Maintenance of Adequate Circulation during Cardiac Standstill Using a Mechano-cardiac Compressor

PHILIP Y. ATTALLA, M.D., CESAR BORQUEZ VIAL, M.D., F.C.C.P.,
PETER V. MOULDER, M.D., F.C.C.P., and WILLIAM E. ADAMS, M.D., F.C.C.P.
Chicago, Illinois

Introduction

The recent rise in the incidence of cardiac arrest may be attributed in part to an actual increase in the frequency of this condition and in part to better recognition by anesthesiologists and surgeons of this ever present danger. In addition, the ever-increasing number of major intrathoracic and abdominal operations must be recognized as a major factor in the increased incidence of cardiac arrest. Improvement in techniques today permits poor risk patients to be subjected to such surgical procedures, and many of them are afflicted by one or more of the conditions often considered to predispose to cardiac standstill.

Cardiac arrest occurs as a complication in approximately 0.1 per cent of all surgical patients. Analysis of 1200 cases of cardiac arrest by Stephenson revealed that 87 per cent of cases occurred in the operating room and 13 per cent elsewhere. Hypoxia, hypercarbia and neurovascular reflexes appear to predispose to cardiac standstill.

Awareness of the possibility of salvage in cases of cardiac arrest is evident in clinical reports regarding this condition. Cole reported 350 cases of cardiac arrest from the literature with recovery of 112 (32 per cent). Papper reported a 44 per cent survival rate following cardiac resuscitation, and estimated that one should anticipate a 75 per cent survival if effective therapy were instituted promptly.

All agree that manual cardiac massage is the treatment of choice for cardiac arrest. However, the major question concerns the length of the interval which intervenes between cardiac arrest and the initiation of effective massage. This question was answered by Stephenson in 1954 when he emphasized the importance of entering the thoracic cavity and starting the massage within four minutes. In his analysis of 1200 cases he estimated that “In 94 per cent of the cases that were considered successful, the heart was massaged within four minutes while only 6 per cent survived after a delay over four minutes.”

Experience has shown that there were great variations in the ability of different surgeons to obtain satisfactory pressures from manual cardiac massage. Inadequate systemic pressure, trauma to the heart, including massive contusions or rupture, acute hemorrhagic necrosis of the ventricle, and pulmonary edema have been reported as some of the complications of manual cardiac massage. Fatigue of the operator commonly results from manual massage, especially if the maneuver had to be carried out for long periods of time, in which case two or more qualified persons had to be available to relieve one another.

*From the Department of Surgery, University of Chicago.
**This work was conducted in part under the E. F. Andrews Fund for Thoracic Surgery and in part under the Douglas Smith Foundation for Medical Research. Presented at the 27th Annual Meeting, American College of Chest Physicians, New York City, June 22-26, 1961.
An additional important question arose. How long should one massage the heart? Often the surgeon is likely to be discouraged too early; however, frequently a flabby and atonic myocardium can be restored to an actively beating organ. Stephenson succeeded in resuscitating a heart to active rhythmical cardiac action after two hours of massage. Hosler in 1950 successfully restored a heart after eight hours of cardiac massage. According to him, one rule of thumb is to continue to massage as long as one is convinced that artificial cerebral circulation has been adequate enough to prevent irreversible damage to the cortical cells.

The next question concerns the value of drugs in cardiac arrest. Experimental investigations by Stephenson in which several medications were injected intracardially were of great value in answering this question. The injection of epinephrine or calcium chloride solution into the heart as soon as it was exposed for cardiac massage was of apparent benefit; however, many cases required only manual massage before a forceful and regular rhythm returned. Procaine added to epinephrine to avoid ventricular fibrillation was discontinued because of the resulting diminution of tone to the myocardium and its questionable protection against fibrillation. The use of nikethamide (Coramine), caffeine and pentylene tetrazol (Metrazol) were also of no value in resuscitating the heart, the reason being that those drugs were primarily cerebral stimulants and would increase the metabolic demands of the already oxygen-depleted cortical cells, thereby causing further neurologic sequela or death.

**FIGURE 1:** (A) The mechano-cardiac pulsator. The inflatable compartment of the cuff connected to the rubber tube through which air can be rhythmically introduced. (B) Rubber cuff deflated. (C) Rubber cuff inflated exerting localized pressure on the left ventricle; right ventricle is compressed indirectly through the pressure transmitted from the left side.
The above findings of Stephenson agree favorably with the experimental work done in this laboratory. However, it was found that the addition of 4 ml. of I-arneronel (Levophed) to 500 ml. of normal saline given through the intravenous catheter in a very slow rate, about five minutes, before the end of the massage was most helpful in increasing the tone of the cardiac muscle fibers.

Consistent with the previous discussion is the opinion that mechanical cardiac massage is the most important factor in the resuscitation of patients undergoing cardiac arrest. Consequently the problem of maintaining adequate systemic circulation during cardiac standstill by mechanical means has created great interest among research workers. Bencini in 1956 employed mechanical pneumomassage of the heart in dogs. Cardiac massage was effected through rhythmdial air inflation into the pericardial sac. This, however, proved to be unsatisfactory because of the resultant high venous and pulmonary artery pressure, and impaired coronary circulation plus the necessity of an intact pericardium and the time required for cannulation. These findings were substantiated in this laboratory by Jones, et al.\textsuperscript{1} Vineberg in 1957 reported his experimental work on the canine heart.\textsuperscript{4} Cardiac arrest was produced after two minutes of anoxia and the heart then was massaged for eight minutes. He used an apparatus which he described as the mechanical heart. Two rubber bags were applied over the left and right ventricles and were inflated rhythmically through air pressure. None of the dogs had any evidence of coronary, myocardial or gross epicardial damage. However,

<table>
<thead>
<tr>
<th>Serial No.</th>
<th>Dog No.</th>
<th>Date</th>
<th>Air Pressure, mm.Hg</th>
<th>Systemic Pressure, mm.Hg</th>
<th>Pulmonary Pressure, mm.Hg</th>
<th>Duration of Massage, Min.</th>
<th>Status</th>
<th>Postoperative Course</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>522</td>
<td>12-30-59</td>
<td>250</td>
<td>85/35</td>
<td>40</td>
<td>40/20</td>
<td>28</td>
<td>Alive</td>
</tr>
<tr>
<td>2</td>
<td>599</td>
<td>1-8-60</td>
<td>300</td>
<td>50/25</td>
<td>30</td>
<td>25/12</td>
<td>18</td>
<td>Alive</td>
</tr>
<tr>
<td>3</td>
<td>820</td>
<td>1-8-60</td>
<td>200</td>
<td>100/60</td>
<td>75</td>
<td>32/17</td>
<td>20</td>
<td>Alive</td>
</tr>
<tr>
<td>4</td>
<td>638</td>
<td>1-12-60</td>
<td>250</td>
<td>85/40</td>
<td>60</td>
<td>35/20</td>
<td>25</td>
<td>Alive</td>
</tr>
<tr>
<td>5</td>
<td>925</td>
<td>1-14-60</td>
<td>275</td>
<td>55/30</td>
<td>40</td>
<td>22/10</td>
<td>15</td>
<td>Alive</td>
</tr>
<tr>
<td>6</td>
<td>529</td>
<td>1-15-60</td>
<td>300</td>
<td>80/20</td>
<td>40</td>
<td>—</td>
<td>—</td>
<td>Alive</td>
</tr>
<tr>
<td>7</td>
<td>628</td>
<td>1-19-60</td>
<td>200</td>
<td>75/45</td>
<td>55</td>
<td>30/22</td>
<td>27</td>
<td>Alive</td>
</tr>
<tr>
<td>8</td>
<td>526</td>
<td>1-20-60</td>
<td>180</td>
<td>70/45</td>
<td>45</td>
<td>32/23</td>
<td>25</td>
<td>Alive</td>
</tr>
<tr>
<td>9</td>
<td>762</td>
<td>1-22-60</td>
<td>275</td>
<td>75/45</td>
<td>50</td>
<td>30/20</td>
<td>22</td>
<td>Alive</td>
</tr>
<tr>
<td>10</td>
<td>865</td>
<td>1-27-60</td>
<td>250</td>
<td>65/30</td>
<td>40</td>
<td>22/18</td>
<td>20</td>
<td>Alive</td>
</tr>
<tr>
<td>11</td>
<td>747</td>
<td>2-1-60</td>
<td>200</td>
<td>65/40</td>
<td>50</td>
<td>30/20</td>
<td>25</td>
<td>Alive</td>
</tr>
<tr>
<td>12</td>
<td>466</td>
<td>2-3-60</td>
<td>100</td>
<td>80/40</td>
<td>50</td>
<td>45/30</td>
<td>35</td>
<td>Alive</td>
</tr>
<tr>
<td>13</td>
<td>944</td>
<td>2-4-60</td>
<td>200</td>
<td>90/50</td>
<td>65</td>
<td>35/20</td>
<td>25</td>
<td>Alive</td>
</tr>
<tr>
<td>14</td>
<td>722</td>
<td>2-8-60</td>
<td>125</td>
<td>70/35</td>
<td>50</td>
<td>30/12</td>
<td>17</td>
<td>Alive</td>
</tr>
<tr>
<td>15</td>
<td>748</td>
<td>2-12-60</td>
<td>200</td>
<td>65/40</td>
<td>50</td>
<td>30/15</td>
<td>20</td>
<td>Alive</td>
</tr>
<tr>
<td>16</td>
<td>523</td>
<td>3-7-60</td>
<td>180</td>
<td>60/35</td>
<td>40</td>
<td>30/20</td>
<td>25</td>
<td>Alive</td>
</tr>
<tr>
<td>17</td>
<td>839</td>
<td>3-16-60</td>
<td>200</td>
<td>65/40</td>
<td>50</td>
<td>30/20</td>
<td>25</td>
<td>Alive</td>
</tr>
<tr>
<td>18</td>
<td>525</td>
<td>4-6-60</td>
<td>140</td>
<td>75/50</td>
<td>60</td>
<td>27/20</td>
<td>25</td>
<td>Alive</td>
</tr>
<tr>
<td>19</td>
<td>520</td>
<td>4-27-60</td>
<td>100</td>
<td>90/50</td>
<td>65</td>
<td>35/15</td>
<td>20</td>
<td>Alive</td>
</tr>
<tr>
<td>20</td>
<td>629</td>
<td>5-12-60</td>
<td>180</td>
<td>65/45</td>
<td>50</td>
<td>32/17</td>
<td>20</td>
<td>Alive</td>
</tr>
<tr>
<td>21</td>
<td>622</td>
<td>5-17-60</td>
<td>140</td>
<td>65/40</td>
<td>50</td>
<td>30/12</td>
<td>17</td>
<td>Alive</td>
</tr>
</tbody>
</table>
the eight-minute period is too short to prove its efficiency in conditions necessitating long periods of massage.

The following report concerns our experience with a mechano-cardiac pulsator which has been developed in this laboratory. The device was found to be capable of maintaining adequate systemic circulation during cardiac standstill for periods of at least two hours.

Experimental Method

Apparatus

The mechano-cardiac pulsator was designed to mimic the normal cardiac cycle and pressures in the different chambers of the heart, viz: a high systemic pressure, a low pulmonary artery pressure with regular rhythmical beats of 80 per minute, with attention to the systolic-diastolic a high systemic pressure, a low pulmonary artery pressure with regular relation. The apparatus consists of a latex rubber bag, shaped like a heart, with upper and lower openings. It is made of two layers (a) an outer firm and less distensible layer, and (b) an inner more elastic one. The two layers are sewn and glued in such a way that one-half forms a blind compartment that does not distend on inflation and lies over the right ventricle, while the other one-half of the circumference forms the inflatable compressible compartment and lies over the left ventricle. The chamber is connected with a rubber tube through which air is rhythmically introduced and the compartment thus inflated (See Fig. 1).

From the previous description it is apparent that the pressure is applied selectively over the left ventricle while the right ventricle is affected indirectly through the transmitted pressure from the left side. Air or oxygen can be used and is received through a pressure outlet. The bag

FIGURE 2A

FIGURE 2B

FIGURE 2A: Rubber cuff ready to be applied around heart. The inflatable compartment is connected to the tube through which the air can be rhythmically introduced.

FIGURE 2B: Rubber cuff applied around the heart with the inflatable compartment overlying the left ventricle.
is inflated by means of a double-action air pump controlled by a cam having a predetermined contour so that the pressure fluctuation of the flexible bag is divided into (a) one-third pressure stroke and (b) two-thirds suction stroke per revolution. This corresponds to the one-third systolic contraction and the two-thirds diastolic relaxation of the normal heart cycle. An average rate of 80 beats per minute was found to be optimal.

Procedure

These experimental studies were made on 21 mongrel dogs. The procedures carried out in each of these dogs were the same and can be summarized as follows: an intravenous cannulation was made to which 500 ml. of normal saline was connected and used later for addition of drugs. The dog was anesthetized using thiopentol sodium (Sodium Pentothal), oxygen and endotracheal tubing. Respiration was maintained by intermittent positive pressure, and electrocardiographic leads were then connected. The dog was placed on the right side and the left thoracic cavity was entered through the fifth intercostal space. The femoral and pulmonary arteries were catheterized with polyvinyl tubing and linked to F-23-d Statham gauges. Pressures were monitored on a four channel Grass polygraph recorder. The lung was retracted laterally and the pericardial sac was opened and holding sutures were applied to the edges of the pericardium. The heart was delivered (Fig. 2) outside the pericardial sac and the bag applied. Cardiac asystole was produced with an electrical shock, using 75 volts A.C. The air then was introduced into the bag through the tube. The air pressure was adjusted and maintained when a maximum systemic pressure was reached. The pericardium was approximated and the sutures were loosely tied around the bag to help maintain it in position. Five minutes before the end of the experiment 4 ml. of Levophed in 500 ml. of normal saline was connected to the intravenous cannula and introduced slowly. The bag was removed and the heart defibrillated using 140 volts A.C. After the heart had been started, a period of at least 15 minutes was allowed to elapse, during which time the heart could be observed before the chest was closed. In our experience after ten minutes of efficient contraction the heart was not likely to stop again.

Result

Twenty-one dogs were used for these studies (See Table 1). The duration of cardiac compression ranged between 20 and 120 minutes. Nineteen • dogs survived the procedure, one dying of anesthesia and the other of

| TABLE 2—SYSTEMIC AND PULMONIC ARTERIAL PRESSURES MAINTAINED IN 21 DOGS OVER PERIODS UP TO TWO HOURS |
|---------------------------------------------------------------|------------------|------------------|-------------------------------|
| Duration in Min. | Systemic Pres. mm.Hg SD | Mean | Pulmonary Pres. mm.Hg SD | Mean | Postoperative Status |
| 120 | 100/80 | 75 | 40/23 | 35 | 19 Alive and well |
| 20 | 50/25 | 30 | 25/12 | 15 | 2 Dead of anesthesia |
| Average | 73/40 | 50 | 30/18 | 22 | |

Dec., 1961

ATTALLA, BORQUEZ VIAL, MOULDER AND ADAMS
FIGURE 3: Maintenance of adequate circulation by mechanical compression during cardiac standstill for periods of (A, upper) 45 minutes; note systemic pressure of 80/40 with a mean of 50 mm.Hg. (B, center) 60 minutes; note systemic pressure of 70/35 with a mean of 50 mm.Hg. (C, lower) 60 minutes; note systemic pressure of 90/50 with a mean of 65 mm.Hg.
drug over dosage. Of the 19 surviving dogs, 14 were alive and well up to two weeks postoperatively and were sacrificed for pathologic studies. None of these revealed any sign of cerebral, pulmonary or cardiac disturbances. The five remaining dogs died between the second and tenth postoperative day from infection of the chest wall, pleura and pericardium, as a result of contamination at the time of surgery.

The following observations (See Table 2) were obtained during cardiac massage on the experimental animals: systemic pressures ranged from 55-100/30-60 with a mean of 30-75 mm. Hg. The pulmonary artery pressures were 25-40/12-3 with a mean of 15-35 mm. Hg. The air pressure necessary for this purpose ranged between 100-300 mm. Hg. Electrocardiographic tracings made before and after massage showed a return of normal rhythmical beats with little or no change in pattern.

Pathologic studies of lung tissue obtained before, immediately after and two weeks postoperatively showed essentially normal parenchyma except for an occasional minimal inflammatory reaction.

Discussion

In the interpretation of the systemic pressures obtained with mechanical compression of the heart, the mean arterial pressures were of most significance. As shown in Table 1, some dogs showed a high systemic pressure while others showed low pressures. Dogs that showed a comparatively low mean systemic and pulmonary pressure did equally well after surgery, these hypotensive pressures did not appear to influence the outcome of surgery since blood volume was maintained at a normal level. The use of hypotensive medication in major surgical procedures agrees favorably with these findings.

FIGURE 4: Maintenance of adequate circulation by mechanical compression during cardiac standstill for two hours. Note systemic pressure of 90/50 with a mean of 65 mm.Hg. Period of resuscitation followed promptly by normal rhythm and pressures, one and one-half hours, three hours, and two weeks postoperatively.
It was of interest to note that in some dogs adequate circulation could be maintained with comparatively low systemic pressures if concomitant low pulmonary artery pressures were obtained.

In the early experiments the average duration of mechanical compression was between 20 and 30 minutes. However, because of the satisfactory results obtained, the duration of massage was progressively increased to 120 minutes. Figure 3 illustrates the satisfactory systemic and pulmonary artery pressures at different durations ranging from 45 to 60 minutes.

Technically it was observed that when the bag fit the heart rather snugly the air pressure needed to produce a satisfactory systemic pressure was comparatively low. An example is illustrated in Fig. 4, where the air pressure of 100 mm Hg produced a systemic pressure of 90/50 with a mean of 65, a pulmonary artery pressure of 45/15 with a mean of 20. In this experiment the mechanical compression of the heart was maintained for two hours at the end of which time the myocardium appeared healthy and was easily restored to a normal rhythm.

**Clinical Application**

In view of these experimental results, it is our opinion that this device would be helpful in the management of clinical cases of cardiac arrest. For practical purposes, once cardiac arrest is established, the chest is entered and the heart is massaged manually. If cardiac action begins promptly, there is no indication for any additional interference. However, in conditions where massage has to be carried out for longer periods, the apparatus could be applied and massage could be maintained more efficiently by mechanical means.

In addition, it is possible that efficient mechanical cardiac massage may be helpful in cases other than cardiac arrest. For example, in surgical procedures for correction of congenital anomalies, conduction defects or acquired valvular disease, mechanical cardiac massage may be valuable in the restoration of normal cardiac rhythm. This technique might be substituted for manual cardiac massage which at times subjects the myocardium to trauma and imposes fatigue on the operator.

**SUMMARY**

A method has been devised by which adequate systemic circulation could be maintained by mechanical cardiac compression for as long as 120 minutes. For this purpose a compressible rubber cuff, the mechano-cardio pulsator, was designed. This consisted of an inflatable compartment making possible selective pressure over the left ventricle and, indirectly much lower pressure over the right ventricle, thus obtaining a satisfactory high peripheral systemic and a low pulmonary pressure. Long periods of massage were maintained without ill effect to the cerebral, coronary or pulmonary circulations. The myocardium could easily be restored to a normal rhythm at the end of the procedure. The possible clinical application of this method is discussed.

**RESUMEN**

Se ha ideado un metodo por el cual se puede mantener una adecuada circulación general mediante la compresión cardíaca mecánica por tan largo tiempo como 120 minutos. Para esto un manguito compresible de goma con un pulsador mecánico se ha construido.

Este consiste en un departamento inflable que hace posible la presión selectiva sobre el ventrículo izquierdo e indirectamente hacer mucho mas baja la presión sobre el ventrículo derecho obteniéndose así una satisfactoria elevada presión general periférica y una baja presión pulmonar. Se mantuvieron largos periodos de masaje sin malos efectos sobre las circulaciones pulmonar, cerebral o coronaria. El miocardio puede fácilmente ser vuelto al ritmo normal al final del procedimiento.

Las aplicaciones clínicas posible son objeto de disertación.

**RESUMÉ**

Une méthode originale permet de maintenir pendant une période allant jusqu'à 120 minutes une circulation générale adéquate grâce à une compression cardiaque mécanique. Dans ce but, une manchette compressive en caoutchouc, le "mechano-cardio pulsator" a été réalisée. Elle consiste en un compartiment gonflable permettant une pression selective sur le ventricule gauche, et indirectement une pression bien inferieure sur leventricule droit; ceci permet d'obtenir de façon satisfaisante une forte pression dans la grande circulation, et une pression pulmonaire basse. De longues périodes de massage ont été maintenues sans effets nocifs sur la circulation cérébrale,
coronare ou pulmonaire. A la fin de l'expérience l'état du myocarde permettait facilement de ramener un rythme normal. L'application clinique possible de cette méthode est envisagée.

**ZUSAMMENFASSUNG**


**REFERENCES**


**OXYGEN POISONING UNDER WATER**

In man, the inhalation of 100 per cent oxygen at ground level leads to the slow appearance of respiratory symptoms resembling progressive coryza. In skin diving during the breathing of oxygen, neurologic effects predominate and the reaction is accelerated. A concept is presented to implicate hyperventilation in "oxygen poisoning," with resultant symptoms of cerebral hypoxia. So many variables are involved that it is futile to speak of safe depth-exposure time during the use of oxygen-rebreathing equipment.