been working on a biochemical study. They have gone away past my comprehension now, but they do not seem to have come up with all the answers as yet.

These animals develop an acidosis with a pH down to 6.6. It would appear to be principally a gaseous acidosis. In the hypothermic state one is dealing with variations in solubility as well as availability of gases in the blood, together with fluid and electrolyte shifts. Thus it is a complex study.

I would like to thank the discussers and also thank the society for the privilege of presenting this paper.

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SURGERY BY DIRECT VISION IN THE OPEN HEART DURING HYPOTHERMIA

Henry Swan, Irvin Zeavin, S. Gilbert Blount Jr., Robert W. Virtue

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SURGERY BY DIRECT VISION IN THE OPEN HEART DURING HYPOTHERMIA

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The heart for centuries was suspected of being a delicate organ; the slightest injury was said to be uniformly fatal. Both the great Billroth and Sir Stephen Paget decreed the organ to lie outside the domain of possible surgery. Yet in reality the heart is a compact muscular organ that, by virtue of highly specialized intrinsic properties, functions continuously throughout the lifetime of the individual. It has an extraordinary capacity to adjust to the changing needs of body circulation. Its inner compulsion toward perpetual function is one of the most critical aspects of the life drive of individuals and species. Only when poisoned or deprived of its flow of nutrient requirements will this persistent organ lie still or lose itself in the quivering death of disorganized activity. A great ability to withstand trauma and to adjust to the stresses imposed by intrinsic disease emphasizes its essential vitality. Given half a chance, the heart will beat.

In the period from 1895 to 1913, Di Vecchio, Haecker, Schepelmann, Elsberg, and Carrel, as well as many others, showed in the experimental laboratory that the heart could withstand surgical trauma and that many complex operative procedures could be performed with relative safety. The main principles of cardiac surgery were well demonstrated and established. The medical tradition of centuries, however, could not be so easily set aside—the heart was delicate and should not be touched! Accordingly, for 25 years the treatment of acute trauma was the only clinical application of this knowledge. In 1938, an event of great import occurred. Pediatrician John Hubbard, of Boston, requested Robert Gross to operate on a child suffering from a patent ductus arteriosus. The successful repair of this congenital "heart" lesion provided the stimulus that has since resulted in the general recognition that the heart is not unique among the organs of the body: it is amenable to surgical therapy.

REVIEW OF SURGICAL PROCEDURES

For the past 15 years in the surgical laboratories and clinics both in the United States and abroad, the principles underlying cardiac surgery have been reexplored and the human application of these techniques has been gradually expanded. In almost all instances, however, these operations have been performed by closed methods; that is to say, the maneuvers within the heart have been done blindly, guided only by the "feel" of the palpating finger. This type of procedure, while often effective, is at best a compromise. To obtain an unimpeded view of the operative field is a fundamental principle of surgery. Adequate exposure for direct vision is an essential component of every safe surgical procedure. In this regard, the interior of the heart has offered some special technical difficulties. Operations on the pericardium, neighboring great vessels, or the exterior of the heart chambers can be easily visualized. The necessity of maintaining circulation during operative maneuvers inside the heart, however, has led investigators to seek the solution of this interesting problem down two separate avenues of study.

The first and more obvious method, of course, was to provide a mechanical pump to furnish the driving force for the blood and then to remove temporarily the heart from the circulation. Either a single pump or two pumps in association with an oxygenator (the animal's own lung, a homologous lung, or a mechanical device) could be utilized, depending on whether one wished to open one or both sides of the heart and depending on whether defects existed in the cardiac septums. This approach to the problem has been vigorously pursued in many laboratories, and recently a few clinical applications have been made.

The technical difficulties associated with this method are great. The instruments are costly and complex and require many skilled persons to use them. A major operative procedure is required to attach the machine to, and later remove it from, the patient's circulatory system, necessarily adding to the magnitude of the total operation and to the postoperative morbidity. The blood of the patient must be heparinized and its capacity to clot later restored with protamine. Overloading of the circulation must be avoided. Hemolysis and air embolism are hazards. Blood flows from the coronary vein into the right auricle and obscures the operative field unless special suction techniques are applied to the sinus. Even so, blood from the thebesian veins on the right and blood from the bronchial artery, via the pulmonary veins, on the left, appear to constitute inescapable flows. At its very best, then, the pump-oxygenators have not yet produced a dry field in which to operate, although the degree of blood flow may be compatible with intermittent visual operative maneuvers. The solutions to many of these problems associated with extracorporeal circulations have been found; others will also be solved; but the inherent characteristics of the technique seem unlikely to change. These adverse characteristics are (1) its complexity and expense, (2) the material increase in the magnitude of operation, and (3) its failure to provide a dry field for operation.

The other avenue of approach to the open heart has been the attempt to lower the metabolism of the patient until circulation can be interrupted for periods of time long enough to allow deliberate and extensive intracardiac maneuvers. It must be remembered that interruption of circulation experimentally was early utilized by Haecker, Schepelmann, and Carrel, and its limitations were explored. In the normal animal, two to three min-

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From the departments of surgery and medicine, University of Colorado School of Medicine.

utes appeared to be the maximum allowable time before cardiac or cerebral damage occurred. This technique has recently been used clinically in a few instances,[1] but the need for longer periods of exposure has sharply limited the magnitude of the procedures that could be performed.

To Bigelow [2] and Boerema [3] must go the credit for the conception and demonstration that general hypothermia can be employed to allow cessation of circulation for as long as fifteen minutes in the dog. Since their initial reports, study of the modality of cold has been made in many laboratories. The risks appeared to be high when cooling was associated with interrupted circulation and the open heart. In Bigelow's original series, only 15% of the dogs survived. In the later studies of Lewis and Taufic [4] and of Cookson and co-workers,[5] the mortality was better but still high. The lethal complications were primarily related to two phenomena: ventricular fibrillation and coronary air embolism. To make the use of hypothermia safe for open cardiac procedures, these two complications must be effectively prevented or managed. Unfortunately, in one clinical trial made prior to the series reported herewith, the mortality was high (about 73%).[6] Much of this mortality was due to the desperate nature of the lesions treated, but some was due to the complications of hypothermia with arrest of circulation. In another series, successful closure of interauricular septal defect was achieved in three of six patients.[7]

EXPERIMENTAL STUDY

On the basis of extensive experimental evidence, together with clinical experience in 15 patients, we believe that hypothermia in association with cessation of circulation may now be performed with a degree of safety that warrants a more extensive clinical trial. In our standard experimental situation, a dog was anesthetized with veterinary pentobarbital (Nembutal) and cooled in ice water to a temperature of 20 to 25 C. Thoracotomy was performed; flow of blood into the heart was occluded for 15 minutes, during which time a right auricular cardiotomy was performed. No other pharmaceutical agents were employed. Artificial respiration was performed by means of a mechanical respirator with oxygen via an endotracheal tube. After operation the animal was warmed in water at 45 C. A great variety of physiological variables were studied with the hope of unearthing changes that might be related to the incidence of ventricular fibrillation. This work has been reported elsewhere.[8] In essence, however, two changes in body constants appeared related to fibrillation.

The first change was in the concentration of carbon dioxide in the blood (and probably the tissues). On the basis of our work together with that of others,[9] it appeared likely that a sudden fall in carbon dioxide from an abnormally high level toward normal was a fibrillatory stimulus in the dog. By means of hyperventilation to control carbon dioxide accumulation (deliberate respiratory alkalosis) the incidence of ventricular fibrillation in the experimental animal was reduced to a level of about 8%.

The second change was found to be a shift in the locus of potassium. During cooling and hyperventilation a fall in the potassium level in the serum was observed. The exact significance of this change in terms of ventricular fibrillation was not understood, but the well-known importance of this ion in relation to cardiac rhythm led us to investigate the use of potassium as a defibrillatory agent. Previously, in our hands, the use of electric shock had been entirely ineffective as a means of resuscitation of ventricular fibrillation in the hypothermic animal. We now found, however, that by means of a potassium chloride solution injected into the coronary circulation we could routinely defibrillate the cold dog's heart and restore normal rhythm.

On the basis of these two phases of the study we felt that ventricular fibrillation complicating hypothermia could be largely prevented; even if it occurred, an effective means of resuscitation was available. The other chief source of worry was related to the prevention of coronary air embolism. Extremely small volumes of air entering the coronary arteries are capable of causing myocardial ischemia and death. If the cardiac septums are intact and air enters the right side of the heart, a considerable volume may escape into the pulmonary circulation without lethal effect. Air admitted directly into the left side of the heart or indirectly via a right-to-left opening, such as a septal defect or pulmonary arteriovenous fistula, constitutes an immediate threat to life even if small amounts should escape into the aorta. For this reason, great care must be exercised to prevent this occurrence during open cardiac operations. On the basis of experience with the experimental creation of auricular septal defects, with the use of an open approach through the right auricle in the warm animal, a technique was developed to prevent this catastrophe.[10] Accordingly, in both our experimental and our clinical experience using hypothermia, this complication did not occur.

Surgeons who have had the opportunity to watch valvular function in the open beating heart are impressed with the dual phase of the act of closure of the atrioventricular valves. The first phase appears to be muscular and involves an actual narrowing of the ring at the base of the valve. The second phase is hydrodynamic and re-

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quires the presence of sufficient fluid within the ventricle to swing the valve leaflets into the position of effective closure. If the ventricle is filled with air, the second phase does not occur, and the valve remains partially open. Under these circumstances, the ventricle develops no head of pressure to open the outflow valves and there is no forward propulsion of either fluid or air; the aortic and pulmonary valves remain closed.

The importance of these observations in terms of air embolism to coronary arteries is obviously great. Air embolism is unlikely to occur during the period when the heart is open. The dangerous moment occurs immediately after closure of the myocardial incision and the return of blood flow. Air trapped in the heart may now be propelled forward into the peripheral or pulmonary circulations. One of the prime means of prevention, therefore, is to remove all air from the heart before closure of the myocardial incision.

The technique evolved may be described as follows. Inflow of blood into the heart is stopped by occlusion of the venae cavae. About one minute is allowed for the beating heart to partially empty itself and the pulmonary circuit. A noncrushing clamp is now placed across the aorta and pulmonary arteries at their point of exit from the ventricles. It is our intent that this clamp should actually occlude the orifices of the coronary arteries as an added means of precaution. That it does so has been demonstrated experimentally by dye injection techniques. Movement of fluid through the exit valves of course ceases at this moment. The heart is now opened, allowing the residual blood to escape and air to enter. The operative procedure is performed within the allotted time limit. Just before closure of the heart incision, the chest cavity is rapidly flooded with Ringer's solution until the entire heart lies under water. As it beats, the air escapes through the cardiac incision that lies uppermost as the Ringer's solution fills the chambers. After a few beats, it can be clearly seen that no more air is bubbling up from the heart. A second noncrushing clamp is then applied (under water) to the cardiotomy incision, closing the heart. The clamp across the aorta and pulmonary artery is now removed. The superior vena cava is released and blood flow allowed to resume. After about 30 to 60 seconds, when the heart seems to be tolerating its work load again, the inferior vena cava is released and total circulation is resumed. The cardiotomy may now be closed with deliberation. It is important not merely to try to fill the heart with Ringer's solution but to completely immerse the heart in the solution, just as one would submerge a sponge in a bucket.

REPORT OF CASES

CASE 1.—The patient was an 11-year-old cyanotic white boy who weighed 74 lb. (33.6 kg.). The clinical diagnosis of isolated pulmonic stenosis with patent foramen ovale was confirmed by catheterization. On Jan. 9, 1953, hypothermia was induced with the patient under thiopental (Pentothal)-cyclopropane-ether anesthesia. After 37 minutes, when his body temperature was 34 C, he was removed from the ice water. His lowest temperature was 28 C. A standard transventricular pulmonary valvulotomy was accomplished without circulatory occlusion. All observers agreed that the heart was unusually stable throughout the procedure. The patient had an uncomplicated convalescence.

CASE 2.—A 12-year-old white girl, who weighed 60 lb. (27.2 kg.), had cyanotic congenital heart disease due to transposition of the great vessels with an interauricular septal defect. A previous shunt operation had been done four years previously with improvement but had closed during the preceding year. At operation on June 9, 1953, hypothermia was induced with the patient under thiopental-cyclopropane-ether. After 35 minutes she was removed from the ice water, with a body temperature of 31 C. Her lowest temperature was 26 C. An intrapericardial anastomosis between the ascending aorta and right pulmonary artery was accomplished without arrest of circulation. The heart was very stable throughout. The patient had an uneventful convalescence.

CASE 3.—The cyanotic congenital heart disease of an 8-year-old white boy, who weighed 63 lb. (28.6 kg.) was confirmed by catheterization to be isolated valvular pulmonic stenosis. At operation on Feb. 19, 1953, hypothermia was induced with the patient under thiopental-cyclopropane-ether anesthesia. After 44 minutes he was removed from the ice water, with a body temperature of 39 C. His lowest temperature was 25.2 C. Circulatory arrest was accomplished by complete cardiac inflow occlusion for 7.5 minutes. Partial excision of the stenosed pulmonic valve was accomplished under direct vision through an incision in the pulmonary artery. Auricular fibrillation occurred during cooling but disappeared on rewarming to 27 C. The patient had an uneventful convalescence.

CASE 4.—The patient was a 7-year-old white boy who weighed 51 lb. (23.1 kg.). Cyanotic congenital heart disease was diagnosed as probable infundibular pulmonic stenosis associated with tetralogy of Fallot. Hypothermia was induced with the patient under thiopental-cyclopropane-ether anesthesia. After 37 minutes he was removed from the ice water, with a body temperature of 30 C. His lowest temperature was 23.6 C. Circulatory arrest was accomplished by complete cardiac inflow tract occlusion for 2.1 minutes. The patient was found to have pulmonic valvular stenosis as part of the tetralogy. Half of the stenotic valve was excised under direct vision. Auricular fibrillation occurred during cooling and disappeared when the patient was rewarmed to 26.5 C. Convalescence was uneventful.

CASE 5.—The cyanotic congenital heart disease of an 8-year-old white girl, who weighed 66 lb. (29.9 kg.), was established by catheterization to be isolated valvular pulmonic stenosis. At operation on March 10, 1953, hypothermia was induced with the patient under thiopental-cyclopropane-ether anesthesia. After 39 minutes she was removed from the ice water, with a body temperature of 30 C. Her lowest temperature was 25.7 C. Circulatory arrest was accomplished by complete cardiac inflow occlusion for 2.5 minutes. Pulmonic valvuloplasty by incision in three places was performed under direct vision. Auricular fibrillation occurred and disappeared when the patient was rewarmed beyond 26 C. Convalescence was uneventful.

CASE 6.—The patient was a 9-year-old white boy who weighed 66 lb. (29.9 kg.). The clinical diagnosis of isolated pure pulmonic stenosis was confirmed by catheterization. At operation on April 14, 1953, hypothermia was induced with the patient under thiopental-cyclopropane-ether. After 35 minutes he was removed from the ice water, with a body temperature of 30.8 C. His lowest temperature was 23.7 C. Circulatory arrest was accomplished by complete cardiac inflow tract occlusion for 2.5 minutes. Pulmonic valvuloplasty by incision in three places was performed under direct vision. Auricular fibrillation occurred and disappeared on rewarming the patient beyond 26 C. Convalescence was uneventful.

CASE 7.—A 26-year-old white woman who weighed 104 lb. (47.2 kg.) had suffered progressive disability from a large interatrial septal defect confirmed by catheterization on two occasions. At operation on April 15, 1953, hypothermia was induced with the patient under thiopental-cyclopropane-ether anesthesia. After 77 minutes she was removed from the ice water, with a body temperature of 29 C. Her lowest temperature was 22.3 C. Circulatory arrest was accomplished by complete cardiac inflow occlusion for 7.5 minutes. The large interatrial septal defect was closed with direct suture. Auricular

fibrillation occurred and disappeared when the patient was rewarmed beyond 26.5 C. She was given a smaller transfusion than would have been usual in such an operation because of fear of heart failure. Shock occurring in the recovery room was successfully combated with 1,500 cc. of blood. Convalescence was slow, with shifting arrhythmias that complicated her course. Two months later the heart was smaller, and a great increase in exercise tolerance had occurred.

CASE 8.—The cyanotic congenital heart disease of a 10-year-old white boy, who weighed 70 lb. (31.8 kg.), was established as tetralogy of Fallot by catheterization. At operation on April 21, 1953, hypothermia was induced with the patient under cyclopropane-ether anesthesia. After 45 minutes he was removed from the ice water, with a body temperature of 31 C. His lowest temperature was 24.6 C. Circulatory arrest was accomplished by complete cardiac inflow occlusion for 8.5 minutes. An infundibular stenosis was excised under direct vision. An anomalous coronary artery frustrated attempt at a larger ventriculotomy to repair the interventricular septal defect. Cardiac arrest occurred during the operation but responded immediately to massage. Auricular fibrillation occurred during cooling and disappeared on rewarming the patient. Convalescence was uneventful.

CASE 9.—A 6-year-old white girl, who weighed 41 lb. (18.6 kg.), had suffered progressive disability from a large interatrial septal defect proved by catheterization. At operation on May 5, 1953, hypothermia was induced with the patient under thiopental-cyclopropane-ether anesthesia. After 40 minutes, she was removed from the ice water, with a body temperature of 29 C. Ventricular fibrillation was noted four minutes later, and cardiac massage was instituted rapidly. Defibrillation was performed with 0.5 mEq. of potassium chloride perfused into the coronary arteries. Her lowest temperature was 22.6 C. Circulatory arrest was accomplished by complete cardiac inflow occlusion for five minutes. A large interatrial septal defect was closed by direct suture. Cardiac arrest occurred after partial closure of the pericardium. Massage and intracardiac injection of 2 cc. of 2% calcium chloride were effective in restoring normal rhythm. Convalescence was uneventful except for temporary bilateral peroneal palsy of unknown cause.

CASE 10.—Isolated pulmonic valvular stenosis without cyanosis was confirmed in a 3-year-old white girl, who weighed 34 lb. (15.4 kg.), by catheterization. On June 12, 1953, hypothermia was induced with the patient under vinyl ether (Vinethene) and ethyl ether anesthesia. After 23 minutes she was taken from the ice water, with a body temperature of 30 C. Her lowest temperature was 25.5 C. Circulatory arrest was accomplished by complete cardiac inflow occlusion for 2.17 minutes. Incision of the thick stenosed pulmonic valve was done in two places under direct vision, forming a bicuspid valve. The patient had an uneventful convalescence.

CASE 11.—The patient was a 4-year-old boy who weighed only 26 lb. (11.8 kg.). His interauricular septal defect with tricuspid regurgitation had produced a very large heart bordering on failure, in spite of digitalis therapy during the past two years. At operation on June 18, 1953, hypothermia was induced with vinyl ether-ethyl ether anesthesia. After 19 minutes the patient was removed from the ice water, with a body temperature of 29 C. His lowest temperature was 21.5 C. Technical repair of the septal defect was accomplished satisfactorily with seven minutes of inflow tract occlusion. The heart went into standstill during occlusion and shortly afterward into ventricular fibrillation. The patient was warmed to 33 C, while cardiac massage maintained the circulation. The ventricles were defibrillated with potassium. The beat, however, was never vigorous, and the patient died with a dilated failing myocardium.

CASE 12.—The frail stature of a 6-year-old boy, who weighed 40 lb. (18.1 kg.), was due to a large interauricular septal defect, although he had never been in frank heart failure. At operation on June 26, 1953, hypothermia was induced with the patient under thiopental-cyclopropane-ether anesthesia. After 35 minutes he was removed from the ice water, with a body temperature of 28 C. His lowest temperature was 25.5 C. A large interatrial septal defect was sutured under direct vision during occlusion of circulation lasting 6 minutes 15 seconds. Auricular fibrillation reverted to sinus rhythm on return of circulation. The patient's postoperative course was uneventful.

CASE 13.—The patient was a 3-month-old boy who was suffering acute heart failure associated with intense cyanosis. His condition improved with digitalis and oxygen, but three days later jaundice developed, thought to be hepatic in origin. On June 26, 1953, because of his large heart and his failure to improve, he was operated on, with a diagnosis of possible pulmonary valvular stenosis. Hypothermia was induced rapidly with the patient under thiopental-ether anesthesia. After 11 minutes he was removed from the ice water, with a body temperature of 30.8 C. His lowest temperature was 25.6 C. Exploration revealed idiopathic pulmonary hypertension. No therapeutic procedure was attempted. Immediate recovery was satisfactory, but the patient subsequently died of his cardiac malformation.

CASE 14.—The cyanotic heart disease of a 28-year-old white mother of 2 children had caused progressive disability for the preceding two years. Two months before admission a right hemiplegia had occurred. Clinical diagnosis of tetralogy of Fallot was confirmed by angiocardiographic demonstration of infundibular pulmonic stenosis. At operation on July 1, 1953, cardiac standstill occurred after induction and intubation but before cooling was begun. Cardiac resuscitation was accomplished after 2 minutes 10 seconds by thoracotomy and massage. The wound was closed tightly with mattress sutures, and the patient then cooled in ice water for 47 minutes to 31 C. Her lowest temperature was 25.5 C. Cardiac arrest again occurred as the chest was being prepared for draping. The previous wound was rapidly reopened and the heart beat restored by massage at 1 minute 10 seconds. From this point on, the heart beat was remarkably stable. With circulatory arrest lasting five minutes, a tight infundibular stenosis was excised under direct vision through a right ventriculotomy. No attempt was made to close a very small interventricular septal defect. Immediately after the patient's recovery from anesthesia, cyanosis disappeared. The postoperative course was uneventful.

CASE 15.—The patient was a 20-month-old girl who weighed 18 lb. (8.2 kg.). Cyanosis during an upper respiratory infection led to the diagnosis of pulmonic valvular stenosis with patent foramen ovale. Operation was performed on July 9, 1953. Hypothermia was induced with the patient under thiopental-ether anesthesia. After 24 minutes she was removed from the ice water, with a body temperature of 31 C. Her lowest temperature was 27 C. Via an incision in the pulmonary artery, plastic revision and partial excision of the stenotic pulmonary valve was performed during circulatory arrest lasting 3 minutes 50 seconds. The patient's operative course was uneventful, and her immediate recovery was quite satisfactory.

COMMENT

These specific operations were chosen deliberately for the initial experience with human hypothermia, because the existing operations for the diseases treated have left much to be desired. As experience has accumulated in various clinics, it has become increasingly clear that the transventricular incision and dilatation of the stenosed pulmonary valve has given very disappointing objective results.[11] It is true the immediate clinical results are excellent. But surgeons who have studied, by actual measurement, the residual right ventricular pressure weeks or months following operation in these same patients have found a disturbing number in whom this pressure is still

11. Bing, R.: Personal communication to the authors. Dodrill, F. D.; Gerisch, R. A.; Johnson, A. S., and Hill, E.: Pulmonary Valvuloplasty Under Direct Vision: Aid of Mechanical Right Heart, read before the American Association of Thoracic Surgery, San Francisco, March, 1953. Humphreys, G. H.; Powers, S. R.; Fitzpatrick, H. F., and Lanman, B. M.: Pulmonary Valvular Stenosis: Clinical and Physiologic Studies of 25 Cases Treated by Valvulotomy, read before the Meeting of Society for Vascular Surgery, New York, May, 1953.

markedly elevated, that is, a systolic pressure of 70 mm. Hg or more. This is a level approximately three times normal, and, although it is lower than it was preoperatively, it is still pathologically elevated. One cannot predict a normal life span for such a patient. It seems desirable, therefore, to attempt a more complete plastic revision of the valve, a maneuver easily made possible by the direct vision technique.

Resection of infundibular stenosis blindly with rongeurs has not appealed to many surgeons. Resection of a precise area under direct vision associated with the additional possibility of closing the ventricular septal defect in tetralogy of Fallot offers the potentiality of actually curing the patient of his intracardiac defects. Clearly, if the procedure is feasible and safe, this would be an objective superior to the addition of a shunt. Resection of the stenosis is not unduly difficult, but closure of the septal defect may prove more arduous.

The operations currently available for interauricular septal defects are all blind manipulations and carry a significant operative risk.[12] Certain types of defects, particularly septum primum lesions overlying the valves, are not amenable to treatment by these methods. An open operative approach to this problem seems worthy of trial.

To date, we have used cooling with cessation of circulation primarily in children, only two patients having been adult. There is good experimental evidence that the young tolerate this procedure with greater safety than the older age group. We hope to establish the safety of the procedure in this younger age group before proceeding to expand slowly into adult ranges.

We believe it is desirable to cool the patients as rapidly as possible, perform the procedure, and then warm to near normal temperatures at once. Cardiac irregularities occur with great frequency in these sick hearts at levels below 28 C. Auricular fibrillation, although common in the human patient, is not a matter of great concern, because, in our experience, if it occurs during cooling, a sinus rhythm will always return at approximately the same temperature during rewarming. Ventricular fibrillation has occurred twice but was successfully reverted on both occasions by the use of potassium. In one patient, however, sustained spontaneous beat could not be subsequently obtained, we believe, because of cardiac dilatation and myocardial failure. This was the only operative death in the series.

The importance of an adequate exposure of the heart and great vessels for this type of procedure must be emphasized. It is essential that all sides of the heart, the superior and inferior venae cavae, the ascending aorta and pulmonary artery, and the lung roots be readily reached. For this, in our experience, there is no incision equal to the bilateral transverse sternal-cutting intercostal incision in the fourth interspace. Although long, the incision involves the removal of no part of the thoracic skelton, is well tolerated by the patient, and heals quickly, with minimal postoperative discomfort.[2]

SUMMARY AND CONCLUSIONS

Fifteen patients have undergone cardiac operations while they were in a state of hypothermia, with body temperatures ranging from 21.5 to 26 C. In 13 of these patients, circulation was stopped for periods varying from 2 to 8½ minutes, and the operation was performed in the open heart under direct vision. There was one operative death in this group. The remainder of the patients have had excellent clinical results, save one on whom no therapeutic procedure could be performed.

Hypothermia was induced during anesthesia by immersing the patient in a tub full of ice water; warming was also achieved in the tub with warm water. Speed of cooling depended largely on body build; the less obese patients cooled more rapidly. Prevention of shivering and hyperventilation were very important aspects of the cooling technique. Potassium appeared to be a valuable agent for combating ventricular fibrillation in the cold patient. The prevention of coronary artery air embolism was of great importance and was achieved by a combination of maneuvers, of which one of the most important was complete immersion of the heart in salt solution at the time of closure of the cardiotomy.

Direct vision intracardiac surgery should be further explored and possibly expanded in scope, since cessation of circulation in the presence of hypothermia allows an essentially bloodless field, with reasonable safety for periods up to at least eight minutes. It is surprising how much can be deliberately accomplished in this period of time. Various forms of pulmonic stenosis in nine patients and interauricular septal defects in four have been successfully repaired by this technique. Other stenotic or regurgitant valve lesions and defects of the ventricular septum may also prove to be amenable to therapy.

4200 E. 9th Ave. (7) (Dr. Swan).

12. Gross, R. E.; Watkins, E., Jr.; Pomeranz, A. A., and Goldsmith, E. I.: Method for Surgical Closure of Interauricular Septal Defects, Surg., Gynec. & Obst. **96**: 1, 1953. Swan, H.: Surgical Closure of Interauricular Septal Defects, J. A. M. A. **151**: 792 (March 7) 1953. Bailey, C. P., and others: Congenital Interatrial Communications: Clinical and Surgical Indications with Description of New Surgical Technique: Atrio-Septo-Pexy, Ann. Int. Med. **37**: 888, 1952.

-8-

APPLICATION OF A MECHANICAL HEART AND LUNG APPARATUS TO CARDIAC SURGERY

John H. Gibbon, Jr.

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APPLICATION OF A MECHANICAL HEART AND LUNG APPARATUS TO CARDIAC SURGERY

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IT IS A PLEASURE to be here and to talk about a subject in which I have been interested for many years. The ultimate objective of my work in this field has been to be able to operate inside the heart under direct vision. From the beginning, I have not only been interested in the substitution of a mechanical device for the heart, but also for the lung. We have always considered congenital abnormalities of the heart the most suitable lesions for operative repair. Many of these abnormalities are septal defects. In the presence of a septal defect, shunting the flow of blood around one side of the heart with a pump, will not provide a bloodless field for operative closure of the defect. An apparatus which embodies a mechanical lung, as well as pumps, enables you to shunt blood around both the heart and lungs, thus allowing operations to be performed under direct vision in a bloodless field within the opened heart. Furthermore, an apparatus which embodies a mechanical lung enables you to provide partial support to either a failing heart or failing lung where a major operative procedure is not contemplated. Such an apparatus can also be used as an adjunct during the course of a major operative procedure. This partial support of the cardiorespiratory functions consists in removing venous blood from some peripheral vein continuously, oxygenating the blood and getting rid of the carbon dioxide in it and then injecting the blood continuously in a central direction in a peripheral artery. Of course, such partial circulation, or cardiorespiratory support, requires the use of a mechanical lung in the circuit.

I shall not describe in detail the entire apparatus. I shall merely discuss six aspects of the problem which I consider of fundamental importance. Four of these concern the apparatus itself, and two concern problems which arise on opening the heart and operating within it under direct vision.

The first feature of a mechanical heart-lung apparatus is a suitable pumping mechanism to move the venous blood from the subject, through the apparatus, and back into an artery of the subject. There is no real problem about a pumping apparatus. There are many ways of moving blood through tubing without producing significant amounts of hemolysis. We have used for many years a roller type of pump which does not contain any internal valves. Such pumps are extremely simple. Because of the absence of valves, the blood circuit is easy to clean and there are no stagnate regions where fibrin might be apt to form. There are many other advantages in this type of pump such as the simple and rapid control of the rate of blood flow. The pumps cause no significant hemolysis. In human patients in which we have used the apparatus, hemolysis has always been well below 100 mg. of free hemoglobin per 100 ml. of plasma. In animal experiments, hemolysis is similarly minimal.

The second main feature of a mechanical heart-lung apparatus is the mechanical lung itself. This presents far more difficulties than pumping blood. I am sure that the most efficient apparatus for performing the functions of the lung has not yet been devised. Our present mechanical lung, however, provides a reasonably satisfactory working solution to this problem. The mechanical lung performs the gas exchange required for respiratory function by filming blood on both sides of screens which have a somewhat larger mesh than ordinary fly screens. These screens are made of stainless steel wire and are suspended vertically and parallel in a plastic chamber. As the blood flows over these screens, it takes up oxygen and gives off carbon dioxide. It should be remembered that it is equally important to remove carbon dioxide from the blood as it is to add oxygen. It is easy to observe that sufficient oxygen is being picked up in the apparatus, as the blue blood entering the oxygenator becomes red as it leaves. This can be determined more accurately, of course, by intermittent sampling or by continuous reading with a Wood cuvette and oximeter. On the other hand, there is no way of estimating the carbon dioxide tension by observing the color of

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the blood. We have solved this problem by reading continuously the pH of the blood as it leaves the oxygenator. As there is no significant increase in fixed acids in the blood in the course of these experiments, the pH changes are due practically entirely to changes in carbon dioxide tension. We have an automatic control which keeps the carbon dioxide tension at the desired normal level and which is operated by any change in the continuously recorded pH level of the blood.

A third important feature of any apparatus which temporarily performs the function of the heart and lungs is constancy of fluid volume. The apparatus should at all times hold a constant volume of blood at any rate of blood flow. If the apparatus is not designed so as to hold a rigid volume of blood at all rates of blood flow, blood might accumulate in the apparatus with consequent depletion of the subject's vascular system and a dangerous drop in the subject's blood pressure. Similarly, if the apparatus should hold less blood at any time, there would be an excessive amount of blood in the subject's vascular system. Obviously the tubing in the blood circuit will always hold a constant amount of blood. There are two places in the circuit, however, where the blood volume might vary. One is in the blood reservoirs at the bottom of the plastic chambers which draw venous blood from the subject, and the other is in the thickness of the film of blood on the screens in the oxygenator. Rigid control of the volume of blood at the bottom of these plastic chambers has been obtained by an electronic device invented by Dr. B. J. Miller in our laboratory. This electronic device senses the level of the blood in these chambers and automatically operates the pumps which draw blood from the chambers. Thus when the level of blood tends to rise, the pump automatically operates at a faster rate. When the level falls the pump automatically is slowed. This electronic circuit has proven eminently satisfactory and maintains a rigid volume of blood in these chambers.

In the second place where blood might accumulate, on the screens of the oxygenator, a very simple way to avoid such an increase is by inserting an additional pump in the circuit which draws not only from the bottom of the mechanical lung but also from the tubing carrying venous blood from the subject. This additional pump operates at a rate which is always greater than the rate of blood flow from the venae cavae of the subject. As this pump operates at a fixed rate, the thickness of the blood on the screens in the oxygenator does not vary.

The fourth important requirement of any mechanical heart and lung apparatus is that the apparatus should remove all of the blood returning to the heart through the venae cavae and yet should not apply too great a negative pressure to the orifices of the cannulae because the venae cavae would then be collapsed around the orifice of these cannulae. We have found that the simplest way of obtaining such a smooth blood flow from the cavae is to interpose a suction chamber between the pump and the cannulae in the venae cavae. The degree of negative pressure can be easily regulated in this chamber and a smooth uniform flow of blood is easily obtained.

In summary, then, every mechanical heart-lung apparatus devised to take over temporarily the entire functions of the heart and lungs must comprise four essential features. First, there must be a good method of pumping blood through the circuit which does not cause hemolysis, which can be quickly and easily adjusted to varying flow rates and finally which enables the blood circuit to be easily and thoroughly mechanically cleaned. Second, the mechanical lung must not only fully saturate the blood with oxygen but must maintain the carbon dioxide tension of the blood at a normal level. The latter requirement may be taken care of by an automatic apparatus which continuously reads the pH of the blood leaving the mechanical lung and adjusts the carbon dioxide tension accordingly. Third, the apparatus must hold a constant amount of blood at all rates of blood flow. This can be accomplished by electronic control of the pumps removing blood from plastic chambers so that the pumps operate always to maintain a constant level of blood in the reservoirs at the bottom of the chambers. The thickness of the blood film on the screens in the oxygenator is kept constant by an extra pump which always circulates a constant flow of blood over the screens. Fourth such an apparatus must be able to remove smoothly all the venous blood returning to the heart through the venae cavae without collapsing these veins. We have found the simplest way of accomplishing this is to interpose a negative pressure chamber between the pump and the cannulae in the venae cavae.

There are two problems concerning operations upon the open heart which merit discussion. The first consists in the disposal of the blood returning to the chambers of the heart even though all the blood flow from the venae cavae is diverted to the apparatus. The second problem is the avoidance of air embolism when the heart is opened.

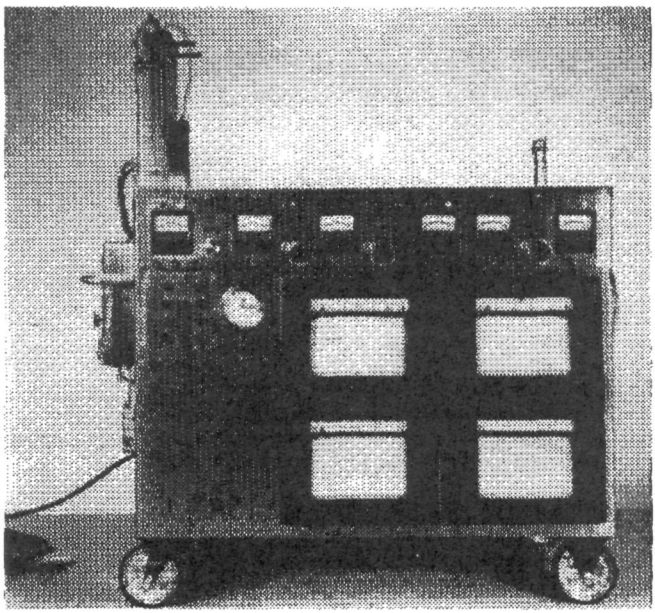

Fig. 1. Front view of apparatus showing the recording and control instruments and the lung suspended above the cabinet on the left.

The first problem is not difficult to solve. When the entire functions of the heart and lungs are taken over temporarily by the mechanical heart-lung apparatus, the myocardium continues to receive its normal flow of oxygenated blood by way of the coronary arteries. This blood is returned to the interior of the heart by way of the coronary sinus and the Thebesian veins. This blood must be disposed of so that the operative field can be clearly visualized when the heart is opened. We have accomplished this by aspirating this blood into a special plastic chamber in which any air aspirated is dissipated. The blood collects at the bottom of this chamber and is pumped back into the main extracorporeal circuit free of air.

Air embolism must be avoided when the heart is opened. If there is no septal defect, operations upon the right side of the heart can be performed without any great danger from air embolism. It is easy to flood the chamber of the heart with blood or salt solution after the operation is completed so as to avoid air embolism. Small amounts of air in the pulmonary arteries are probably not significant. On the other hand, operations on the left side of the heart, or on the right side of the heart in the presence of a septal defect, present a real problem in the prevention of air embolism into the ascending aorta. The immediate result of such air embolism is usually blockage of the coronary arteries with ventricular fibrillation and death. Our solution of this problem is to insert a small plastic catheter through a stab wound in the apex of the left ventricle. Suction is applied to this plastic catheter during the course of the open cardiotomy so that any air or blood entering the left ventricle takes the path of least resistance out through this plastic catheter instead of being

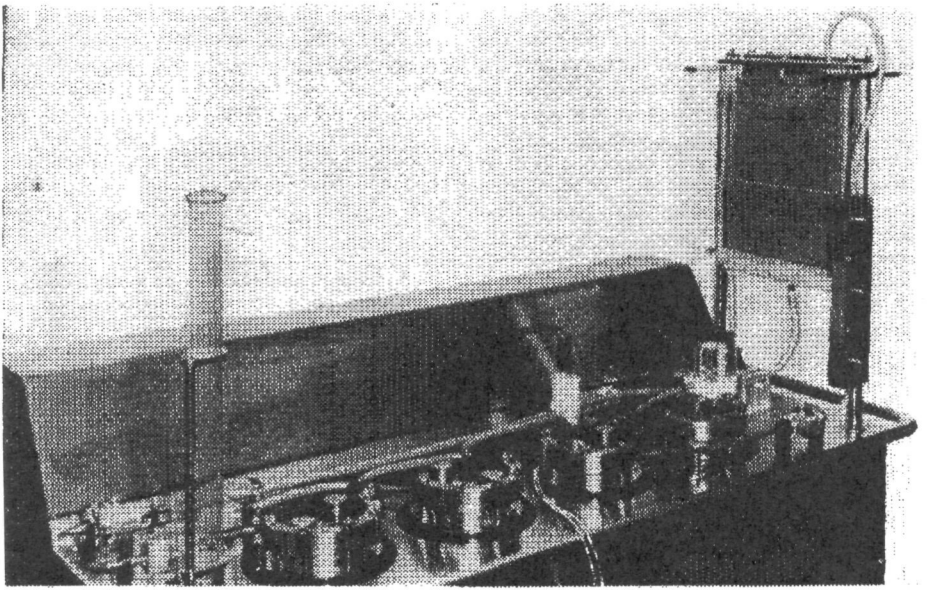

Fig. 2. Oblique rear view of apparatus showing the rotary blood pumps and the battery-type screen lung suspended above the cabinet on the right side.

ejected into the aorta. This plastic catheter is also connected to the debubbling chamber which receives the cardiac venous blood aspirated from inside the heart. Thus this blood is also returned to the circuit, and so to the subject, after the air bubbles are removed. After the wound in the heart is closed, and no further bubbles of air appear in the tubing connected to this catheter, it is removed and the small stab wound in the left ventricle closed by suture. Since employing this method in both animals and patients, we have had no instances of air embolism.

Figure 1 shows the front view of the apparatus which I have described, with the recording and control devices on the front panel. Figure 2 shows the rear view with the roller type pumps on top of the cabinet. Two rollers on a revolving arm pass over the rubber tubing which is clamped in a semicircular position. The rollers move the blood through the tubing and the blood cannot flow back because there is always a roller compressing the tube. To the right of Figure 2 is the mechanical lung which consists of vertical screens suspended in parallel in the plastic case. Blood passes onto the screens through slits at the top of the lung. The blood collects in the bottom of the plastic case as it leaves the screens. The pump returning the oxygenated blood to the subject is automatically controlled by the electronic device which senses the level of the blood at the bottom of the plastic case, through which the blood passes. The lucite block near the oxygenator contains glass and calomel electrodes which continuously measure the pH of the blood. The filter consists of a screen with wires 150 microns in diameter and a 300-micron mesh. We do not know whether such a filter is necessary before returning the blood to the subject. However, we regard it as a good safety precaution in human patients. The tube at the end of the apparatus returns the blood to the patient through a cannulae directed in a central direction in an artery. In human patients we employ the central end of the divided left subclavian artery. The other two tubes are connected with cannula which are inserted into the superior and inferior venae cavae.

Oxygen is blown over the screens suspended

in the plastic case. Thus the blood film on the screens is exposed to an atmosphere of pure oxygen. The lung shown in Figures 1 and 2 has six screens. We have a larger mechanical lung with eight screens which are of longer length and which we have used on adult patients. An additional pump draws blood both from the bottom of the oxygenator and from the tubing containing the venous blood coming from the patient. The pump maintains a constant rate of flow through the oxygenator so that there is no variation in the thickness of the films on the screens. The electronic control circuit maintains the blood level in the bottom of the plastic case constant at all rates of flow. The pump removing the blood from this chamber is controlled by this electronic device.

There are two plastic negative pressure chambers. One of them collects the blood from the venae cavae and the other (Fig. 3) is the debubbling chamber in which the blood from the cardiac veins and from the left ventricle is collected. As the blood passes down the sides of this plastic chamber any bubbles of air are dissipated. Last spring we reported the successful repair of interatrial septal defects in animals using a flap of pericardium. We have been prepared to use such a flap of pericardium in human patients. We found, however, as Swan has, that it is quite easy to close such defects with a continuous suture in the open heart under direct vision and that consequently a pericardial graft is not needed.

The inferior vena cava is cannulated by a "tygon" tube passed into the inferior vena cava by way of the right atrial appendage. The superior vena cava is cannulated by a "tygon" tube passed through a stab wound in the right atrial wall. Oxygenated blood from the apparatus is pumped into the aorta through the divided central end of the left subclavian artery. Ligatures passed around the superior and inferior venae cavae are tied over the enclosed cannulae. This diverts all the venous blood to the extracorporeal blood circuit. In addition to closing atrial septal defects in dogs with the pericardial graft, we have successfully closed interventricular defects in dogs by direct suture. The defect is exposed by an incision in the anterior wall of the right ventricle parallel to the left anterior descending coronary artery.

There has been a progressive decline in operative mortality in successive series of animals operated upon in our laboratory. Three years ago we had an 80 per cent mortality. In the most recent series this mortality has declined to 12 per cent. By operative mortality we mean any death which could be attributed to the operation and any death occurring the first month after operation. We have successfully temporarily taken over the entire blood flow through the heart and lungs of a dog for as long as one hour and forty minutes with prolonged survival in a healthy condition.

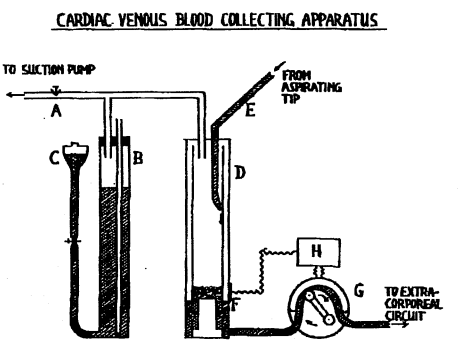

Fig. 3. Diagram of the cardiac venous blood collecting apparatus. The diagram is self-explanatory. The rotary pump G returns the blood to the main extracorporeal circuit after it has dissipated its bubbles in the inner chamber of cylinder D.

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The average saturation of the venous blood entering the apparatus is 63 per cent. We regard a normal saturation of venous blood with oxygen as the best indication of an adequate blood flow to the tissues. If the saturation of venous blood with oxygen falls to low levels it is obvious that there is an inadequate blood flow to the tissues. We have been successful in maintaining the pH in a normal range. The hemolysis in this group of experiments averaged 35 mg. of free hemoglobin per hundred ml. of plasma. You are all aware that this is an insignificant amount of hemolysis and that a similar degree of hemolysis can occur if blood is forced rapidly through a fine needle. There is only slight increase in the fixed acids, generally in the neighborhood of three millimoles per liter which is within the normal diurnal variation.

Now I suppose what you are all interested in is not how many animals we have successfully operated upon but how many humans we have operated upon. The details of our animal experiments have appeared in two articles recently published. The human patients we have operated upon, using the apparatus, have not yet been reported.

We have used the apparatus to carry temporarily the entire cardiorespiratory functions of four human patients. The first was operated upon a year and one-half ago, and the last in July, 1953, of this year. We have one surviving patient who is quite well in every way with complete closure of an atrial septal defect. The three deaths have all been due to human error and not to failure of the apparatus.

The first patient, who was operated upon a year and one-half ago, was a fifteen-month-old baby that weighed eleven pounds and was in severe congestive cardiac failure. Attempts at cardiac catheterization in this baby were unsuccessful. It was the opinion of everyone who saw this baby that the cardiac abnormality was an interatrial septal defect. We explored the right side of the heart using the apparatus and discovered that no atrial septal defect existed. The child died after operation and at postmortem was shown to have a huge patent ductus arteriosus which had not been recognized at the time of operation. This, of course, illustrates the importance of complete exploration of every heart which is operated upon. We might have saved this child's life if we had closed the ductus.

The second patient was operated upon May 6, 1953. She was an eighteen-year-old girl who had a large interatrial septal defect proved by cardiac catheterization. The patient had been symptom free until about six months before operation, when she began to show symptoms of right- sided heart failure. She was hospitalized three times in these six months. Every time she returned to ordinary activity, she had symptoms of heart failure. Cardiac catheterization revealed an atrial septal defect with a left to right shunt through the defect amounting to nine liters per minute. The patient was connected with the apparatus for forty-five minutes and for twenty-six minutes all cardiorespiratory functions were maintained by the apparatus. She had a large interatrial septal defect which was quite easily closed with a continuous silk suture. The patient's postoperative convalescence was uneventful. She was readmitted to the hospital in July, 1953. At this time, cardiac catheterization showed that the septal defect was completely closed and that there was no evidence of any shunt. The cardiac murmur had completely disappeared and she was in good health. We believe that a transverse incision extending from one axilla to the other opening both pleural cavities through the fourth interspace, and dividing the sternum, gives the best exposure for this type of cardiac operation. The chest wound heals quite solidly and results in an inconspicuous scar beneath the breasts.

The last two patients were operated upon in July, 1953. They were both underdeveloped girls aged five and one-half years. Each of them weighed only about thirty pounds. The first child had a large interatrial septal defect proved by cardiac catheterization. Cardiac arrest occurred after we had opened the chest but before we had cannulated any vessels. The heart became blue and dilated as the chest was being explored. We tried for one hour to establish normal cardiac contractions but were unable to do so. We then rather reluctantly cannulated the superior and inferior venae cavae and the left subclavian artery while an assistant massaged the heart. As soon as the patient was connected with the apparatus the heart action became strong and the color of the heart pink. We then opened the right atrium and repaired five separate defects in the interatrial septum. After the defects were closed and the heart wound sutured, the ligatures around the venae cavae were cut allowing the heart to take over part of the circulation. Whenever we stopped the artificial support by the machine, the heart dilated and began to fail. Partial support by the extracorporeal blood circuit was maintained for three or four hours at the end of which time the cannulas were withdrawn and the chest was closed. The patient's heart, however, dilated and cardiac arrest occurred. Death, of course, in the patient cannot be attributed in any way to the use of the heart-lung apparatus as cardiac failure occurred prior to the use of the apparatus. Perhaps the dilatation of the heart and cardiac arrest was the result of a reversal of the shunt through the interatrial defect due to blood transfusion which was given during the early part of the operation.

The second five and one-half-year-old child had a proven interatrial septal defect by cardiac catheterization. It proved impossible, however, to pass the catheter into the right ventricle. On clinical grounds an interventricular septal defect was thought to exist in addition to the interatrial defect. It was known that the patient had a left superior vena cava which was somewhat larger than the right superior vena cava. The child turned out to have not only a huge interatrial septal defect but also a large interventricular septal defect and a small patent ductus arteriosus. Cannulation proceeded normally in this child and when we opened the right atrium we found it to be flooded with bright red blood returning to the atrium through the tricuspid valve. Ae we could not get a clear field to work and the flow of bright red blood was so excessive, we closed the atrium and removed cannulae. The child died after the operation, which was to be expected due to our failure to correct any of the cardiac defects.

(Motion picture shown)

This motion picture was taken during the course of the operation in which the five separate interatrial defects were sutured. It

illustrates the value of being able to visualize the interatrial septum. It seems to me that the four smaller defects might have been missed by the employment of indirect blind methods. The film clearly shows how simple it is to keep the operative field clear of blood and that the heart appears of normal color and is beating well because the myocardium is receiving oxygenated blood from the apparatus through its coronary vessels.

In conclusion, I would like to say that I think the work I have reported is some of the early work in this field and that there is considerably more work to be done. It seems to me that there will always be a place for an extracorporeal blood circuit because it permits a longer safe interval for opening the heart than can ever be obtained by any of the hypothermia methods.

Discussion

DR. F. D. DODRILL, Detroit, Michigan—You have just heard an excellent review of the mechanical heart work by the leading pioneer in this country. Dr. Gibbon has had vastly more experience than the rest of us in this field, and I am envious of his vast accomplishments in this work.

When I first began this work several years ago, it was not definitely known, nor is it now definitely known, just how this can best be done. It was originally thought by those working in the field one could not bypass either side of the heart without completely bypassing the entire heart and lungs at the same time. As time has gone on and various workers have made definite contributions along this line, it is now apparent that either the right side or the left side of the heart may be bypassed while the opposite side of the heart and lungs continue to perform their functions.

We began a few years ago, therefore, to explore the possibilities of the following types of procedures: (1) bypass of the right heart, (2) bypass of the left heart, (3) bypass of both sides of the heart using the lungs for oxygenation, and (4) bypass of the heart and lungs using the mechanical oxygenator. We have performed more than 100 operations on the experimental animal doing one of these various procedures.

Our apparatus is so constructed that it can perform any or all of these functions. Insofar as the mechanical heart itself is concerned, I feel there are three factors which are important. These are: (1) it should be strong, sturdy and not subject to breakdown, (2) it should be so constructed that all parts coming in contact with the blood can be sterilized by ordinary autoclaving, and (3) it should produce and maintain a pulsatile flow in the vascular system.

Bypass of the Right Heart.—Our experimental work in bypass of the right heart has been highly successful in the experimental animal. This consists in taking the blood from the superior and inferior vena cava, passing it through the right side of our mechanical heart and back into the pulmonary circuit through the artery to the right lower lobe of the lung. By this method, the right side of the heart can be bypassed while the opposite side and the lungs continue to perform their functions. Also, if one wishes, the blood may be taken from the right atrial appendage. By this method not only the superior and inferior vena cava flow, but the coronary sinus flow, as well, can be completely diverted from the right side of the heart. These connections depend upon the type of procedure and the exposure which one is attempting.

In our experimental work on the right-sided bypass, we encounter severe hypotensive reflexes. These hypotensive reflexes are greatly increased by even the slightest degrees of anoxia. This reflex has been referred to as the Bainbridge reflex but it may be possible, that additional reflexes may be present. It is my impression that a great deal of physiological investigation is needed along this line. On the left side, however, these hypotensive reflexes are much less acute and oftentimes in the experimental animal we see no evidence at all of a decrease in the blood pressure during a left-sided bypass. Using such a procedure, any purely right-sided heart disease may be exposed and corrected under direct vision. The examples of such conditions are pure pulmonary stenosis with an intact cardiac septa and diseases of the tricuspid valve also with an intact septa. Figure 1 illustrates the pulmonary valve in a patient with pure pulmonary stenosis during a right-sided bypass. This valve was exposed for a period of twenty-five minutes while the mechanical heart pumped approximately 4½ liters of blood per minute. The left side of the heart continued to perform its function as did the lungs. While the right-sided bypass of the heart seems to be a rather practical procedure, it should be pointed out that there are not many pathological conditions of the right side of the heart alone in which such a procedure can be used. The great majority of patients with pulmonary stenosis have a defect in either the intratrial or interventricular septum and in such a patient a unilateral bypass is, of course, out of the question. There are rare instances of large emboli lodging in the right side of the heart which give some warning before death and it is possible that such large emboli could be removed during a right-sided bypass.

A right-sided bypass is a practical procedure for patients with pure right-sided disease. There is no need at all for bypassing the lungs as well for exposure of a purely right-sided defect. The main advantage of using the mechanical lung along with the mechanical heart is that the connections of the apparatus to the anatomical structures are much easier. However, with a right-sided bypass, the connections are likewise easy and should present no obstacle at all to the operating surgeon. Of all these various procedures which can be done in the way of

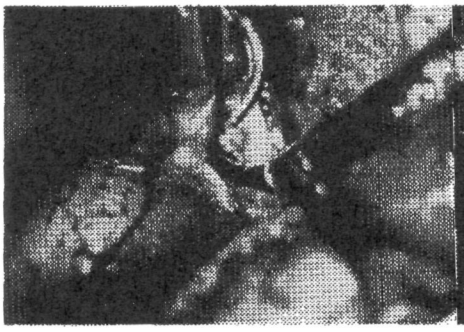

Fig. 1. Stenotic pulmonary valve in a seventeen-year-old boy.

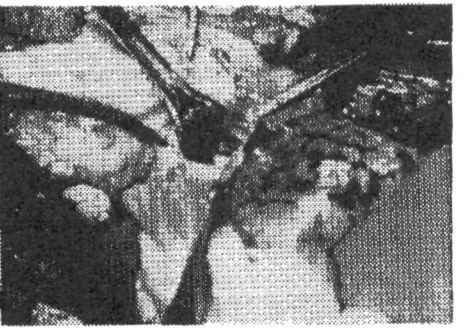

Fig. 2. Open left strium exposing the mitral valve in a fifty-year-old woman.

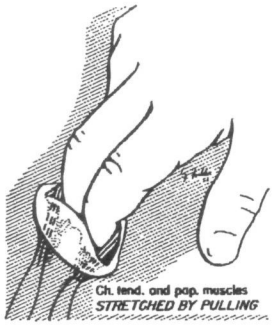

Fig. 3. A method of elongating the chordae tendineae in a patient with mitral regurgitation.

bypassing the entire heart or a portion thereof, I strongly feel that a right-sided bypass alone is a practical procedure which will be useful in years to come. The pathological conditions, however, are rather limited for this type of a procedure.

Bypass of the Left Heart.—A great deal of animal experiments have been done on the left-sided bypass. This consists in taking the blood from the pulmonary veins, passing it through the left side of the mechanical heart and back into the aorta which is its ultimate destination. The experimental work on dogs is extremely gratifying. We have been able to expose the mitral valve in dogs for fifteen consecutive times without a fatality. During the left-sided bypass, the right side of the heart and the lungs continue to perform their functions. During such a procedure, it is necessary to maintain a sufficient systemic blood pressure and preferably to maintain it by a pulsatile flow. The hypotensive reflex which is rather acute on the right side, especially if there exists any degree of anoxia, is not so acute on the left side. In numerous animal experiments, we have not encountered such a reflex at all. We have applied this procedure to a few patients. Figure 2 illustrates the open left atrium with the mitral valve in the depths of the cavity. This patient made an uneventful recovery and is much improved from the surgical procedure. It seems logical to assume that if the mitral valve can be exposed, there is more apt to be an opportunity to improve valve function especially in mitral regurgitation. Figure 3 illustrates the elongation of the chordae tendineae in a patient with mitral regurgtation during a left-sided bypass. Although, the valve and the chordae were not visualized, the arterial pressure pattern shows conclusively that the mechanical heart was completely maintaining the systemic circulation. It has now been over one year since this patient was operated and he is vastly improved, even to the point of almost a complete disappearance of his loud murmur. One additional patient has also been treated in a similar manner with encouraging results. There are several factors in the production of mitral insufficiency; however, the most important one seems to be the shortening of the chordae tendineae and sometimes the papillary muscles as well. The valve leaflet itself may be nearly normal, and if the chordae can be lengthened to the point where it permits valve closure, the regurgitation is markedly diminished or corrected. Oher types of procedures have been done during a left-sided bypass. The aortic valve may be manipulated by inserting a finger into the left atrial appendage down through the mitral valve and upwards through the aortic valve. A patient with aortic stenosis has been so treated and the valve was easily fractured with the finger. Whether or not this procedure will be better than the method of going directly through the left ventricle remains to be seen.

Bypass of Both Sides of the Heart.—A bypass of both sides of the heart using the lungs for their natural functions is a more difficult procedure from the technical standpoint. We have been able to do this, however, quite satisfactorily in experimental animals and have applied it to one patient. Both sides of the heart were completely taken over by the mechanical device. A stenotic

pulmonary valve was corrected and the interventricular septum was exposed. Unfortunately, this patient had, in addition to the pulmonary stenosis, marked infundibular stenosis and could not be sufficiently corrected. During the course of the procedure, the systemic blood pressure as well as respiratory function were quite satisfactory. Unfortunately, the patient succumbed on the fourth postoperative day from atelectasis and pneumonitis.

A Combination of Hypothermia and the Mechanical Heart.—These various procedures which I have shown you have been done solely with the mechanical heart. We are now working along the lines of the combination of hypothermia and the mechanical heart. Whether or not various types of intracardiac surgery will be done under hypothermia alone, using the mechanical heart alone or a combination of these two methods remains to be seen. The advantage of combining hypothermia with the mechanical heart is that during hypothermia, the circulating blood volume is markedly reduced and the work of the mechanical heart is vastly decreased. Moreover, with the circulation of such a small volume of blood, only one lobe of the lung needs to be used for respiration. Such a small quantity of blood can be easily circulated through one lobe of the lung while the rest of the lungs are at rest. This vastly minimized the technical difficulties with the use of the mechanical heart alone. It is easy to cannulate one of the upper pulmonary veins, to pass the blood through the left side of the mechanical heart and back into the aorta. The right-sided connections for such a procedure are similar to a complete bypass of the heart and lungs and consists simple of cannulating the superior and inferior vena cava and passing the blood back into the pulmonary circuit. The lung is a very intricate organ. It is not known but that it may perform other functions aside from the uptake of oxygen and the release of carbon dioxide. It seems as though a good hard attempt should be made at using the lung for its natural function before we completely discard it.

DR. CLARENCE DENNIS, Brooklyn, New York.—After Dr. Maurice D. Visscher and Dr. Owen H. Wangensteen jointly suggested to me, late in 1945, the undertaking of a project to develop an artificial heart-lung apparatus, I very quickly became aware of the activities of Dr. John H. Gibbon, Jr., and his group in Philadelphia. I consulted him at that time, and was very cordially received, shown protocols, shown the apparatus as it had developed up to that time, and welcomed into the group of those working on this project. Between that time and this, there have been associated in the research project with Dr. Karl E. Karlson and me approximately eighteen physicians. Work has been carried out first at the University of Minnesota and more recently at the State University of New York, and has been supported by the United States Public Health Service, the Graduate School of the University of Minnesota, the State University of New York, the Life Insurance Medical Research Fund, and private sources. In our search for an answer to this problem, my associates and I have come to have the very highest regard for the ingenuity, integrity, and cordiality of Dr. Gibbon and his associates. Success could not have come to finer people.

Dr. Gibbon has very carefully listed the qualifications of a satisfactory artificial heart-lung apparatus. We have

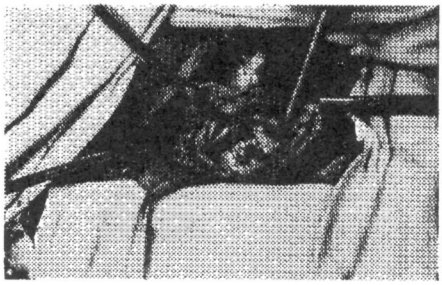

Fig. 1. Closure of inter-atrial septal defect, May, 1951. Closure was easily performed with interrupted silk sutures under direct vision. The patient suffered air embolism before opening the atrium, a consequence of human error in failure to switch on an automatic control mechanism. She died of complication of air embolism after several hours of partial support by the machine.

been concerned with an additional qualification, namely, the ability to render the whole apparatus absolutely free of bacterial contamination. The reason for our preoccupation with this qualification arises from the work of Dr. Russell M. Nelson, who was a member of our research group three years ago. Dr. Nelson showed that our apparatus at that time was contaminated with the paracolon bacillus, and that injection intravenously into normal dogs of a re-suspended fourteen-hour culture of this organism resulted in a symptom complex which had been responsible for most of the deaths prior to that time. This symptom complex developed rapidly and killed some dogs in less than three hours. The affected dogs showed a rapidly progressive metabolic acidosis, an incoagulable state of the blood, development of effusions into the serous cavities, massive gastrointestinal hemorrhage, and death in shock.[3] Satisfactory sterilization of the apparatus removed this symptom complex from our list of problems. The machine which we formerly used could not tolerate autoclaving, and sterilization by formaldehyde proved fairly regularly to be incomplete. Nevertheless, it was possible for us to do a long series of animal perfusions with this old apparatus, with no more than a 10 per cent mortality attributable to the perfusion *per se*.[1]

We gained so much confidence with this apparatus that, in conjunction with Dr. Richard Varco, we perfused two patients in efforts to achieve satisfactory closure of inter-atrial defects.[2] We were unsuccessful in salvaging either of these patients, but it was the consensus that the failure was not due to any intrinsic defect in the apparatus, but rather to human errors. The repair which was accomplished in the second patient is shown in Figure 1. This patient was lost as a conse-

quence of human error, namely, failure to turn on the automatic control apparatus, which had been designed and proven adequate to maintain the desired blood level in the reservoir of the oxygenator. Air embolism occurred because of this oversight. The patient survived approximately eight hours after the procedure, but only by virtue of partial support by the pump-oxygenator, and the closure at the time of autopsy was perfectly adequate. Dr. Gibbon's observation is in agreement with ours, namely that the margins of most inter-atrial septal defects in clinical patients are thick, and firm, and silk closure, therefore, is not usually difficult of accomplishment. Closure in this instance, in the summer of 1951, was very easily accomplished.

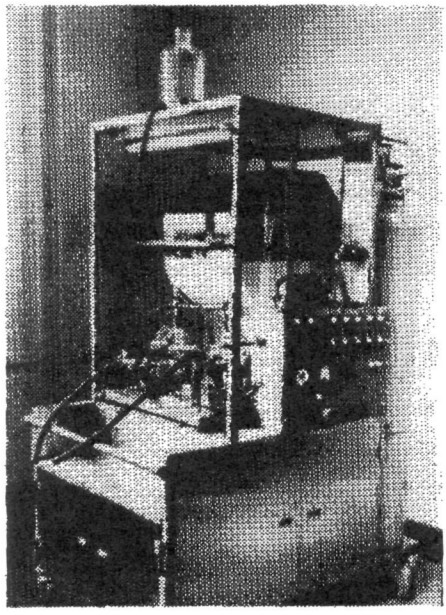

Fig. 2. The present pump-oxygenator apparatus. The entire blood-bearing unit can be autoclaved after assembly. Oxygenation is accomplished by filming on steel mesh discs which are mounted on a rotating horizontal shaft. The pumps are a modification of the Dale-Shuster pattern. Risk of human error has been reduced by use of largely automatic controls.

Because of our concern over the occurrence of human errors and because of our concern with regard to absolute sterility, we have spent the past year and a half in the construction of a new apparatus, the blood-bearing portion of which can be assembled and autoclaved as a unit. This apparatus is not yet complete, but has reached a stage of construction which has permitted us to employ it for approximately two dozen trial perfusions. The apparatus in question is indicated in Figure 2. In this apparatus, oxygenation is accomplished by the filming of blood near the center of a 50 cm. disc of stainless steel mesh which is mounted on a slowly rotating horizontal shaft. It will oxygenate 500 to 600 cc. of blood per minute from half saturation to full saturation and has a volume content of approximately 65 cc. of blood at any given moment. The pumps are a modification of the Dale-Shuster pattern. They are activated by hydraulic pressure, which is produced by a mechanical cam and bellows arrangement below the surface of the table. The apparatus as a whole will handle about 5 liters of blood per minute. It has been calculated that it should be capable of adding in excess of 350 cc. of oxygen per minute and in perfusions in large dogs has been measured to add 210 cc. per minute. We now regularly observe sterile blood cultures at the end of perfusion, and hemolysis produces approximately 1 mg. per cent of plasma hemoglobin per minute of perfusion.

There are many problems which remain and which are the source of considerable concern at the present time. It has been found that our greatest problem is that of postoperative hemorrhage. A technique of protamine titration, which has been employed over a period of several years in our laboratory, indicates that the addition of protamine to the animal is effective for only an hour or two and that additional protamine thereafter must be added until approximately six hours have passed. The platelet count is not appreciably lowered, and this, therefore, is not the reason for our hemorrhagic difficulties. It is suspected that there is excessive trauma to the blood which may be responsible for the degree of hemorrhage which we have experienced, but the low plasma hemoglobin concentrations cast a doubt even on this suggestion. Preliminary studies suggest fibrinolysin as the offender.

Perhaps our major remaining problems with the new machine rotate around the completion of satisfactory automatic controls. We have, at times, utilized the suggestion of Professor Dogliotti of Turin, Italy, that the pumping of blood from the machine to the arterial system of the subject be governed entirely by the arterial blood pressure of the subject. At other times, we have maintained a constant volume in the extra-corporeal circuit. The latter appears to be the preferable arrangement. As far as controls are concerned, the removal of blood from the venae cavae has been simplified by setting the apparatus up in such fashion that the pumps fill by gravity from the vena cava.

There remain several metabolic problems that have to be studied. An occasional perfusion is characterized by a profound loss of circulating plasma sodium. An occasional perfusion is also complicated by development of marked metabolic acidosis, even when there is a negative blood culture. Finally, there is occasionally a profound disappearance of circulating protein, which, as yet, we have not been able satisfactorily to explain.

It is likely that Gibbon has better solutions to many of these problems than we, but all of them must be painstakingly resolved before utilization of pump-oxygenators in clinical surgery can become general.

(References on Page 185)

cooled. Such a technique in practice may prove cumbersome and time consuming.

One may expect an increased incidence in wound infections with hypothermia. Another complication to be considered is the rewarming shock which has been observed experimentally and may be reduced by the use of our radio-frequency rewarming technique.

Regarding the actual technique of hypothermia, one may suggest rapid cooling in a cold water bath for infants and small children and the use of cooling blankets for larger children and adults. There should be continuous electrocardiogram recordings and rectal temperature.

The infants and children should be anesthetized and intubated before cooling as their cooling period may only be a matter of fifteen to twenty minutes. In the adults, we have cooled them with sedative alone to about 33°C., at which time they are given pentothal anesthesia with intubation and from that point down to 30°C., they are given positive pressure at twenty respirations a minute, in order to blow off excessive CO_2 and maintain a slightly elevated pH. If positive pressure is carried out for too long a period, it is suspected that this may increase the venous pressure and pre-dispose to ventricular fibrillation.

The operative technique has already been mentioned and it is recommended that rapid rewarming be carried out either by warm water at 40°C., or a radio-frequency device to a body temperature of 34° to 35°C. The final three or four degrees rewarming should be carried out in bed with warm water bottles.

Thus, at present, it is felt that hypothermia soon will be made safe for children. Adults cannot be cooled safely to body temperatures which are low enough to permit extensive intracardiac surgery. The answer to the safe cooling of adults may lie in such problems as the release of oxygen to tissues, or in understanding an anerobic type of tissue metabolism possessed at birth which gradually alters with maturity. It is suggested that cyanotic children are already conditioned to low oxygen tensions and very likely possess a slightly different tissue oxidative system. Such children may be expected to cool more safely than those that are not cyanosed.

Regarding the future of hypothermia in surgery, one is still optimistic. Extension of its use to surgery of the aorta is a natural step and many other possible uses such as liver surgery may be found. It requires study and care in its clinical application. Hypothermia as applied to cardiac surgery has, as its greatest asset, its simplicity.