ELECTIVE CARDIAC ARREST DURING CARDIOTOMY

Summary of 37 Cases

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Elective cardiac arrest with potassium citrate affords a quiet, bloodless field for intracardiac operations. It is the most recent and one of the most useful modes of deliberate physiological trespass, following in the wake of controlled respiration, induced hypotension, and induced hypothermia. Reported in 1955 by Melrose and associates in England (1), elective cardiac arrest with potassium citrate was first used in the United States by Kolff, Effler, and coworkers (2, 3, 4). It is our purpose to review briefly the technique of elective cardiac arrest employed by us and to discuss particularly the administration of anesthetics and other drugs during open-heart operations on 37 patients. Diagnosis, treatment, and results in these 37 patients have been published in detail (5).

PRINCIPLES OF ELECTIVE CARDIAC ARREST

Potassium, calcium, and sodium in proper proportions are necessary for normal cardiac activity (6). An excess of serum calcium or a deficiency in serum potassium with a normal serum calcium causes a lengthening systole and finally arrest in systole. An excess of potassium causes a longer and longer diastole with arrest in diastole. Potassium and calcium in normal concentrations in the perfusion fluid will not alone sustain the heart beat. Sodium is needed to preserve excitability and contractility (fig. 1).

Cardiac arrest was first accomplished experimentally (1) by the following procedure: the animal was connected to an artificial heart-lung, the aorta was clamped, and potassium citrate was injected into the root of the aorta. Arrest was readily accomplished, but efforts at restarting the heart by cardiac massage, or by injection of calcium chloride (and sometimes adrenaline and neostigmine), were followed in most cases by ventricular fibrillation. However, when the animal’s heart was perfused with a solution of potassium citrate ranging in concentration from 1 to 20 mg. per milliliter in Locke’s solution, arrest occurred regularly, and normal cardiac rhythm was restored in from

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one and one-half to two minutes after perfusion with pure Locke's solution. The citrate radical reduced the ionized calcium in the blood and was later metabolized in the liver.

A dry field for operating upon an interventricular septal defect was achieved for short intervals by Lillehei and coworkers (7) who placed a clamp across the ascending aorta. Elective cardiac arrest with potassium citrate extends these intervals safely and further improves operating conditions by providing a motionless heart (4). Even while the aorta is clamped, however, a considerable quantity of blood may flow into the heart from the lungs in a patient who has a tetralogy of

![Diagram](image_url)
Fallot or an open ductus arteriosus. This blood can be taken from the heart by a low-vacuum suction device and returned to the oxygenator.

TECHNIQUE OF ELECTIVE CARDIAC ARREST

Preoperative studies of patients who were to undergo open-heart operations included cardiac catheterization, radiography, angiography (with the help of moving pictures made with the image intensifier), measurements of intracardiac and intravascular pressures, and determinations of oxygen saturation. Fluid and electrolyte balance were carefully evaluated in order to avoid overhydration and sodium imbalance in these patients who may be on the brink of cardiac decompensation. Determinations of pH and carbon dioxide content of venous blood were made.

![Diagram of technique of elective cardiac arrest.](image)

**Fig. 2.** Diagram of technique of elective cardiac arrest. Potassium citrate, 0.5 Gm. in 20 ml. of heparinized blood, is being injected into the first portion of the aorta, proximal to a clamp. The sleeve on the needle prevents puncturing the posterior wall of the aorta. Cannulas in the venae caval conduct venous blood to the oxygenator, and one in the left subclavian artery returns blood from the oxygenator to the patient’s aorta. (Reprinted with permission from Effler, D. B., Groves, L. K., Sones, F. M., and Kolff, W. J.: Cleveland Clin. Quart. 23 (April) 1956.)

Elective cardiac arrest was produced in this series of 37 patients by a method that was virtually the same as that used by Melrose and associates (1) and that has been previously described in detail (3, 4). After each patient’s blood had been heparinized (2 mg. of heparin per kilogram of body weight) and his circulation had been assumed by the artificial heart-lung, a clamp was placed on the root of the aorta. Immediately proximal to that clamp, a solution of potassium (2 ml. of 25 per cent potassium citrate made up to 20 ml. with heparinized blood) was injected into the lumen of the aorta just above the orifices of the coronary arteries (fig. 2): this quantity of solution contains 4.5 mEq. of potassium. Arrest of the heart followed, the right ventricle was in-
Elective cardiac arrest during cardiotomy

cised, and the defect was repaired. The heart beat reappeared after
the clamp was removed from the aorta and the blood from the artificial
heart-lung had flushed the potassium out of the coronary circulation
(figs. 3 and 4). The clamp usually was removed from the aorta before
the ventricular incision was completely closed. This procedure per-
mitted the potassium-rich coronary blood to escape from the heart and
prevented it from reaching the general circulation; it allowed the right
ventricle to fill with blood and helped to avoid air embolism.

Blood loss was carefully measured during the operation by collect-
ing all of the blood aspirated from the operative field in a 1,000-cc.

Fig. 3. Electroencephalographic and electrocardiographic tracings before and after in-
duction of cardiac arrest. There is little significant change in the electroencephalogram. The
upper tracing of the electrocardiograms shows the rapid disintegration of the complex after
the injection of potassium, and the lower shows the absence of all activity.

Fig. 4. Electrocardiographic tracings showing resumption of cardiac activity following
removal of aortic clamp. Irregular activity appeared within a few seconds, and a normal
rhythm was re-established a few minutes later.
graduate. A balance between loss and replacement was struck occasionally and the loss was replaced during the procedure. After the cannulas were removed from the venae cavae and from the left subclavian artery, the pump oxygenator was disconnected and the patient's oxygenation and circulation were again provided by the patient's own lungs and heart.

Management of the procedure included observation of the electrocardiogram (for arrhythmia), the electroencephalogram (for evidence of cerebral oxygenation in the absence of direct blood pressure readings), the venous pressure (central or peripheral, as a measure of overloading the circulatory system or indication for transfusion), the temperature, the blood pressure, the pulse, and the rate of flow of blood from the artificial heart-lung.

Heart-Lung Machine.—The heart-lung machine consists of a pump and an oxygenator. Respiration during open-heart operations performed here was provided in infants and children by the Kolff dis-

![Fig. 5. Kolff disposable artificial lung (right) and artificial lung in plastic bag with tube for oxygen inlet at the bottom. (Reprinted by permission from Kolff, W. J., and others: Cleveland Clin. Quart. 23 (April) 1956.)](image)

posable membrane oxygenator and a 3-pump system. With this device oxygenation takes place through polyethylene tubing that alternates with layers of Fiberglas window screen wrapped around a hollow cylindrical metal core (fig. 5). One such unit oxygenates 75 ml. of blood per minute. The venous blood returned to the unit is low in oxygen inasmuch as the flow to the patient is low. However, the oxygenator succeeds in raising the saturation to more than 90 per cent (92 to 98 per cent in five experiments (2)). The membrane oxygenator is impractical for patients weighing more than 20 kg, because of the large quantity of blood required for priming (500 ml. of blood per unit).

The Björk oxygenator (8) in which discs of plastic revolve in a trough containing blood is used for patients weighing more than 20 kg. (5) (fig. 6). One pump is required for this oxygenator.

Anesthetics and Other Drugs Administered.—Light general anesthesia was our goal during open-heart operations. For premedication
FIG. 6. Diagram of operation of the Björk oxygenator. Blood in the trough is picked up in thin layers on the surfaces of the rotating discs, and is exposed to an atmosphere of oxygen.

TABLE 1

<table>
<thead>
<tr>
<th>Drug</th>
<th>Average Dose, Initial or Additional</th>
<th>Total Dose</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>Meprobamate hydrochloride (intramuscularly)</td>
<td>1 mg./kg.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pentobarbital sodium (subcutaneously)</td>
<td>2 mg./kg.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thiopental sodium (rectally in children)</td>
<td>22 mg./kg.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thiopental sodium (intravenously)</td>
<td>1 mg./kg.</td>
<td>4-21 mg./kg.</td>
<td>11.7 mg./kg.</td>
</tr>
<tr>
<td>Succinylcholine chloride,</td>
<td>1 mg./kg.</td>
<td>2-12 mg./kg.</td>
<td>4.7 mg./kg.</td>
</tr>
<tr>
<td>d-tubocurarine, in adults (intravenously)</td>
<td>15 mg. (children) 50 mg. (adults)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heparin (intravenously)</td>
<td>2 mg./kg.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Isoproterenol hydrochloride (intravenously)</td>
<td>0.01-0.02 mg./kg. every 15 min. as required</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Protamine sulfate (intravenously)</td>
<td>3 mg./kg.</td>
<td>Minimum 25 mg. 6 mg./kg.</td>
<td></td>
</tr>
<tr>
<td>Sodium bicarbonate, 5% (intravenously)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cefazolin*</td>
<td>0.02 mg./kg.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Administered only if digitalization is indicated.

(Data Compiled from 37 Cases)
we employed pentobarbital sodium, 2 mg. per kilogram, given by mouth one and one-half hours before operation, and meperidine (Demerol®) hydrochloride, 1.0 mg. per kilogram, administered subcutaneously one hour before the procedure (table 1). Atropine was not given preoperatively because its vagolytic action may produce tachycardia; if needed, it was given in the operating room. Amnesia was induced in adults by the intravenous administration of thiopental (Pentothal®) sodium. In children, the same agent was given by rectum in doses of 22 mg. per kilogram of body weight. This induction was carried out in the patient’s room, and when he became drowsy, he was transported to the operating room.

A plastic cannula inserted under local anesthesia into the great saphenous vein in the femoral triangle was advanced until its tip lay within the inferior vena cava at the lower border of the liver. In some patients the cannula was placed in the great saphenous vein just anterior to the internal malleolus of the ankle, and was advanced only a few centimeters. The cannula was connected to a battery of stopcocks through which the various agents used during the procedure were injected. The volume of fluid held by the cannula was determined before it was placed in the vein by filling it with a syringe and noting the quantity required. Each injection of medication thereafter was followed by this quantity of fluid to assure immediate delivery of the medication to the patient’s blood stream. Between these injections the intravenous fluid dripped at a low rate to keep the cannula open. During the period of heparinization, no flow was required.

An additional dose of thiopental sodium and one of succinylecholine chloride (1.0 mg. per kilogram of body weight in children, and a total dose of 50 mg. in adults) were given intravenously; an endotracheal tube then was inserted. In children no cuff was used on the tube. Equal quantities of nitrous oxide and oxygen were used for the maintenance of anesthesia until immediately before the patient’s circulation was transferred to the heart-lung machine, at which time oxygen was used to hyperventilate the patient’s lungs. During extracorporeal circulation, the lungs were kept distended with the above-mentioned mixture of nitrous oxide and oxygen to avoid the possible toxic effect of pure oxygen in contact with the alveolar membrane adjacent to which no blood was circulating. Room air or a mixture of helium and oxygen would also be satisfactory.

During perfusion, drugs were injected as needed into the outflow tract of the pump-oxygenator from which they proceeded directly to the patient. If drugs were injected into the cannula in the inferior vena cava, they would pass into the oxygenator where they would be diluted and delayed in reaching the patient. If complete heart block occurred and the ventricular rate was below 40, isopropylarterenol (Isuprel®) hydrochloride was administered intravenously.
At the end of the perfusion the heparin still present in the patient's blood was neutralized by the intravenous injection of protamine sulfate (3 mg. per kilogram). After the perfusion, only minute doses of thiopental sodium were used and then only when necessary; the patient seemed to be unusually sensitive to barbiturates after the period of artificial oxygenation. Nitrous oxide was a safe agent for use at this time.

Postoperative care of the patient included the intravenous administration of a solution of fructose containing protamine sulfate (3 mg. per kilogram to neutralize heparin in the blood and to prevent heparin rebound), sodium bicarbonate (4.5 mEq. per kilogram to correct metabolic acidosis, if present), and occasionally aminophyllin (as a bronchodilator), the maintenance of body heat, and careful control of fluid balance.

**DISCUSSION**

Elective cardiac arrest with potassium citrate was employed during open-heart operations in 37 patients. The duration of the arrest av-

<table>
<thead>
<tr>
<th>Diagnosis</th>
<th>No. of Patients</th>
<th>No. of Deaths</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interventricular septal defect</td>
<td>6</td>
<td>3</td>
</tr>
<tr>
<td>Younger than 2 years</td>
<td>12</td>
<td>3</td>
</tr>
<tr>
<td>Older than 2 years</td>
<td>9</td>
<td>0</td>
</tr>
<tr>
<td>Tetralogy of Fallot</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Transposition of great vessels</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Ostium primum</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Interauricular septal defect (ostium primum)</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>and mitral stenosis</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Interauricular septal defect and single ventricle</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Interauricular septal defect and pulmonary stenosis</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Interauricular septal defect and mitral insufficiency</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Pulmonary stenosis and tricuspid insufficiency</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Aortic stenosis</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Total</td>
<td>37</td>
<td>13</td>
</tr>
</tbody>
</table>

eraged 17 (7 to 40) minutes. A summary of the data in these patients is presented in table 2. The amount of potassium citrate solution required to induce cardiac arrest was approximately 1 ml. of the solution per kilogram of body weight. In the first 10 patients, the blood flow from the machine was 35 ml. per kilogram per minute. Later, flows up to 70 ml. in children and 40 to 50 ml. per kilogram per minute in adults were used. Physiological changes that occurred during the procedure included a fall in body temperature, a rise in serum hemoglobin, a fall in the blood platelet count, and the appearance of acidosis.

The temperature of the patient fell at the beginning of the perfusion when the blood in the oxygenator was mixed with the patient's
blood. The lowest temperature of any patient in this series was 32 C. It is believed that body temperatures below 28 C. in patients with heart defects, are accompanied by the danger of cardiac irregularities, the most serious of which is ventricular fibrillation (9). However, moderate reduction of the patient’s temperature is beneficial, as it reduces metabolism during the period of arrest. A warming blanket was placed beneath the body of the patient before the operation was begun, and water of appropriate temperature (not to exceed 45 C.) was circulated through it to maintain the body temperature within safe limits.

The serum hemoglobin rose as a result of the destruction of red cells in the oxygenator. The use of plastic rather than rubber tubing has so far corrected this fault that hemolysis has not occurred since this change was made. Immediately after the procedure, a fall in the blood platelet count occurred but the count returned to normal within one hour (2).

Acidosis, both respiratory and metabolic, occurred during perfusions in which the blood flow was less than normal. As the flow increases, respiratory alkalosis may result, which can be corrected by adding 1 per cent of carbon dioxide to the atmosphere in the oxygenator. Metabolic acidosis is favored by hypoxia. As mentioned previously, the fall in pH of the blood may be corrected postoperatively (table 1) by the infusion of a 5 per cent solution of sodium bicarbonate, 4.5 mEq. per kilogram of body weight. The administration of sodium bicarbonate was necessary only to patients carried on the membrane oxygenator. None was given to patients for whom the Björk oxygenator was used because it allowed a flow rate that was more nearly normal.

Changes in the electrocardiogram that follow open-heart operation included atroventricular block and ST-segment depression. Temporary atroventricular block was presumed to result from the effect of an excess of potassium and of a deficiency of oxygen upon the conduction system, and was observed in nearly every instance before the normal rhythm was restored. The block usually was two or three to one, and there was occasionally temporary complete dissociation of the auricular and ventricular contractions. Isopropralterenol hydrochloride, 0.01 or 0.02 mg. (0.02 mg./cc.) was administered intravenously in the treatment of complete heart block with a ventricular rate below 40. Depression of the ST segment (the result of myocardial hypoxia) was seen regularly. It improved and finally disappeared spontaneously as the myocardium recovered.

Air embolus constitutes a hazard in the bloodless heart. It occurred four times in this series in spite of careful filling of the heart chambers with blood and saline solution. When emboli of air were seen, the perfusion was continued and the air bubbles could be seen to move on through the coronary arteries and their branches. In the cases in which this event occurred, no permanent damage resulted.
During elective cardiac arrest, the defect may be completely closed before any strain is put upon the suture line. Since the heart is still, the danger that the first suture will tear is lessened and the sutures need not be placed so deeply as is necessary while the ventricle is moving. One disadvantage of the procedure is that it is not possible to determine immediately whether a suture in the interventricular septum has damaged the bundle of His, as indicated by the appearance in the electrocardiogram of atroventricular block. However, persistent atroventricular block occurred in only 2 of the 37 cases. In each of these, the condition was not fatal because the idioventricular rate was fast enough to provide ample circulation.

There were 13 deaths in 37 patients operated. Four of these were nonpreventable surgical deaths. Of these, 3 had transposition of the great vessels and the other had a single ventricle. Three patients died of pulmonary complications: 2 had severe pulmonary hypertension and the other died one week postoperatively with a post-mortem finding of atelectasis. Six patients were considered to be surgical failures, in that the pathology was not adequately corrected. Anesthesia was not implicated in any of these patients, as all of the deaths occurred after awakening and after postoperative chest roentgenograms had revealed expanded lungs.

The incision in these patients, which was a bilateral thoracotomy with transection of the sternum, added to the morbidity and caused impairment of respiration. Respiration was aided by intermittent positive pressure breathing by mask or through tracheotomy as required during the first 12–24 hours postoperatively. Adults received bilateral intercostal blocks (D3, 4 and 5) to decrease pain and thereby increase respiratory exchange.

There are still many problems, such as electrolyte and acid-base balance, which must be studied closely during the postoperative period. A detailed study of these changes is now in progress.

**Summary**

Thirty-seven patients were carried under light general anesthesia (thiopental and nitrous oxide and oxygen) for open-heart surgery during elective cardiac arrest. Light anesthesia allowed rapid recovery, lessened the danger of nausea and emesis, and permitted a better evaluation of the general condition of the patient.

A solution of potassium in heparinized blood was injected into the coronary circulation (via the ascending aorta) to produce temporary standstill. Metabolic acidosis was controlled to some extent by the respiratory alkalosis which accompanies the use of hyperventilation.

The postoperative period seemed to be more critical than the period of operation and careful observation and supervision were required. Respiratory exchange, body temperature, and blood pressure must be kept within normal limits.
REFERENCES


