Open Intracardiac Operations: *

Use of Circulatory Arrest During Hypothermia Induced by Blood Cooling

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OVER THE PAST two years 52 patients have been treated by open intracardiac operation at the Mayo Clinic during total circulatory arrest and hypothermia induced by blood-stream cooling. The principal guides to safety in this approach were obtained from studies on the relation of body temperature to oxygen uptake and to safe circulatory-arrest time.[2, 9, 11, 15, 17] Excellent results were obtained in the great majority of cases. Evidence of nonfatal brain damage in one patient operated on by the technic of Drew and Anderson during 45 minutes of total circulatory arrest has resulted in our reluctance at present to use circulatory arrest for longer than 30 minutes.

Material and Methods

Two technics for cooling and warming were utilized. In 29 cases extracorporeal circulation was established with a Mayo-Gibbon pump-oxygenator, as described previously.[16] In 23 cases pumps were substituted for the left and right ventricles, but gas exchange occurred in the patients' own lungs, as described by Drew and Anderson. Anesthetic management was not different from that usually employed during open intracardiac operation; halothane was the principal agent.[6]

In both technics rates of blood flow of 2.0 to 2.4 liters per minute per square meter of body surface were used during cooling and warming. The temperature of water entering the heat exchanger (Brown-Emmons type[5]) was manipulated so that the temperature of blood passing through the heat exchanger was changed by no more than 12° C.; this is believed to minimize the risk of bubble formation.[8] The range of water temperature was 4° to 42° C. Whole-body temperature was estimated from measurements of the temperature of the esophagus and of mixed venous blood. After the desired level of hypothermia was reached and just prior to the establishment of circulatory arrest and the opening of the heart, the ascending aorta was cross-clamped. The perfusion was then stopped. Venous lines were left open until blood ceased flowing from the patient. Upon resumption of the perfusion for warming, this blood was returned to the patient. The residual air was aspirated from the heart, and the aorta was unclamped. The heart was defibrillated electrically when the patient's temperature reached about 30° C. Warming was usually continued until the patient's temperature rose to 37° C.

Figures 1, 2 and 3 illustrate the apparatus used in the technic of Drew and Anderson. Bypass of the left side of the heart was established, and cooling was started. Bypass of the right side of the heart was added when the heart became ineffective (27° to 31° C.). During warming, bypass of the right side of the heart was discontinued after cardiac action became effec-

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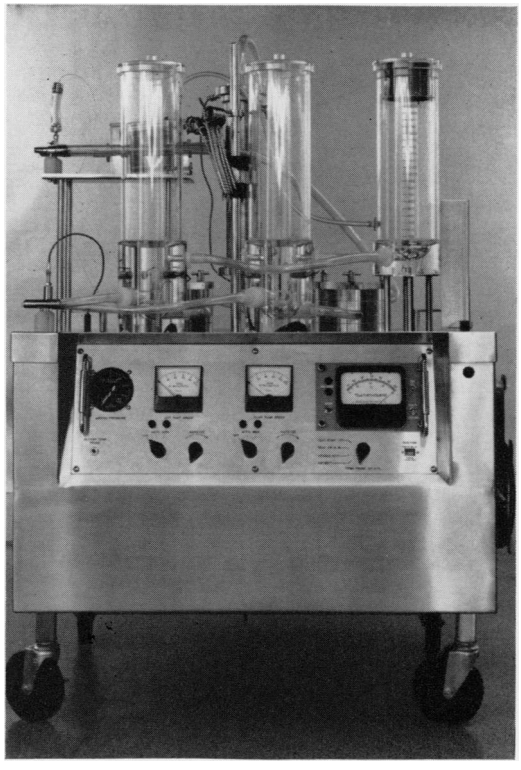

FIG. 1. Unit for profound hypothermia. This unit is employed for bypass of the right and left ventricles. Gas exchange occurs in the patient's own lungs.

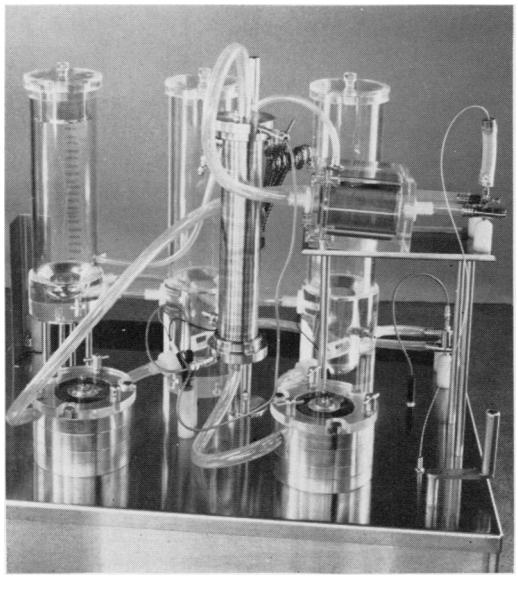

FIG. 2. Closeup of Figure 1.

tive (30° to 33° C.); bypass of the left side was continued until warming was completed.

In all patients in whom the technic of Drew and Anderson was employed, it had been decided prior to operation that the intracardiac repair would be done under conditions of total circulatory arrest. A similar decision had been made in some cases among the group in which the pump-oxygenator was employed. In others of this group, induced hypothermia and circulatory arrest were used as an emergency measure because of a situation of duress.

Results

Circulatory Arrest After Hypothermia Induced with Pump-Oxygenator (Table 1). Six of seven patients survived closure of a functioning Potts anastomosis during circulatory arrest and subsequent complete repair of the tetralogy of Fallot during perfusion.[13] One of the seven patients died of uncontrollable hemorrhage from the reconstruction of the outflow tract. There was no evidence of cerebral damage in any of these patients. Four of five infants with complete transposition of the great vessels survived the Senning procedure[12] for transposition of the great veins; one infant died 14 hours after operation, with high atrial pressures and clinical evidence of low cardiac output. An infant operated on during 70 minutes of total circulatory arrest by a now discarded method of atrial rearrangement died a few hours after operation from hemorrhage, surgical trauma, and cardiac decompensation. There was no evidence of cerebral damage in any of these patients.

A patient with aortico-pulmonary fistula, ventricular septal defect, and complex anomaly of the systemic venous return survived the procedure but became uncommunicative and lethargic 24 hours after operation. Recovery from this alteration in brain function began by the ninth day and was complete on the twenty-first postoperative day. This patient was operated

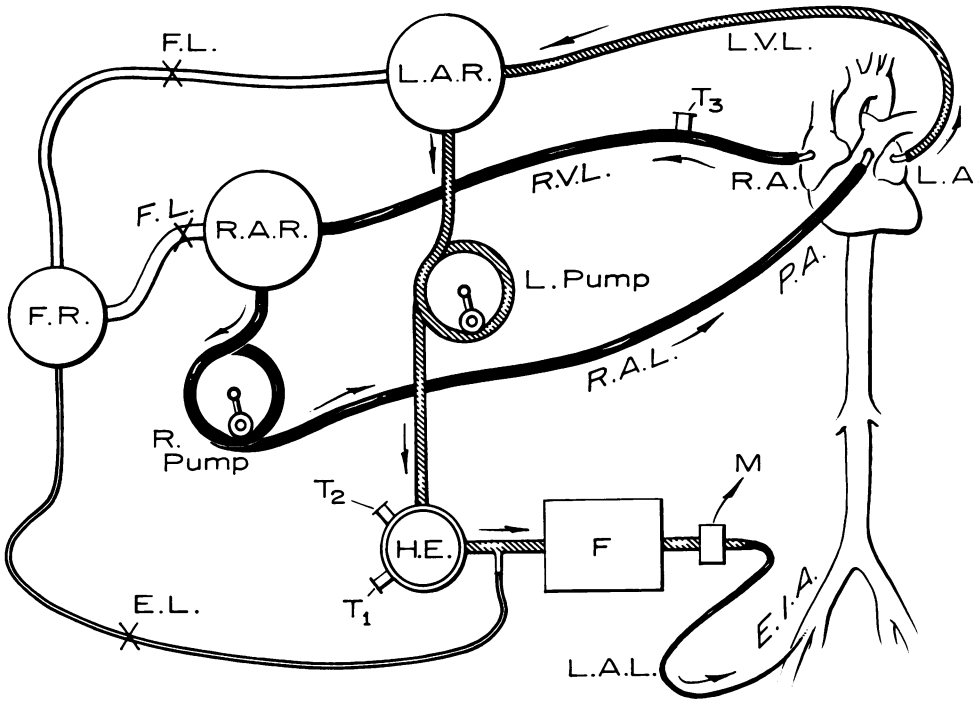

FIG. 3. Blood flows by gravity drainage from right atrium (R.A.) along right-heart venous line (R.V.L.) to right atrial reservoir (R.A.R.). A single-roller pump (R. Pump) moves blood from reservoir along right-heart arterial line (R.A.L.) to a no. 28 plastic catheter inserted into pulmonary artery (P.A.) through a small incision in right ventricle.

Left-heart venous line (L.V.L.) drains blood from left atrium (L.A.) to left atrial reservoir (L.A.R.). Blood is moved from this reservoir by another single-roller pump (L. Pump) through a modified Brown-Emmons heat exchanger (H.E.), filter (F.), and left-heart arterial line (L.A.L.) to a cannula in right external iliac artery (E.I.A.). Both atrial reservoirs may be filled from or emptied into the filling reservoir (F.R.) by the filling lines (F.L.) or emptying line (E.L.).

Pump speeds are controlled manually or they may be controlled automatically by level-sensing devices in both right and left atrial reservoirs. By either method, rate of arterial flow is held approximately the same as rate of venous return. At least 150 ml. of blood is kept in reservoirs to ensure against possibility of pumping air into arterial lines.

Temperature of blood entering and leaving heat exchanger is recorded by thermistor leads T_1 and T_2 inserted into ends of heat exchanger. Temperature of mixed venous blood from right atrium is recorded by a thermistor lead (T_3) inserted into a manifold placed along right-heart venous line (R.V.L.). Patient's temperature is recorded by a thermistor in center of esophagus.

Pressure in left-heart arterial line is monitored by a manometer (M) connected to a three-way manifold inserted into left-heart arterial line.

on in October 1958, and circulatory arrest was prolonged beyond a point that was safe at that body temperature. Dissection and closure of a large patent ductus arteriosus was accomplished without ill effect during total circulatory arrest in two young patients with associated defects. Four infants did not survive closure of a ventricular septal defect during circulatory arrest. One had the rare situation of a truly hypoplastic left ventricle, and this patient died in hemorrhagic pulmonary edema. A patient with extremely high pulmonary vascular resistance died with low cardiac output. Another infant, who had progressive and poorly treated tachycardia, died eight hours after operation. None of these patients showed any evidence of cerebral complications. The fourth infant was well until 40 hours after operation, when he convulsed, became comatose, and died a few hours later. Normothermic extracor-

TABLE 1. *Total Circulatory Arrest After Hypothermia Induced with Pump-Oxygenator (October 1958 to October 1960)*

Conditions	No. Patients	Body Temperature (C. °)	Circulatory Arrest Time (min.)		Hospital Deaths	
			Ave.	Range	No.	%
Elective						
Tetralogy of Fallot, with the Potts anastomosis	7	27	10	4–15	1	14
Complete transposition of great vessels (Senning operation)	5	12	60	54–65	1	20
Complete transposition of great vessels (now discarded type of repair)	1	12	70	—	1	100
Aortico-pulmonary fistula, ventricular septal defect, and anomalies of systemic venous return	1	22	38	—	—	—
Patent ductus arteriosus and ventricular septal defect or mitral insufficiency	2	28	5	4–5	—	—
Ventricular septal defects in infants	4	23	15	11–21	4	100
Emergency						
Tetralogy of Fallot	8	18–27	13	5–25	5	63
Origin of both vessels from right ventricle and pulmonic stenosis	1	22	20	—	1	100

poreal circulation is now our method of choice for the management of similar cases.

In nine patients scheduled for normothermic perfusion, flooding of the operative field by an immense bronchial blood flow or hemorrhage encountered in dissecting out an old Blalock anastomosis prompted an emergency decision to use hypothermia and circulatory arrest. All patients were deeply cyanotic. Seven had previously been operated on for a Brock or Blalock procedure. Six of these patients died postoperatively. Three patients died two to 24 hours after operation, with a low cardiac output. One patient died from hemorrhage. Another died five days after operation, with a mediastinal hematoma, staphylococcal mediastinitis, and blood-stream infection. A patient with origin of both vessels from the right ventricle and pulmonary stenosis died because of inadequate relief from the pulmonary stenosis. None of these patients showed evidence of cerebral damage.

Circulatory Arrest After Hypothermia Induced by Technic of Drew and Anderson. The 23 patients operated on by the technic of Drew and Anderson are listed in Table 2. There have been no deaths and no complications in patients operated on for repair of the ostium secundum or sinus venosus type of atrial septal defect. The average amount of thoracic drainage during the first 24 hours postoperatively was 290 ml./square meter. Urinary outputs were excellent. Although both patients with total anomalous pulmonary venous connection to the left innominate vein survived, lethargy, ataxia, and inability to swallow appeared 48 hours after operation in the patient in whom circulation was stopped for 45 minutes. Electroencephalographic evidence of subcortical brain dam-

TABLE 2. *Total Circulatory Arrest After Hypothermia Induced by Technic of Drew and Anderson (February to October 1960)*

Conditions	No. Patients	Body Temperature (C. °)	Circulatory Arrest Time (min.)		Hospital Deaths	
			Ave.	Range	No.	%
Ostium secundum type of atrial septal defect	12	22	14	10–19	—	—
Sinus venosus type of atrial septal defect, with anomalous pulmonary venous connection	5	15	29	24–33	—	—
Total anomalous pulmonary venous connection	2	13	—	45–59	—	—
Acquired valvular heart disease	2	15	—	22–53	2	100
Common atrium, incompetence of mitral valve, and congenital complete heart block	1	12	—	46	1	100
Transposition of great vessels (now discarded type of repair)	1	11	—	74	1	100

age was noted. Fortunately, the patient's status has improved steadily since that time, and at present she is nearly asymptomatic.

Two patients with acquired valvular heart disease were in severe and intractable cardiac failure before operation. Both died from an inadequate cardiac output within

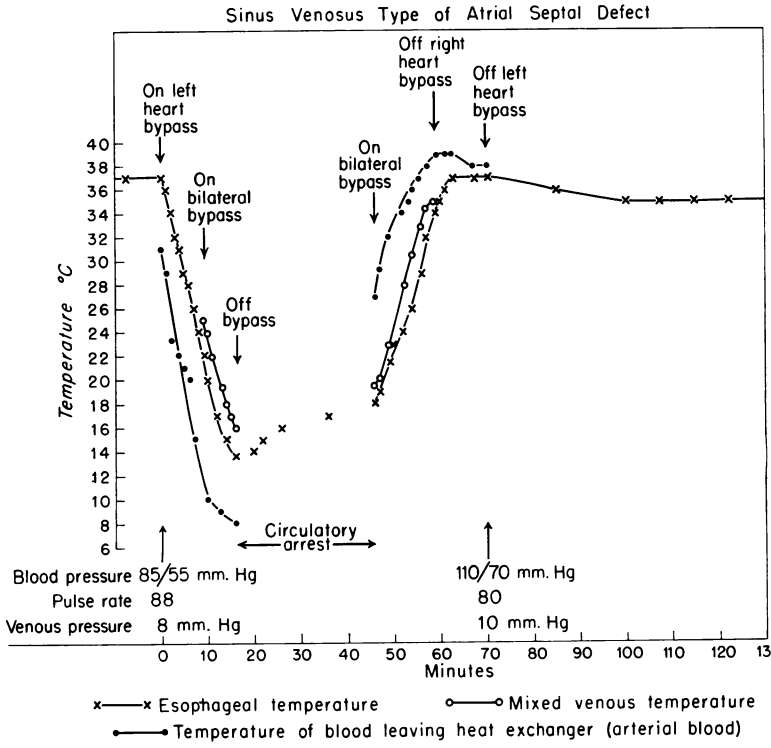

FIG. 4. Diagram depicts events that occurred from beginning of cooling to end of rewarming during repair of sinus venosus type of atrial septal defect under conditions of circulatory arrest with profound hypothermia.

20 minutes after rewarming and cessation of bypass of the right and left sides of the heart. A patient with common atrium, incompetence of the mitral valve, and congenital complete heart block died four hours after operation after having been tachypneic since the operation. A patient with complete transposition of the great vessels and ventricular septal defect was in severe cardiac failure prior to operation; severe pulmonary hypertension was present, with a pulmonary-systemic blood flow ratio of less than 1. Transposition of the venous return and repair of the ventricular septal defect were accomplished. After repair, pulmonary arterial pressure was higher than aortic pressure. Gradually progressing right-heart failure caused death on the sixth postoperative day.

Figure 4 depicts temperatures recorded during a typical operation in which the technic of Drew and Anderson was employed. During the 30 minutes of circulatory arrest the esophageal temperature drifted upward 4.5° C. After cessation of perfusion, esophageal temperature drifted down to 35.5° C.

In all patients operated on by means of the technic of Drew and Anderson, there was an average upward drift of temperature during the period of circulatory arrest of 1° C. for every 9 minutes of arrest. After rewarming, an average downward drift of 1.5° C. occurred. Wide variation in temperature drift was noted among individual patients, and no pattern could be established for age, surface area, or habitus. However, drift did appear to be inversely proportional to the duration of cooling and rewarming when the usual flow rates were used. Diaphragmatic movement often appeared during warming; it was easily controlled with hyperventilation.

Comment

The use of periods of total circulatory arrest in operations being performed with the aid of a pump-oxygenator was a natural evolution, once the efficient Brown-Emmons heat exchanger became available. It had been shown that short periods of circulatory arrest during moderate hypothermia were well tolerated,[1, 4, 7, 14, 18] and experimental data suggested that longer periods would be tolerated during profound hypothermia. Our experience has indicated the usefulness of this approach for patients with tetralogy of Fallot and a functioning Potts anastomosis. Others have employed it for certain intracardiac procedures.[10] It has also been advantageous to us in performing the Senning procedure for transposition of the great vessels, although the periods of circulatory arrest have been longer than, ideally, they should have been. Use of induced hypothermia and circulatory arrest as an emergency procedure during whole-body perfusion has not been rewarding in our experience.

The use of bypass of the right and left sides of the heart for cooling and warming the patient while his own lungs are used as the oxygenator represents a change in basic approach to open intracardiac operations. The intracardiac operation is done in its entirety during circulatory arrest, under superb conditions. The absence of intracardiac return of blood (which obviates the need for intracardiac suckers or vents), the perfectly quiet heart, and the absence of the distractions of perfusion during the repair are all advantageous to a surgeon. The left atrial and pulmonary arterial cannulations needed for this technic are sometimes troublesome, but they are acceptable in light of the advantages of the method.

The hazards inherent in the use of prolonged periods of total circulatory arrest during profound hypothermia induced by blood-stream cooling in this manner are in dispute. Drew and Gordon and their coworkers[9, 11] have reported no untoward sequelae. Björk has reported brain damage leading to death in several patients in

whom circulatory arrest was maintained for longer than 30 minutes.

This lack of agreement and our own experience make us at present unwilling to prolong the total time of circulatory arrest beyond about 10 minutes when body temperature is 28° C., 15 minutes when it is 22° C., and 30 minutes when it is 12° to 14° C.

The technic of Drew and Anderson at present appears to us useful for intracardiac operations that can be completed within a period of circulatory arrest of 30 minutes, except in the following situations: when the possibility exists of aortic valvular incompetence during cooling or warming; when the patient has a common atrioventricular canal, in which condition the heart should be beating while sutures are placed near the bundle of His; and when pulmonary stenosis with small pulmonary artery is present. The technic has not been used enough in patients with chronic heart failure for us to be sure whether it is applicable with the same safety as is whole-body perfusion for such patients, and at present we prefer not to employ it for them. The possible hazards in the use of this technic in patients with extremely high pulmonary vascular resistance are not known. Although clinically useful within these limitations, the technic requires further investigation before it can become more generally applicable in intracardiac operations.

Summary

Details have been reported of an experience with open intracardiac operations in which circulatory arrest was used during hypothermia induced by blood-stream cooling. In one group of patients a pump-oxygenator was employed, and in another the patients' lungs were used as the oxygenator. Within certain limitations, the technic of Drew and Anderson appears useful for intracardiac operations that can be completed within a 30-minute period of circulatory arrest.

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Book Review

SURGICAL UROLOGY: A HANDBOOK OF OPERATIVE SURGERY. By R. H. Flocks, M.D. and David Culp, M.D. Chicago, The Year Book Publishers, Inc., 2d ed., 1961, 441 pages, $10.50.

This Handbook with its clear illustrative plates should be handy reference item to any surgeon, including the urologist, who wishes to look up quickly the latest fundamental concepts underlying urologic surgery and the significant advances which have been made in the fields of urology since the publication of the first edition of this Handbook in 1954.

The concise manner of its presentation should be familiar to all surgeons who have in their basic libraries the publications of The Year Book Publishers. Among the important additions to the text in this second edition are enlarged sections on the treatment of tumor of the testis and the treatment of prostatic cancer.

Advances in urologic surgery, which have been included in this edition, are the newer operations for correction of ureteral reflux, newer operations for exstrophy of the bladder, for undescended testis, for biopsy of the prostate, for bladder neck contracture, for pyeloplasty, and for vesico-cutaneous anastomosis.

One entirely new section describes the use of small and large bowel segments for newer plastic procedures performed upon the urinary tract. The simple, clear, black and white, line-drawing illustrations by Mr. Paul Ver Vais are especially commendable. BLAIR O. ROGERS, M.D.