ELECTIVE CARDIAC ARREST IN OPEN-HEART SURGERY

Report of Three Cases

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IN 1954, Warden, Cohen, Read, and Lillehei[1] reported their initial experience in open-heart surgery with cross-circulation technics. Their imaginative approach and experience have given impetus to the solving of the most formidable problem in cardiac surgery. In succession, the principle of cross circulation using compatible donors, the utilization of the dog-lung preparation, and finally the perfection of the bubble-type oxygenator have introduced the era of open-heart surgery. Their work has given promise that safer and more economical methods will evolve for performing direct-vision surgery within the living heart.

Open-heart surgery requires occlusion of the venous systemic return to the heart with detour of the unsaturated blood to an oxygenator that will return blood through a major artery, usually the subclavian (Fig. 1). This bypassing procedure permits satisfactory perfusion of vital organs with a reduced flow of blood employing the "azygos flow principle."[2] This technic permits open-heart surgery via auricle or ventricle, but it does not offer a dry operating field. Although no blood returns via the venae cavae, there is a significant flow through the coronary circulation, emptying by way of the coronary sinus and the thebesian veins into the heart. In addition there may be partial aortic valvular incompetence with retrograde flow through a septal defect, and there may be a significant collateral circulation emptying into the left side of the heart, the latter in those cases where there is obstruction of the right ventricular outflow (e.g. tetralogy of Fallot). Since these channels may permit a considerable loss of blood after ventriculotomy, the total loss may amount to several liters for the time required to perform the intracardiac procedure. The handicaps

This work was supported by a grant to Doctor Kolff from the Cleveland Area Heart Society.

imposed by excessive blood loss are obvious. These are compounded by the impaired visualization of the surgical field and the constant distraction that it affords. This anticipated loss of blood makes a large reserve of blood mandatory.

The ideal method of open-heart surgery is that which affords a dry field and a motionless heart. Lillehei and his group[1] have employed temporary aortic occlusion by tourniquet to reduce for very brief intervals the volume of blood returned from the coronary vessels. However, they pointed out that this method must be used with caution, because it may result in dangerous myocardial

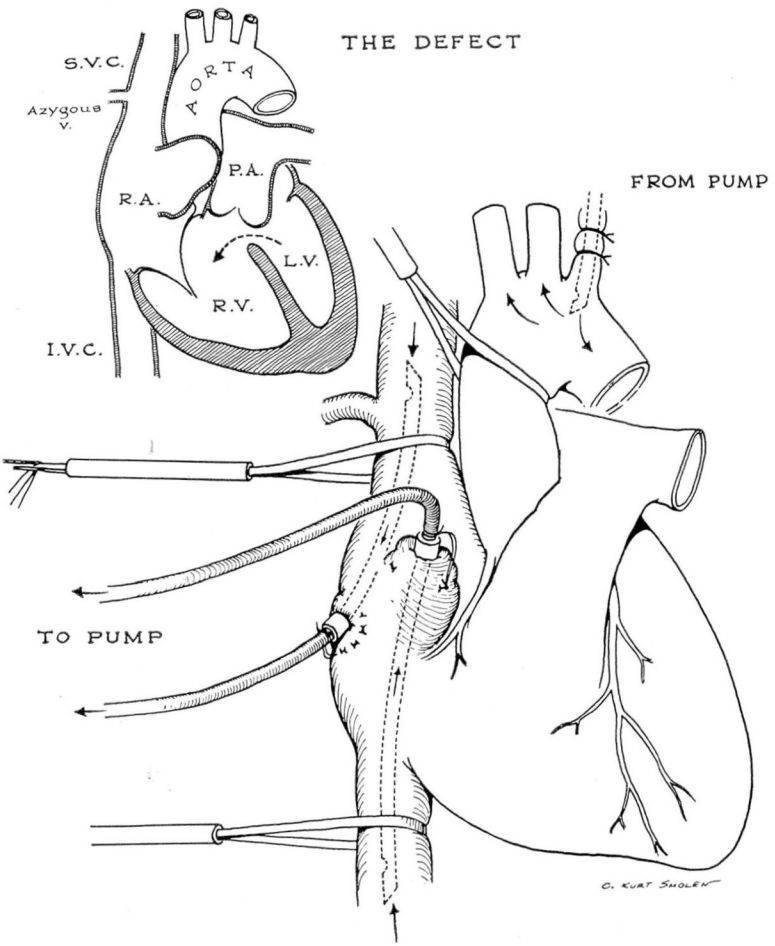

Fig. 1. Schema demonstrating the usual pattern of cannulation employed in operations with artificial maintenance of circulation. Thirty-five ml. per kg. per minute of the systemic venous return is diverted to the oxygenator by intracaval catheters. Blood returning from the oxygenator enters the aortic arch by way of a subclavian artery. This return flow of oxygenated blood perfuses the coronary arterial system, as well as the brain and other vital organs.

ischemia. Experience in the laboratory has shown that, as such, aortic occlusion provides a dry field with excellent intracardiac visualization, but that aortic occlusion while the heart is beating may cause dangerous myocardial ischemia. Since the open heart continues to beat actively during the bypassing procedure, it is logical to presume that the myocardium continues to demand oxygenated blood, even though the cardiac output is very small.

As indicated in the preceding report by Kolff and associates, it was our belief that controlled cardiac arrest would offer the ideal adjunct to open-heart surgery. Laboratory application of the method suggested by Melrose and associates[3] showed that it was a simple matter to arrest the beating heart in a healthy animal, perform an open-heart procedure, and re-establish a normal rhythm within a comparatively short time. In brief, this method consists of applying the usual technics to bypass the beating heart with a heart-lung machine, and then of injecting a potassium citrate—blood mixture into the occluded aorta immediately above the coronary ostia (Fig. 2). We use 2 cc. of a 25 per cent solution of potassium citrate mixed with 18 cc. of heparinized blood. The heparinized, oxygenated blood is taken from the pump reservoir. This simple procedure results in prompt asystole and allows direct visualization within the chambers under ideal surgical conditions: there is no blood flow and the field is both dry and motionless. This elective cardiac arrest can be terminated at will by removing the aortic occluding clamp and permitting arterial blood to perfuse the heart and to remove the potassium citrate solution. Within a matter of minutes the heart resumes a progressively stronger beat until a normal sinus rhythm has been established. Cardiac massage or stimulation has not been necessary to re-establish heart beat. In dogs this method can be safely employed for periods of 15 to 20 minutes without producing the unfavorable sequelae of myocardial ischemia. It seems logical to assume that the healthy human myocardium at complete rest can tolerate anoxia for prolonged periods of time, in contrast to the myocardium that is doing work. On the basis of these experimental observations, we decided to use elective cardiac arrest by potassium citrate perfusion as an adjunct in open-heart surgery.

Report of Cases

Case 1. A 17-month-old child weighing 22 pounds, was admitted to the Hospital for surgical treatment of a large interventricular septal defect on February 13, 1956.

Past history. The diagnosis had been made during a previous hospitalization (May 27, 1955). The physiologic data obtained from catheterization studies performed at that time (F.M.S.) are presented in Table 1.

Present illness. The child had no signs of congestive failure. There had been recent improvement in functional status, suggesting further disease of the pulmonary artery with decrease in the left-to-right shunt.

Laboratory studies. The electrocardiogram showed sinus tachycardia with right ventricular hypertrophy. The hemoglobin content was 11.4 gm. per hundred milliliters;

red cell volume 39 ml. per hundred milliliters; serum sodium 145, serum potassium 5.1, CO_2-combining power 17.6, and plasma chloride 102 mEq. per liter; blood-urea content 36 mg. per hundred milliliters; and blood pH 7.27.

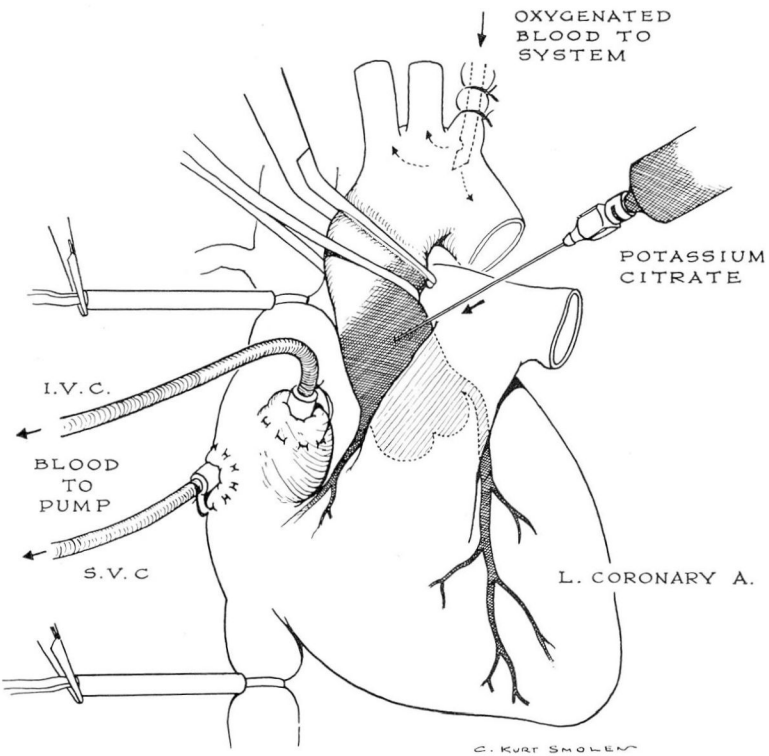

Fig. 2. Technic of elective cardiac arrest by coronary perfusion with a potassium citrate—blood mixture. The venae cavae are occluded by umbilical tapes and the heart is bypassed with the extracorporeal pump-oxygenator. The aorta has been occluded midway between the aortic valve and the innominate artery. The potassium citrate—blood mixture is indicated as being injected directly into the occluded aortic segment and perfusing the coronary bed. Less than 2 cc. of a 25 per cent solution of potassium citrate mixed with 18 cc. of oxygenated heparinized blood usually is necessary to induce arrest in a child's heart. The induced arrest is associated with myocardial paralysis. The heart appears to dilate as it becomes flaccid. Actually the dilatation is apparent rather than real, because of complete relaxation of the muscle fibers.

Operation. On February 17, 1956, open-heart surgery was performed under endotracheal anesthesia. A sternal transecting approach was used to open both pleural spaces. Artificial maintenance of circulation was established by cannulating both caval veins and the left subclavian artery. The ascending aorta was mobilized by sharp dissection and

elevated by umbilical tape. When these preparations had been completed, the superior and inferior caval veins were occluded and the venous return to the right side of the heart was bypassed to the Kolff oxygenator (Fig. 2). The heart was permitted to empty by beating for approximately 30 seconds and then the aorta was occluded at a point approximately 2 cm. distal to the aortic valves. A solution of potassium citrate (2 cc. of 25 per cent potassium citrate) in 20 cc. of heparinized blood was then injected directly into the aorta proximal to the occluding clamp. This induced cardiac arrest within one minute.

The flaccid right ventricle was then opened by a long incision. The blood was aspirated from it and the motionless surgical field was clearly visible and easily examined. The high septal defect was identified and four interrupted silk sutures were carefully placed to approximate its edges. The inspection and closure of the septal defect required approximately 10 minutes. After closure of the septal defect, the occluding clamp was removed from the aorta, the coronary circulation promptly resumed, and closure of the ventricular incision was begun. Before the closure was completed, the heart resumed a vigorous beat with sinus rhythm. After a short trial period, first with and then without support by the heart-lung machine, the heart action was considered adequate, and the chest incision was closed in the usual manner with suction drainage of 20 cm. of water to each pleural cavity.

Postoperative course. During the immediately postoperative period, care was taken to maintain normal body temperature and blood volume. Convalescence was satisfactory, and the child was discharged on March 3, 1956, 15 days after operation.

Table 1.—*Findings on catheterization studies (Case 1)*

Sample No. and location	Pressure (mm. Hg)	Oxygen content Volume %	
1. Superior vena cava	—	7.6	
			Av. 8.0 vol. %
2. Inferior vena cava	—	8.4	
3. Right auricle, high	2.0	7.6	
			Av. 7.8 vol. %
4. Right auricle, low	2.0	8.0	
5. Right ventricle, midzone	55/3	10.4	
			Av. 10.5 vol. %
6. Right ventricle, outflow tract	55/2	10.6	
7. Left main pulmonary artery	54/21	10.4	
			Av. 10.45 vol. %
8. Main pulmonary artery at bifurcation	47/20	10.5	
9. Femoral artery	98/55	11.3	(84% capacity)
Oxygen capacity		13.6	(100% capacity)
	Chest thickness, 10 cm. 0 pressure, 5 cm. above back		

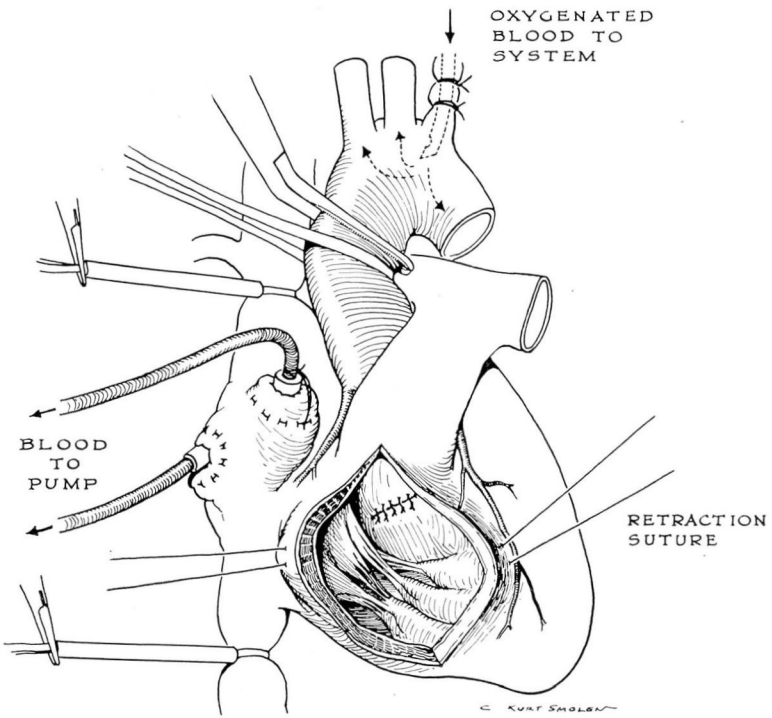

Fig. 3. Visualization of the operative field in closure of a high interventricular septal defect. A long incision is made in the anterior wall of the right ventricle, and excellent exposure is obtained by retracting sutures. The blood loss is restricted to that present in the right auricle and ventricle at the time of arrest. Release of the occluding clamp allows prompt coronary perfusion by the high pressure within the aortic arch. This washes residual excess potassium out of the coronary bed, so that the heart spontaneously resumes its normal beat.

Case 2. A 4-year-old child weighing 29 pounds was admitted to the Hospital on February 26, 1956.

Past history. Catheterization studies (F.M.S.) during a previous hospitalization on January 25, 1955, had revealed a small intra-atrial septal defect and a large left-to-right shunt at the ventricular level.

Present illness. Combined catheterization and cardioangiographic studies were performed on February 28, 1956 (Table 2), confirming the diagnosis of a high interventricular septal defect.

Laboratory studies. The electrocardiogram demonstrated sinus tachycardia and right ventricular hypertrophy. The hemoglobin content was 11.2 gm. per hundred milliliters, and the red cell volume was 40 per cent. The blood-urea content was 33 mg. per hundred milliliters, serum sodium 140, serum potassium 4, and plasma chlorides 110 mEq. per liter.

Table 2.—*Findings on catheterization studies (Case 2)*

Sample No. and location	Pressure (mm. Hg)	Oxygen content Volume %	
1. Superior vena cava	—	11.3	Av. 11.4 vol. %
2. Inferior vena cava	—	11.5	
3. Right atrium, high	1.0	10.9	Av. 11.1 vol. %
4. Right atrium, low	1.0	11.3	
5. Right ventricle, outflow tract	85/6	15.1	Av. 14.3 vol. %
6. Right ventricle, midzone	85/6	13.5	
7. Left atrium	2.0	16.1	
8. Pulmonary vein	3.0	16.5	
9. Left ventricle	105/6	16.5	
10. Femoral artery	105/57	16.5	(90% capacity)
Oxygen capacity		18.3	(100% capacity)
	Chest thickness, 14 cm. 0 pressure, 7 cm. above back		

Operation. On March 12, 1956, open-heart surgery was performed under endotracheal anesthesia. The surgical approach was identical to that employed in the first patient. The caval veins were occluded, connections made to the Kolff oxygenator and pump, and cardiac arrest was induced by direct injection of 16 cc. of the potassium citrate-blood mixture into the proximal aorta. The heart beat stopped within 50 seconds and the heart remained completely flaccid during the remainder of the procedure. A long incision was made in the wall of the right ventricle. Excellent exposure of the interventricular septum was obtained, and the large, high, septal defect was easily visualized. It was closed with five interrupted silk sutures. The procedure required seven and one-half minutes after induced arrest. The occluding clamp was removed during the ventricular closure. The heart resumed a progressively stronger beat within 38 seconds of return of the flow of blood, and both sinus rhythm and an effective beat were established in a short time. The cannulae were removed and the chest was closed in the conventional manner.

Postoperative course. The immediately postoperative condition was excellent. The child promptly regained consciousness; color was good and all reflexes were normal.

Blood loss was carefully measured and replaced. There was no evidence of cardiac arrhythmia at any time. Approximately 10 hours after surgery the child suddenly died after fainting while sitting up.

Autopsy revealed dilatation of the right auricle and ventricle. There was no evidence of significant bleeding. The septal defect was satisfactorily closed and there was no impairment of the right ventricular outflow tract, nor of the aortic or pulmonary valves. The reason for the sudden cessation of the heart beat was not apparent.

Case 3. A 3-year-old child weighing 32 pounds was admitted to the Hospital on March 4, 1956, for surgical treatment of a high interventricular septal defect.

Past history. Catheterization studies were performed by one of us (F.M.S.) during a previous hospital admission on June 29, 1954 (Table 3). Prior to that time the child had

Table 3. — *Findings on catheterization studies (Case 3)*

Sample No. and location	Pressure (mm. Hg)	Oxygen content Volume %	Oxygen content % Saturated
1. Superior vena cava	—	10.9	68.1
		Av. 11.1	
2. Inferior vena cava	—	11.3	70.6
3. Right auricle—high	1.0	10.7	66.8
		Av. 11.45	
4. Right auricle—low	1.0	12.2	76.2
5. Right ventricle, midzone	79/2	13.7	85.6
		Av. 13.85	
6. Right ventricle below pulmonary valve	76/0	14.0	87.5
7. Main pulmonary artery	76/22	14.1	88.1
		Av. 14.13	
8. Left main pulmonary artery	80/16	14.0	87.5
9. Right main pulmonary artery, proximal	60/18	14.3	89.3
10. Pulmonary vein—left middle	—	15.7	98.1
11. Left auricle	7.0	15.5	96.8
12. Right auricle (check)	—	11.1	69.3
13. Femoral artery	115/60	15.5	96.8
Oxygen capacity		16.0	100.0

had anoxic attacks. A heart murmur first had been detected at six weeks of age. During the first year of life the patient had gained weight slowly and had several bouts of pneumonitis accompanied by cough and fever.

Laboratory studies. The electrocardiogram demonstrated right ventricular hypertrophy and sinus tachycardia. The findings on all blood studies were within the normal range.

Operation. On March 15, 1956, open-heart surgery was performed under endotracheal anesthesia. The sternum was transected as described in Case 1. The left subclavian artery was cannulated for return of arterialized blood from the Kolff oxygenator; both venae cavae were then cannulated through the wall of the right ventricle. The proximal aorta was mobilized and umbilical tape placed around it to assist in occlusion. After the venae cavae had been occluded and the oxygenator and pump had begun to operate, the heart was paralyzed in diastole by injecting potassium citrate-blood mixture (17 cc.) into the proximal occluded aorta. A long incision was made in the right ventricular wall, and the right ventricle was inspected. The septal defect was lower than had been anticipated and was located with some difficulty immediately behind the septal leaflet of the tricuspid valve. It was necessary to cut one large papillary muscle to expose the defect, which was closed with five interrupted silk sutures. The transected papillary muscle was then sutured to its base. Identification and closure of the septal defect required approximately 13 minutes. The occluding clamp was removed from the aorta and the blood flow to the coronary system was restored. Twenty-five seconds later the heart beat spontaneously returned and it proceeded to a normal effective sinus rhythm. The right ventricle was open for approximately 16½ minutes. The remainder of the operative procedure was completed as usual.

Postoperative course. The immediately postoperative period was uneventful. Convalescence in the Hospital was satisfactory except for superficial bleeding from the incision approximately 24 hours after surgery. The bleeding was controlled by pressure dressings and transfusion of 50 ml. of blood. The child was discharged from the Hospital on March 29, 1956.

Summary and Conclusions

Successful extracorporeal maintenance of circulation and oxygenation using the 'small-flow' (35 ml. per kg. of body weight per minute) principle has introduced an era of open-heart surgery. As part of the search for safer and simpler methods of intracardiac surgery, controlled cardiac arrest was effected as an adjunct to the use of the artificial heart-lung. The method described in this report is based on that of the experimental work of Melrose and associates.

Elective cardiac arrest by injection of potassium citrate-blood mixture via the root of the aorta into the coronary vessels is believed to be a simple and safe procedure that offers great promise as a means of simplifying technic in open-heart procedures.

Three case reports are presented. In each case intracardiac operations were performed after cardiac arrest had been induced by coronary perfusion with potassium citrate solution. The results obtained encourage continued use of this procedure.

In each of the reported cases, the Kolff oxygenator (described in the preceding article) was employed.

Addendum

Since this paper was submitted for publication, the technic of elective cardiac arrest has been used successfully in an additional five cases.

Acknowledgments

We are especially appreciative of the assistance and advice of Donald E. Hale, M.D., Department of Anesthesiology, and John W. King, M.D., Department of Clinical Pathology.

References

1. Warden, H. E., Cohen, M., Read, R. C., and Lillehei, C. W.: Controlled cross circulation for open intracardiac surgery; physiologic studies and results of creation and closure of ventricular septal defects. J. Thoracic Surg. **28**: 331-343, Sept. 1954.
2. Andreasen, A. T., and Watson, F.: Experimental cardiovascular surgery. Brit. J. Surg. **39**: 548-551, May 1952.
3. Melrose, D. B., Dreyer, B., Bentall, H. H., and Baker, J. B. E.: Elective cardiac arrest. Lancet **2**: 21-22, July 2, 1955.