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ANESTHESIA IN THE SURGICAL TREATMENT OF CONGENITAL PULMONIC STENOSIS * †

M. H. HARMEL, M.D., AND AUSTIN LAMONT, M.D.

Baltimore, Md.

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-

* From the Department of Surgery, Division of Anesthesia, Johns Hopkins University and Hospital, Baltimore, Md.
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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 re-vascularized 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 abnormalities, including auricular flutter which lasted twenty minutes. *

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

Case 32.—This patient, aged 2 years, successfully survived two operative procedures. Unlike most of the other patients, he had hypochromic microcytic ane-

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* 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 noted, 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.
miae 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 administered 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 hemotherax (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 (subelavian, 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
Surgical Treatment of Congenital Pulmonic Stenosis

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

**CARDIAC WEAKNESS DURING OPERATION AND DEATH BY AGENT**

![Diagram showing the percentage of cases, cardiac weakness, and deaths with ether, cyclopropane, and both agents.](image)

**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.

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<th>Table 1</th>
<th>Relationship of Pulse Rate and Blood Pressure to Anesthetic Agent</th>
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<td></td>
<td>Ether</td>
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<tr>
<td>Tachycardia</td>
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<td>Bradycardia</td>
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<td>Hypertension</td>
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<td>Hypotension</td>
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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 bronchial 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-
STROKED 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>
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<th>Content, vol. per cent</th>
<th>Oxygen Capacity, vols. per cent</th>
<th>Saturation, per cent</th>
<th>Carbon Dioxide Content, vols. per cent</th>
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</thead>
<tbody>
<tr>
<td>After 10-20 minutes of anesthesia</td>
<td>+6.9</td>
<td>-1.2</td>
<td>+36</td>
<td>+5.4</td>
</tr>
<tr>
<td>6-12 minutes after end of operation, breathing room air</td>
<td>+3.4</td>
<td>-2.8</td>
<td>+23</td>
<td>+4.2</td>
</tr>
</tbody>
</table>

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 untired 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-
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.

DEATHS BY OPERATION AND VESSEL USED

![Diagram showing deaths by operation and vessel used]
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 mucous 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

<table>
<thead>
<tr>
<th>From beginning of anesthesia to closure of incision</th>
<th>Average</th>
<th>Longest</th>
<th>Shortest</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2 hr. 40 min.</td>
<td>3 hr. 40 min.</td>
<td>1 hr. 40 min.</td>
</tr>
<tr>
<td>From opening of pleural cavity to closure of incision</td>
<td>2 hr.</td>
<td>3 hr.</td>
<td>1 hr. 15 min.</td>
</tr>
</tbody>
</table>

4. **Days from Operation to Discharge from Hospital**

<table>
<thead>
<tr>
<th>Average of 72 Patients</th>
<th>Longest</th>
<th>Shortest</th>
</tr>
</thead>
<tbody>
<tr>
<td>27</td>
<td>58</td>
<td>14</td>
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</table>

**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.

**References**


There will be a joint meeting of The American Society of Anesthesiologists, Inc. and The Ohio Society of Anesthesiologists, November 1st and 2nd, 1946, in Cincinnati, Ohio, at the Hotel Gibson. The complete program should appear in the next issue of Anesthesiology.