Clinical Experiences with Induced Cardiac Arrest During Intracardiac Surgical Procedures *

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THE ADVANTAGES of a quiet, bloodless heart during intracardiac operations are evident. During the conventional bypass of the heart with the pump-oxygenator, while the heart continues to beat, there is a continuous flow of blood from the coronary sinus which may obscure the operating field in the ventricle or atrium even though attempts are made to remove the blood by aspiration. If the pump run is prolonged, it is mandatory that the aspirated blood be returned to the pump-oxygenator system. A certain amount of hemolysis and other trauma to the blood is produced by this manipulation. With the open beating heart, there is danger of air embolism to important systemic arteries. Finally, it is not unlikely that at least some of the procedures which are now carried out in the open heart would be more effective if they were done with the care which is possible in a quiet as well as a dry field.

During the latter part of the year 1954, we began some investigations in our laboratory to see if a method of stopping and starting the heart at will could be devised. We quickly found that stimulation of the vagus nerve was ineffective. A cursory review of the work of Björk led us to pass by temporarily the possibility of using acetylcholine. The possibilities of the use of potassium chloride were suggested because it had been employed as a defibrillating agent by Hooker [5] and by Wiggers.[15] We found that prompt cardiac standstill was produced when this drug was injected into the left ventricle. Since no pump-oxygenator was available at that time, we were dependent on manual systole for resuscitation. During this phase of the recovery process, a coarse ventricular fibrillation usually appeared and this was abolished with one or two countershocks. With the animal under hypothermia to protect the nervous system, complicated operations were carried out within the atrial and ventricular cavities. The results of these experiments were reported in 1955 before the American Association for Thoracic Surgery.[6] In October of that year, we attempted the correction of transposition of the great vessels in a tiny, desperately ill child. Under conditions of deep hypothermia, the heart was stopped by the potassium chloride method and the arterial trunks were transposed to a corrected position by suture. After 18 minutes of caval occlusion, an attempt was made to start the heart, but because of leaks in the suture line, no effective head of pressure could be developed in the pulmonary artery from which the coronaries arose, and the heart never showed any evidence of activity.

Although the incidence of resuscitation in experimental animals was very good after potassium chloride arrest (19 out of 20 hearts in one series were resuscitated), we continued to search for a safer method. In November 1955, we decided to re-in-

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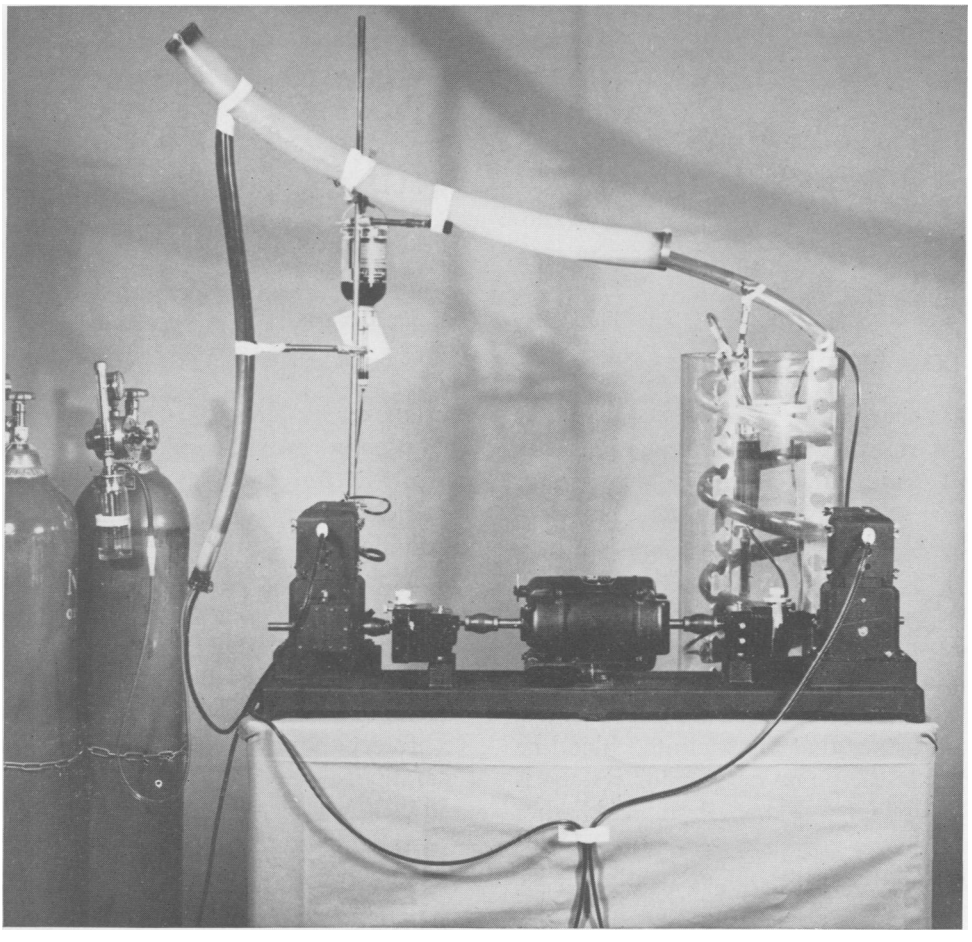


FIG. 1. Pump-oxygenator of the DeWall-Lillehei type. Blood is pumped from the vena cavas into the vertical oxygenating tube on the left; bubbles are removed in the larger inclined tube and the defoamed blood collects in the helix in the water bath, where it passes through a filter and is pumped into the subclavian artery by the head of the Sigmamotor pump on the right.

vestigate the effectiveness of acetylcholine as a cardioplegic drug. It worked very well.[4, 7, 14] The agent was introduced through a catheter in the aorta and resuscitation was obtained by perfusing the coronary arteries with oxygenated blood from a reservoir. The reservoir source of oxygenated blood was of course soon replaced with a pump-oxygenator, which not only provided the ideal way of resuscitating the heart but permitted an apparently unlimited operating time while the heart and lungs were out of the circulation. We chose to use a pump-oxygenator of the bubble type devised by DeWall, Lillehei and their associates[9] (Fig. 1). We have continued to use their method with no important modification except that the flow rates have been doubled—from approximately 30 cc./min./kilo to 50–60 cc./min./kilo.

After having adopted acetylcholine as a preferable cardioplegic drug, we learned of the work of Melrose of London who had stopped hearts in the laboratory by intracoronary perfusion with potassium citrate.[11] He advised us that our earlier difficulties with a solution of potassium salt were probably due to the fact that we had used the

chloride instead of the citrate.[10] We suspect that the difficulty (ventricular fibrillation) was due more to the method of resuscitation (cardiac massage) than to the type of potassium salt used, but we have not carried out experiments to settle this point. We did induce cardiac arrest in a small series of ten animals by the Melrose technic and observed that the phase of resuscitation compared favorably with that of a similar series of acetylcholine-induced arrests, but it was not superior and there was one instance of irreversible ventricular fibrillation following a second arrest with potassium citrate.[12] Effler and his associates [3] have used the Melrose method in clinical cases. Acetylcholine has been employed by Moulder and his associates to slow or stop the heart during cardiotomy under hypothermia.[13]

The mthod of inducing cardiac arrest which we have adopted is illustrated in Figure 2. Following the introduction of the appropriate cannulas into the subclavian artery and the vena cavas and their attachment to the pump-oxygenator, the pump run is begun and the snares are tightened about the vena caval cannulas. If the check on the level of blood in the helix of the oxygenator system shows that inflow and outflow rates are equal, we proceed to stop the heart. A non-crushing clamp is placed across both the aorta and pulmonary artery. Although clamping of the pulmonary artery is not essential, it does no harm and separation of the two vessels by dissection carries some hazard. A figure-of-eight suture is placed on the anterior surface of the aorta before the clamp is tightened. The needle of the syringe containing the acetylcholine is thrust into the aorta through the figure-of-eight suture, and the contents of the syringe is injected rapidly, so that it enters the coronary arteries. (The dose of acetylcholine which we have used is 10 mgm. per kilogram of body weight of the commercial preparation Acecholine, Anglo-French Laboratories.) The heart stops when about two-thirds of the solution has been injected,

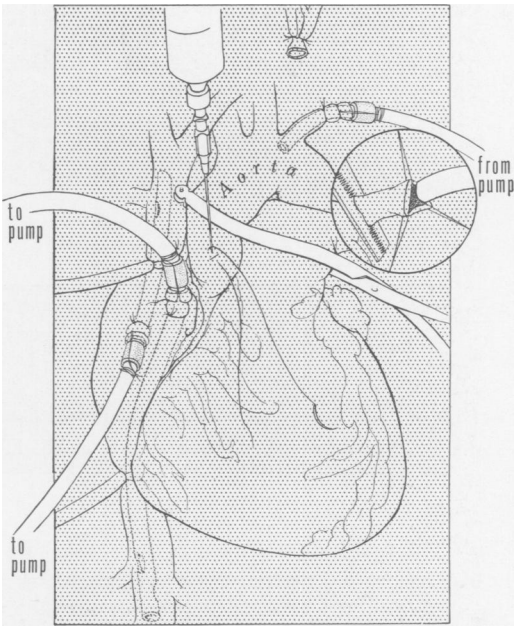


FIG. 2. Method of inducing cardiac arrest with acetylcholine, following cannulations for pump-oxygenator by-pass of heart.

but the rest is given. A second syringe containing a similar amount of acetylcholine is in readiness and may need to be used if a technical error has resulted in a loss of some of the first solution. Although apparently in arrest, the heart beats when the ventricular wall is stimulated mechanically by forceps or needles. There is usually no activity during the suture of the interventricular septal defect or procedures on the values. No additional acetylcholine is given for the sporadic beats which arise as a result of direct stimulation.

When it is desired to resuscitate the heart, one has simply to remove the clamp from the great vessels. This permits the oxygenated blood from the pump-oxygenator to flow via the aorta into the coronary arteries. The acetylcholine is washed out of the coronary arteries into the coronary veins where it escapes into the right auricle via the coronary sinus. During the repair of an interventricular septal defect, there is an

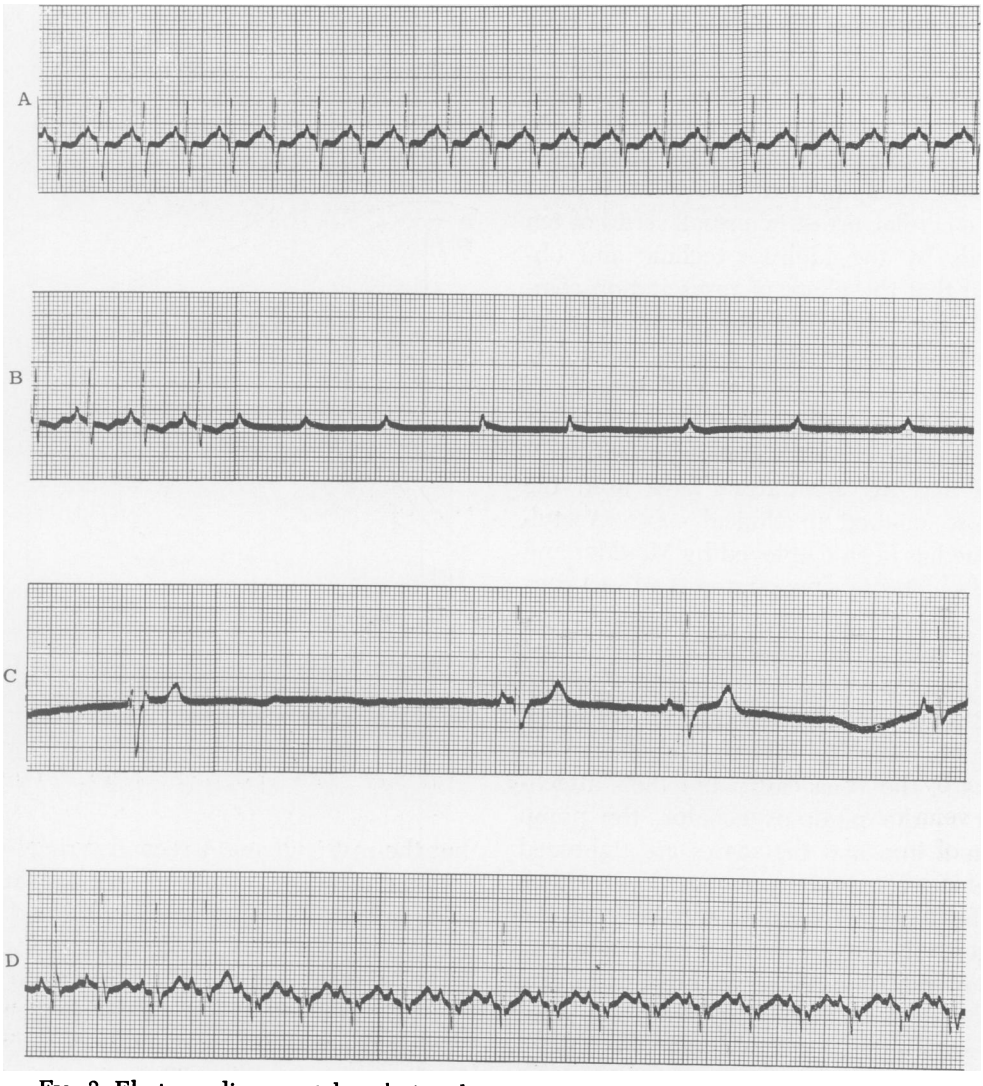


FIG. 3. Electrocardiograms taken during the repair of an interventricular septal defect in a three-year-old child. A. Tracing before arrest of heart. B. Sudden cessation of ventricular systole following injection of acetylcholine. Note that auricle continues to contract. C. Early ventricular activity following removal of aortic clamp to permit coronary perfusion with oxygenated blood. D. Resumption of regular rhythm.

incision in the right ventricle from which the blood containing the drug can escape. However, since acetylcholine is rapidly destroyed or at least neutralized in the body,[2] the importance of having the safety valve feature is to avoid distention with blood per se. It has been our policy to remove the aortic clamp before beginning the closure of the right ventricle. This suture line can be put in easily during the resumption of the heart beat and the presence of a vigorous contraction as the last part of the ventriculotomy incision is closed, with the coronary sinus blood spurting out, practically insures against air being trapped in the right heart. If the surgical procedure is being done through an atrial incision, i.e. for atrioventricularis communis type of defects, the right ventricle and atrium are filled with the venous blood from the pa-

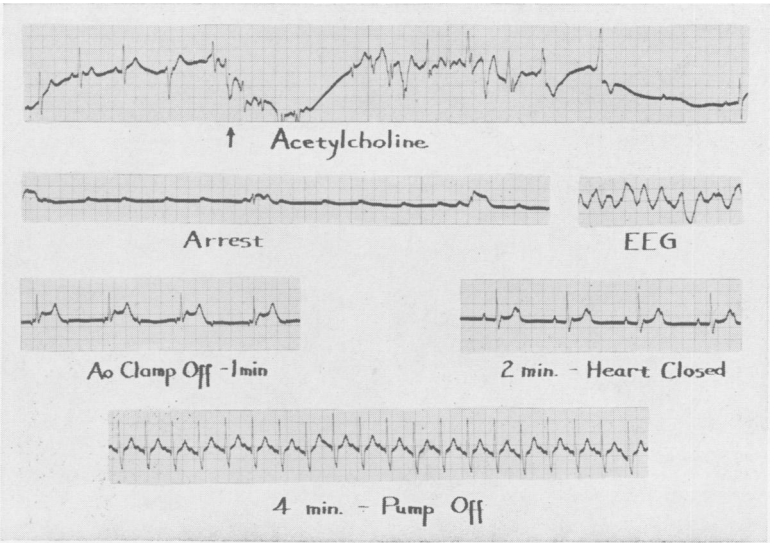


FIG. 4. Electrocardiograms taken during closure of interventricular septal defect in a six-year-old boy. The lower three tracings were made one, two and three minutes following the release of the aortic clamp.

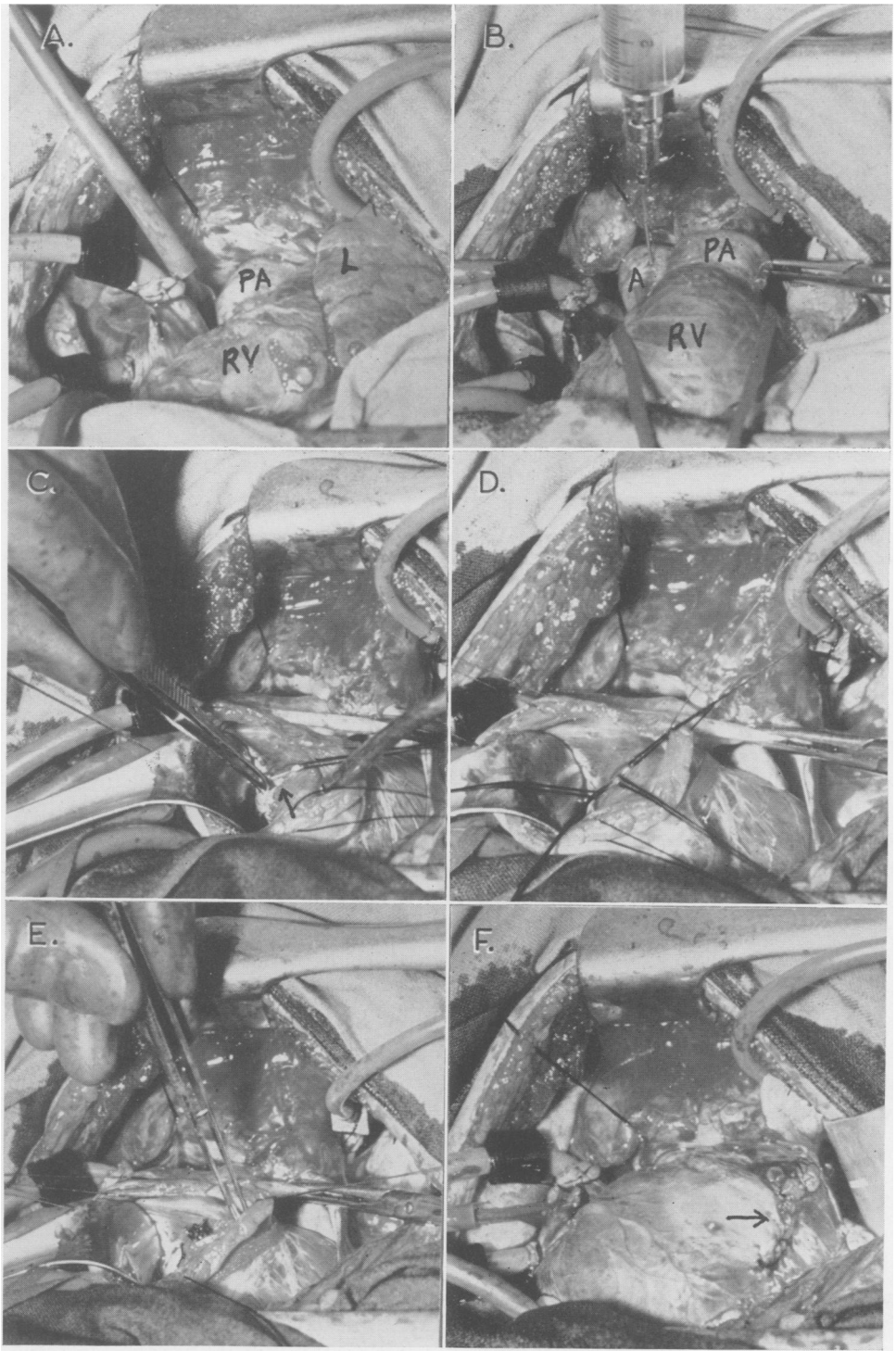
tient by the momentary release of one of the vena caval snares before complete closure of the atrial incision.

In case there is neither a ventriculotomy no atriotomy, as would be true during operations on the aortic valve through an aortic incision, it is necessary to provide for the escape of bronchial blood returning through the pulmonary veins to the left heart and for the removal of coronary sinus blood from the right atrium during the early part of the resuscitation phase when the aortic clamp has been removed with resumption of flow in the coronary arteries but before the heart has begun to beat. Otherwise, there might be deleterious stretching of a ventricle. If such overdistention were observed, it had better be corrected by a single manual compression of the heart, but we prefer not to massage the heart at this time because of the danger of inducing ventricular fibrillation.

The electrocardiogram reveals all sorts of bizarre patterns during the arrest and subsequent resuscitation. Probably every arrhythmia and abnormal pattern known to cardiologists has been recorded on the monitoring electrocardiograph. Two examples are shown in Figure 3 and 4.

CLINICAL USE OF INDUCED CARDIAC ARREST

Since October 1955, induced cardiac arrest has been used as an adjunct in 80 cardiac operations. Fifty-four of these operations have been for the repair of interventricular septal defects in 53 patients (one patient had a second operation and a second arrest for the repair of recurrence of the defect). Details of these operations have been reported elsewhere.[8] Induced cardiac arrest seems to be especially valuable for this type of surgical procedure. In the perfectly dry and quiet field, suturing can be done with great accuracy (Fig. 5). Restoration of the heart beat has been no problem. One of the very early cases with poor coronary perfusion because of the low flow from the pump presented a heart which was assisted with manual systole. Ventricu-



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lar fibrillation appeared in three hearts during resuscitation. One of these had fibrillated twice before the cannulation for the pump-oxygenator, and the last cannulas were put in while the heart was being massaged. Sinus rhythm was restored in each case with one light countershock.

Atrioventricular block has been the most vexing problem in the septal defect cases. It was present in nine of the ventricular septal defect operations but three of these converted to sinus rhythm during the first few hours. The block has remained in one patient who is alive four months after the operation but in five, the persistent block seemed to be the chief factor in the death of the patients. The incidence of ten per cent of the complication of atrioventricular block is distressing and could be considered as an indictment of the method of stopping the heart. However, it is known that the same complication plagues those surgeons who repair the defects without stopping the heart and the answer cannot be had until after an analysis of a considerable number of cases done by both methods.

The mortality rate as a result of early and late deaths in the interventricular septal defect cases is shown in Table I. The mortality rate of 35 per cent in the entire series is due to the fact that it includes the nine tiny babies who died after operations done in desperation because the children had ceased to grow and appeared to be near death. Five of fourteen of such children were salvaged. It is evident that in the older age group, over three years, the prognosis becomes infinitely better. Of the nineteen patients in this group who have been operated on with flows of 50 cc./kilo/min., only one failed to survive, giving a mortality rate of only about five per cent.

TABLE I. *Mortality Rates in Closure of Ventricular Septal Defects*

Age	No. Cases	Deaths	Mortality Rate
All cases	54	18	35%
Under one year	14	9	65%
Over 1 year	40	10	25%
Over 2 years	27	5	18%
Over 3 years (pumped 50 cc./kilo/min.)	19	1	5%

After the value of induced cardiac arrest was evident in the septal defect operations, the method was employed in a wide variety of congenital and acquired lesions in 26 patients. Most of these were in a precarious condition and no alternate operation seemed available.

Some of the congenital anomalies encountered almost defy classification. Seven had complicated anomalies of the atrial septum and/or insertion of the pulmonary veins (all septum secundum defects and most primum defects are repaired by closed technics). A tiny infant of three months was found to have a triatrial heart of the type where there are two left atria, both communicating with the right atrium through septal defects. Into one of the atria the pulmonary veins emptied, while the mitral

FIG. 5. Series of photographs taken during the repair of an interventricular septal defect in a seven-months-old child. A. At completion of cannulation for pump run. Five tubes are visible. Starting at the upper right hand corner and proceeding clockwise, they are: subclavian inflow cannula, inferior vena caval snare, superior vena cava outflow cannula, inferior vena cava outflow cannula, and superior vena cava snare. B. Injection of acetylcholine into aorta proximal to clamp which also occludes the pulmonary artery. Incision will be made in the bulging portion of the right ventricle (RV). C. Defect is seen through ventricular incision (arrow). The forceps enters the defect and pulls it toward the right; the first suture is exerting traction toward the left. D. Four sutures have been placed through the margins of the defect. E. Sutures have been tied after having been passed through a pledget of compressed Ivalon sponge. F. Clamp on great vessels has been removed, ventricular wound sutured (arrow), and heart is beating.

valve drained the other atrium. Correction was achieved by removing the septum from between the two left atria and closing the large interatrial septal defect remaining. This infant died during the first postoperative night of atelectasis. There were three cases of atrioventricularis communis with mitral valve clefts. All had suturing of the mitral valve and closure of the septal defects without the addition of prostheses. All survived the immediate postoperative period. One of the children died a month after the operation with signs of congestive failure and autopsy showed a single coronary artery, Another with persistent atrioventricular block died three months after operation; postoperative catheterization had indicated that there was recurrence of the interatrial defect. At the present time, we are inclined to believe that a prosthesis of compressed Ivalon® sponge should be inserted with circumferential sutures to avoid tension and distortion of the structures in the valve area.

One child had anomalous insertion of the veins of the right lung into the right auricle, without an interatrial septal defect. It was found to be impossible to create a septal defect to which to suture the veins without opening the auricle. We tried to create the defect by the closed method of Blalock and Hanlon, but this was impossible because the left atrium was small and the septum was attached far to the left. Under direct vision, after attachment of the pump-oxygenator, the septum was incised to make a defect and the indicated plastic repair was carried out with recovery of the child.

A tiny infant had a very unusual type of heart. The superior vena cava which was on the left entered the left auricle. All of the pulmonary veins entered the right auricle and there were interatrial and interventricular septal defects. A plastic repair of the septum corrected the double anomalies of the venous drainage, but a small atrial wound was made in transplanting the septum and after resuscitation of the heart, fatal hemorrhage ensued. A child with a functionally single auricle had such a small mitral valve that it was located with great difficulty. An interatrial septum was created out of the available tissue and the heart beat was restored. The child died during the first postoperative day and autopsy showed an unrecognized interventricular septal defect. The thrill over this high defect was erroneously interpreted to be due to relative infundibular stenosis. Sampling of the blood in the ventricle following the repair of the first defect would have revealed the second.

Two children were operated on for congenital aortic stenosis. Through a longitudinal incision in the aorta, it was perfectly easy to make incisions into the commisures to relieve the stenosis. Unfortunately, induced arrest was faulty in one of these patients because the aortic clamp had not been placed entirely across the aorta, permitting perfusion of the coronary arteries before the aortotomy was made. The valve was opened while the heart was beating, but during the closure of the aortic incision, ventricular fibrillation ensued and this was very resistant to defibrillation. Eventually, a fairly good beat was obtained, but in the recovery room, bleeding from one of the chest drainage tubes was observed and it was necessary to open the chest in the operating room. A small leak in the aortic suture line was repaired but during the closure of the chest incision the heart fibrillated again and this time it could not be resuscitated. We believe that it would have been preferable when it was observed that the induced arrest was not complete to have sutured the aortic incision and introduced more acetylcholine before proceeding with the valvotomy.

We have operated on one adult patient with aortic insufficiency. Again, good cardiac arrest was not obtained because most of the acetylcholine undoubtedly passed into the left ventricle through the incompetent aortic valve rather than into the

coronary arteries. With the heart beating, an aortic valve prosthesis of the watch-spring type (Jacobson and his group) was inserted. The huge ventricle began to fibrillate during the closure of the aortic incision and although defibrillation was eventually obtained, the patient expired in the recovery room four hours later. Blood pressure determinations had shown that the valve prosthesis had been functioning in a satisfactory manner. In order to obtain perfect arrest in a subsequent case, we shall have facilities for perfusing the coronary arteries directly through their ostia.

We have operated on one case of tricuspid insufficiency and one of mitral insufficiency. No curative operation was possible and both succumbed on the day of operation. Operation was undertaken on a man with an aneurysm of the ascending aorta which had come to occupy the entire right upper chest with erosion of the upper two ribs. With separate perfusion of the left common carotid artery, and a clamp across the aorta between the innominate artery and the left common carotid, the huge mass was incised and the great masses of clot were lifted out. The vessel was then trimmed and tailored until the lumen could be restored. A graft consisting of a child's aorta connected the reconstructed ascending aorta with the common origin of the left subclavian artery and left common carotid arteries. The pump run was one hour and three minutes. A feeble but unsatisfactory heart beat was restored; the patient expired in the operating room.

Three operations have been carried out for tetralogy of Fallot. All were desperate cases of shunt failure. One had had closure of the Blalock type of anastomosis on both sides, another closure of a single anastomosis and a third had difficulty because of an overly large aortic-pulmonary anastomosis. All died following satisfactory anatomic correction, two of heart block and another of cerebral complications of unknown origin. Three patients with pulmonic atresia died after operations which apparently provided anatomic correction of the defects. Three infants died after attempts at correction of transposition of the great vessels, but in only one was the pump-oxygenator used. The other two cases was operated on under hypothermia before the oxygenator was available. In the case done under extracorporeal circulation, the interatrial septum was transposed so as to give complete correction of the blood flows. The color of the child was remarkably improved but heart block proved fatal. Three infants were found to have single ventricles and all expired soon after exploration.

A right ventriculotomy was carried out on an infant of five months because of catheter findings and physical signs of interventricular septal defect. No defect could be found until an atriotomy revealed that the shunt was actually from the left ventricle to the right auricle. This defect was easily closed and the child is well.

SUMMARY AND CONCLUSIONS

A method of inducing cardiac arrest as an adjunct for intracardiac operations has been described. This involves the perfusion of the coronary system with a solution of acetylcholine. Resuscitation of the heart is obtained by perfusion of the coronaries with oxygenated blood from a pump-oxygenator system.

A clinical experience of 80 operations is reported. Fifty-four operations were for the repair of interventricular septal defects and 26 were for a variety of congenital and acquired lesions of the heart. Cardioplegia appears to be a valuable aid in these complicated cardiac operations.

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Discussion

Dr. Dennis: Mr. Chairman, members and guests: A group of us, working at the State University of New York in Brooklyn, has become very much impressed with the problems of air embolism. As a means to gain a better understanding of this problem, deliberate injection of gas into the internal carotid artery has been utilized. When the injection is slow, there is a gradual deepening of anesthesia during the course of that injection, and there is a tendency to wake up rather slowly. Dogs may wake up completely, walk around the room, perhaps even eat, and then, at the end of 12 to 18 hours, they will lose consciousness, go into shock, and die in spite of anything we can do to try to salvage them. It is our suspicion that a lack of familiarity with this course of events has led to failure to recognize air embolism on the part of many people who are working in this field.

Incidentally, the electroencephalogram taken during the course of injection and immediately afterward, in these dogs, shows no abnormality whatsoever, and yet the dogs will die from air embolism, and at autopsy will have extensive brain damage, which has been responsible for their deaths.

Appreciation of this difficulty led us to use ventricular fibrillation to stop the pumping action of the heart while the heart is open and circulation is being carried by a modification of the pump-oxygenator which our group reported to this organization in 1951. We have used potassium for arrest, and we have tried acetylcholine for arrest, but have been bothered with failure of the heart to recover in a considerable fraction of the patients and dogs in which this technic has been employed.

Ventricular fibrillation has been used in the creation and closure of septal defects in 35 dogs, and in placement of synthetic mitral valves in over 75 dogs. It has worked nicely in 5 clinical cases as well. There is a tendency to spontaneous reversion to normal rhythm, which is easily controlled, and it has been our experience that defibrillation has regularly occurred with a single shock when it is desired to have the heart start again.

This method has the advantage of providing a continuous coronary perfusion in a relatively quiet heart, without a limit as to the length of time that the surgery may require. It would seem to be useful wherever the cardiotomy is needed without necessity for a full dry surgical field. Thank you. [Applause]

Dr. Cooley: I agree with Dr. Lam and others who advocate the use of cardioplegic agents in