PROGRESS IN CARDIOVASCULAR SURGERY

Veno-Arterial Pulsatile Partial Bypass for Circulatory Assist*

ALFRED GOLDMAN, M.D., F.G.C.P., ERNO BOSZORMENYI, M.D., FUMIHiko UTSU, M.D.,
VIOGICA ENESCU, M.D., HAROLD J. C. SWAN, M.D. AND ELIOT CORDAY, M.D., F.G.C.P.**

Los Angeles, California

A computerized pulsatile arterio-arterial system for postsystolic myocardial augmentation has been developed by Chesnut,5 and Watkins and Callaghan.6 They determined that the circulatory assist by arterio-arterial pumping is due to lowering of the left ventricular pressure work as a result of conditioning the aorta to a lower pressure at the moment of aortic valve closure. This system has been utilized in humans for circulatory assists in coronary occlusion, shock states, and poor surgical risk patients undergoing various operative procedures.6 Hahnloser et al6 have more recently evaluated the hemodynamics of the new Simas† fluid coupled (rather than pneumatic coupled) pulse generator with its improved synchronizing electronics. Their conclusions were that this arterio-arterial counterpulsation pump performance was superior to pneumatically coupled systems previously studied.6 Synchronization with cardiac events could be readily achieved even with rapid heart rates. Cardiac dynamics were benefitted as shown by reduction of: left ventricular systolic pressure; ventricular external pressure work; and the index for myocardial oxygen consumption. On the other hand, adverse effects with arterio-arterial pumping inferred from the measurements of cardiac output, aortic pressure, renal and carotid artery blood flows and central venous oxygen saturation were considered.7 Despite the advantages of arterio-arterial pumping, according to the techniques of Callaghan and Watkins, veno-arterial pumping would appear more suitable for circulatory assist in various shock states and arrhythmias.

Veno-arterial pumping is still in a developmental stage and a large number of workers have contributed to its present knowledge. Stuckey et al.9 in 1957, employed partial bypass with pump oxygenator, but without synchronization in the treatment of three patients with myocardial infarction with one survivor. Connolly et al.10 in 1958, suggested a circuitry and technique of veno-arterial pumping with external closed chest cannulation of the terminal aorta and vena cava so that the unoxgenated vena caval blood would be pumped, non-synchronized, into the femoral artery. He further suggested that the entire bypass could be in operation in 20 minutes and could be carried out in the emergency room or at the bedside. Claus et al.11 in 1961, stressed both the importance of pulsatile flow to avoid increasing pressure work of the left ventricle and the increasing of coronary perfusion by elevating the diastolic pressure in the aorta when synchronization during cardiac diastole is used. Connolly,12 in 1964, suggested that recent developments in disposable oxygenators primed without blood may partially solve some of the problems associated with lengthening the safe period of bypass which may be necessary to support successfully the failing heart. Brief et al.13 in 1964, utilized arterio-arterial counterpulsation14 for the


From the Medical Research Institute, Cedars of Lebanon Division, Cedars-Sinai Medical Center, and Departments of Medicine and Thoracic Surgery. Study supported by grants from the NIH (FR 0568-04), the NIH (HE 09143-05) and (HE 10841-01), the Beneficial Standard Life Insurance Company, and the Abe Lastfogel, Jack Feldman, Jules Stein and Hal Wallis Foundations.

†Sundstrand, Denver (now Hamilton Standard, Winsor Locks, Conn).
treatment of canine irreversible hemorrhagic shock and found no significant difference in the course of the controls and counterpulsated groups. They found that the pH consistently increased during the pump run and that the excess CO₂ could be readily cleared with the aid of the oxygenator. They observed hepatic congestion and portal hypertension, but at the same time, they indicated that pulsatile flow may result in better tissue perfusion than non-pulsatile flow, and also that synchronized pulsatile diastolic pumping could avoid increasing pressure work of the left ventricle. Lefemine et al. further confirmed that synchronized arterial counterpulsation can reduce mean aortic systolic pressure and maintain or elevate the mean diastolic pressure. They stated that synchronized arterial counterpulsation is an effective method for reducing mean systolic pressure and myocardial oxygen consumption while maintaining coronary perfusion, and in addition "arterial counterpulsation appears to be an excellent method of assisting the failing myocardium and merits further investigation and application," and they reported one surviving and two non-surviving patients supported by assisted circulation with oxygenator and synchronization. Watkins and Callaghan have treated 23 patients with arterio-arterial postsystolic augmentation with varying results.

This presentation will show: (1) our adaptation of the Simas system for veno-arterial pumping, (2) the superiority of

**Figure 1:** Diagram of veno-arterial circuitry. The circuitry or "hook-up" transports venous blood by gravity drainage from the right atrium via the venous catheter inserted through the femoral vein (22F polyethylene) to the oxygenator-heat-exchanger. Within the ejection chamber enough negative pressure is created by the withdrawal stroke of the hydraulic pump system to suck into it not only oxygenated blood from the oxygenator, but also aortic blood. On the push, or ejection stroke, the added increment of right heart blood together with the aortic blood is pumped back into the aorta during the postsystolic phase. The phasing and the rate are synchronized to the "R" wave of the ECG. During ventricular fibrillation (no "R" wave) the rate of the automated pacemaker is 70 per minute. The stroke volume delivered may be adjusted from 0 to 120 ml. The details and circuitry locations of the oxygenator and the one-way prosthetic valve assembly are indicated.
veno-arterial over arterio-arterial pumping, and (3) suggestive clinical application for emergency use at the bedside.

We have instituted two important changes in the Simas computerized pulsatile system in order to effect improved circulatory assist. These changes are: (a) adaptations for veno-arterial pumping, and (b) the inclusion of an oxygenator. This new circuitry is shown in Figure 1. Note that blood is drawn from the right atrium via a femoral vein catheter, oxygenated and transported to the pressure pulse generator (PPG) ejection chamber. From the PPG, blood is pumped into one or both femoral arteries synchronized with the postystolic phase of the cardiac cycle by the Simas system's millisecond timing, so that the increment of blood provided by the pump enters the aorta after the aortic valve has already closed during diastole. Veno-arterial pumping adds to the stroke-volume of the arterio-arterial pumping an additional variable volume of venous blood (oxygenated), the desired amount of which is set by the pump operator.

A one-way low resistance prosthetic heart valve has been adapted in the PPG ejection chamber stack to which the venous line is connected. Clamping the venous line between the oxygenator and the PPG converts the circuit from veno-arterial to arterio-arterial pumping, both synchronized. When the venous line is unclamped and open, the pumping system is combined veno-arterial and arterio-arterial. Thus the benefits of both pumping systems are instantly available. More importantly, an increased circulating volume can be pumped not only without adding to the work of the left side of the heart, but also to reduce the work of the right ventricle and the pressure of the venous circulation including the right atrium. Reduction in external left ventricular pressure work is assured because pumping is phased by the millisecond timing to inject blood into the aorta only during the early postsystolic period. This post-systolic phased pulsatile pumping appears to have advantages over continuous extracorporeal perfusion particularly for prolonged circulatory assist because the former, veno-arterial pumping, does not inject blood into the aorta against ventricular systole while the latter, continuous extracorporeal method, increases the work of the left ventricle, especially in normal sinus rhythm.

We have used two oxygenator systems which are placed in the position of gravity drainage of the right atrium in the venous circuit. These two systems are: (a) the plastic bag,†† and (b) the omnithermic disposable bubble oxygenator.‡‡ Both oxygenators are satisfactory, but the omnithermic has the advantage of a built-in heat exchanger. The inclusion of the oxygenator removes CO₂ and completely saturates and arterializes all blood being pumped into the aorta via the femoral artery cannulae.

**Methods**

A total of 74 dogs were perfused with the Simas system the past ten months, of which veno-arterial pumping was performed upon 52 mongrel dogs. These animals, weighing 20 to 35 kg. of either sex, were anesthetized with 6 mg./kg. of intravenous pentobarbital sodium. Intratracheal intubation and respiration with room air were established via a tied-in, snug fitting, heavy plastic tubing 2 cm. in internal diameter and a variable stroke and volume Harvard respirator. The chest was opened bilaterally through a long incision in both fourth intercostal spaces with transection of the sternum. Hemostasis was secured with electrocoagulation and ligation. The main pulmonary artery was dissected from the aorta, freed of fat and adventitia for approximately 3 cm. for placement of an electromagnetic flow probe* to measure the cardiac output. Additional electromagnetic flow probes were placed around: (1) the left anterior descending coronary artery for measuring partial coronary flow; (2) the right carotid artery; and (3) the left renal; (4) the mesenteric (after laparotomy). The

††Travenol Laboratories, Morton Grove Illinois.
‡‡Bemley Laboratories.
circumflex coronary artery was dissected out and a ligature placed around it at its takeoff from the main left coronary artery. Central aortic and central venous pressures were measured by P-23 GB and P-23 BB Statham strain-gauge transducers via Courand catheters inserted into the left brachial artery to the aortic root, and the brachial vein to the right atrium respectively. After completion of these dissections, heparin, 2.5 mg./kg. body weight and repeat doses of 1.0 mg./hr. were administered intravenously. A direct writing visual recorder 16 channel polygraph (Electronics for Medicine) was used for recording ECG and all other flow and pressure data. After taking the control measurements of regional flows and pressures, appropriate sized Teflon cannulae (12, 14 or 16 F) previously attached to the pressure pulse generator (PPG) were inserted into each surgically isolated femoral artery through a 0.5 cm. arteriotomy. A 50 cm. long 22 F polyethylene catheter, fenestrated throughout 10 cm. from its tip, was passed through the left femoral vein and inferior vena cava into the right atrium. Through the right femoral vein 5 per cent glucose and water, Ringer's or physiologic saline solution was administered on demand.

pH, pO2, pCO2 hematocrit (Hct) and hemoglobin (Hgb) were measured in 20 of 27 dogs with ventricular fibrillation. Blood gas analyses were performed in an "I.L." analyzer which utilizes a Clark electrode for pO2, Sevringhaus electrode for pCO2, and standard glass electrode at 37° for pH. Data was recorded to compare the pump effect during sinus rhythm (pre-pump control) and ventricular fibrillation with both arterio-arterial and veno-arterial (A-A and V-A) pumping. Ventricular fibrillation was produced by: ligation of the circumflex coronary artery by myocardial "bead shock" and by surgical shock. In the case of circumflex coronary ligation (27 dogs), the veno-arterial pumping commenced at the time of ligation and continued for one hour of ventricular fibrillation; only short runs of arterio-arterial pumping were made to collect comparison data. Blood samples from the right atrium and the ascending aorta were taken at the onset of ventricular fibrillation and repeated after one hour, immediately before defibrillation.

RESULTS

Blood Gas Analysis and pH.

The testing of the effect of the oxygenator upon oxygen saturation of the arterial and venous blood together with pCO2 clearance was highly satisfactory in that an adequate arterial saturation and a diminution of elevated pCO2 was readily achieved during one hour of ventricular fibrillation pumped with V-A circuitry and oxygenator. But the pH became more acidic reaching severe levels at the end of one hour approximating pH 7.0. Despite the acidosis the ventricular fibrillation was readily defibrillated to sinus rhythms at the end of one hour of pumping. Since relatively good oxygen saturation was obtained from the root of the aorta after one hour's pumping we assumed the acidosis was metabolic, and related to the severe shock state of the animal.

Nevertheless, these results indicated that the oxygenator aided markedly in maintaining the "integrity of the myocardium" since in another group of animals pumped with V-A circuitry but without an oxygenator defibrillation after one hour's pumping could not readily be accomplished.

Bead Shock:

A typical example of the severe shock state produced by this method of myocardial shock is depicted in Table 1. Here are compared control values of the coronary blood flow in the left anterior descending coronary artery; the cardiac output as measured by the flow in the main pulmonary artery in liters/min.; and the blood pressure in the left ventricle and ascending arch of the aorta. After recording the control values with the ECG in normal sinus rhythm, cardiogenic shock was produced by injecting small plastic beads into the left circumflex coronary artery after the method of Agress modified by Corday. The re-
resulting second pre-pump control shock values are recorded in the middle column and in the last column are the values with veno-arterial pumping 30 ml. stroke volume. The ECG showed great deterioration and the rhythm became irregular, nodal or sinus, from the coronary shock. The flow in the left anterior descending coronary artery dropped from 31.6 to 5.2 ml./min. and the blood pressure in the root of the aorta fell from 122/78 to 30/14 mm. Hg with an associated elevation of the left ventricular and diastolic pressure indicating ventricular failure. With the V-A circuitry, oxygenator, and pump now turned on, the coronary flow increased 500 per cent (3rd column) and equals approximately 85 per cent of the normal sinus rhythm pre-pump control value. The aortic root peak pressure increased 200 per cent to 62 systolic. The left ventricular end diastolic pressure is reduced from 15 to 12 mm. Hg. These data indicate that veno-arterial pulsatile partial bypass for circulatory assist can restore the coronary circulation in "experimental bead shock of severe grade."

**TABLE 1—"BEAD CORONARY SHOCK" TREATED BY VENO-ARTERIAL PUMPING.**

<table>
<thead>
<tr>
<th></th>
<th>CONTROL</th>
<th>CARDIOGENIC SHOCK</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>BEFORE PUMP</td>
<td>V-A PUMP 30 cc/stroke</td>
</tr>
<tr>
<td>ECG</td>
<td><img src="image" alt="ECG" /></td>
<td><img src="image" alt="ECG" /></td>
</tr>
<tr>
<td>CORONARY FLOW (LAD) cm/min</td>
<td>31.6</td>
<td>5.2</td>
</tr>
<tr>
<td>PA FLOW L/min</td>
<td>1.27</td>
<td>0</td>
</tr>
<tr>
<td>BLOOD PRESSURE</td>
<td>122/78</td>
<td>26/16/52</td>
</tr>
<tr>
<td>LEFT VENTRICULAR PRESSURE</td>
<td>122/14</td>
<td>30/14</td>
</tr>
</tbody>
</table>

Veno-arterial pumping with oxygenator restored the coronary flow in the left anterior descending artery to approximately 85 per cent of the pre-pump control and increased 500 per cent the shock coronary flow (5.2 to 26.7 ml/min.).

**Circumflex Coronary Ligation Ventricular Fibrillation:**

We considered that ventricular fibrillation induced by ligation of the circumflex coronary artery at its origin would be a severe test of the benefits of this circulatory assist because in this arrhythmia, coronary and systemic flows are zero, therefore any measured flow is due to pumping. Besides, this arrhythmia is frequently encountered as a fatal complication in patients undergoing treatment in intensive cardiac care areas. Furthermore, we tested comparatively the benefits of circulatory assist of both V-A and A-A pumping and the data of a typical experiment are shown in Table 2.

The direct writing polygraph records five regional flows, central arterial and venous pressures and ECG during V-A and A-A pumping. During one hour’s ventricular fibrillation induced by ligation of the circumflex coronary artery, V-A pumping produced an increase of one and one-half times the carotid artery pre-pump control flow. A-A pumping produced only one-fifth of the control carotid artery flow. During
Typical experiment showing five regional flows recorded simultaneously, central aortic (aortic root) and venous pressures (right atrial). The data show carotid flow is eight times more with veno-arterial than arterio-arterial pumping, 25 times more coronary flow with veno-arterial pumping (3.8 ml for A-A and 98.6 ml for V-A pumping).

V-A pumping, coronary flow was elevated seven and one-half times the pre-pump control. With A-A pumping, the coronary flow fell markedly to approximately one-fourth the pre-pump control. There is an absence of recording of pulmonary flow during ventricular fibrillation with both methods of pumping, as well as diminished mesenteric and renal flows. Also note (next to bottom line) that the central aortic pressure peak

### Table 2—Circumflex Coronary Ligations Ventricular Fibrillation.

| Comparison of A-A and V-A pumping, composite results of 27 experiments showing that the mean left anterior descending coronary flow was only 2 ml/min. with A-A pumping but was markedly increased to 27 ml/min. with V-A circulatory assist. |
is 136 mm. Hg with V-A pumping, but this drops to severe shock level of 48 mm. Hg with A-A pumping. In addition, the central venous pressure (right atrial) has also been adequately maintained with V-A pumping, but not during A-A pumping, there being a rise of approximately 100 per cent in right atrial pressure when V-A is changed to A-A pumping. These data demonstrate that hemodynamic restoration of coronary and carotid flow is better achieved with V-A pumping under these experimental conditions and also demonstrates the better beneficial control of central venous and aortic root blood pressure.

Table 3 reflects the measurements of the LAD coronary mean blood flow in normal sinus rhythm and during circumflex coronary artery ligation ventricular fibrillation with A-A and V-A pumping in 27 dogs. This data shows that the mean flow in normal sinus rhythm pre-pump control (without pumping) was approximately 10 mL/min. with a maximum of 26 mL/min. With A-A pumping in ventricular fibrillation, LAD coronary blood flow mean value was approximately 2 mL/min. and a maximum of 5 mL/min., but V-A pumping produced a marked increase in coronary flow during ventricular fibrillation so that the LAD coronary flow in 15 (55 per cent) of the 27 dogs was higher than the highest recorded flow in the normal sinus rhythm pre-pump control. The mean value was approximately 27 mL/min. and the maximum 164.5 mL/min. Considering the shock state of these animals and that the coronary flow in ventricular fibrillation is zero, these flow measurements show conclusively that V-A pumping produces coronary flows capable of restoring pre-pump control levels in every case and also makes available a coronary flow with a mean value two and one-half times the control values. In 26 of these 27 animals, defibrillation was readily accomplished at the end of an hour’s V-A pumping, with only one or two electric shocks.††

††Bircher A.C. defibrillator

Discussion

Ventricular fibrillation with a flow measurement of the LAD coronary artery was chosen as the experimental model to compare not only the flow value but also the maintenance of the viability of the myocardium by the veno-arterial pumping. The experimental conditions were extremely severe because the animals generally had low blood pressures as a result of myocardial shock and from opening both major body cavities as well as surgery for numerous incisions and dissections that had to be made to place the cannulae, catheters and flow probes. Approximately 25 per cent of the 74 animals developed spontaneous fibrillation as a result of manipulation to the coronary vessels and the concomitant shock state, and then were pumped. The only fluid replacement utilized was 5 per cent glucose in water, physiologic saline, or Ringer’s solution. Therefore, defibrillation after one hour’s pumping during ventricular fibrillation was a severe test of the maintenance of the “myocardial integrity.” This was especially true of the 27 animals that had left circumflex coronary artery ligation to produce ventricular fibrillation.

The question of why the marked diminution of regional coronary and carotid flow with A-A pumping in ventricular fibrillation compared to V-A pumping is related to the lack of enough circulating volume to keep an adequate forward flow in the arterial tree. Ordinarily the arterial flow in ventricular fibrillation is zero, or approaches it, and unless the arterial tree is distended with sufficient volume of circulating blood, withdrawal from the femoral arteries and re-injection (A-A pumping), no matter what the force of the pump, produces mainly only collapse and distention of the arterial tree, and so cannot restore adequate circulating volume to the coronaries even though the resistance of the coronary circulation is markedly diminished in ventricular fibrillation. The success of V-A pumping in restoring coronary flow is no doubt related to the increased volume of blood made available to the arterial
system by virtue of additions of an increment of oxygenated venous blood to each ejection stroke of the pump. This is tantamount to giving a continuous pulsatile postsystolic arterial transfusion with oxygenated blood.

The venous pressure elevation on changing from V-A to A-A pumping is proof that adequate volume of blood was available for circulation into the arterial tree (Table 2). V-A pumping accomplishes this circulation, but A-A pumping does not during ventricular fibrillation.

This study indicates that pulsatile veno-arterial pumping with oxygenator-heat-exchanger may be able to resuscitate hearts in ventricular fibrillation that have become resistant to electrical and pharmacologic cardioversion. Our experience in the laboratory suggests that suitable clinical trials are warranted for this V-A pumping system. Simas A-A pumping has already been reported in a limited number of patients in shock states, coronary shock, respiratory failure and bad risk patients undergoing major surgery. V-A pumping should be adaptable to even a broader group of patients including those in both left and right heart failure with high venous pressures and low arterial oxygen saturations. Also patients in surgical shock and acidosis associated with low cardiac outputs should be amenable for this circulatory assist.

Corday and Williams have described the effect of shock on the hepatic, mesenteric and renal regional blood flows and state that each organ has its own characteristic vascular response to shock and vasopressor drugs. The circulation of the intestine, as well as that of the kidney, plays a vital role in circulatory homeostasis during acute shock. The vascular resistance in each of these organs increases markedly following hemorrhage. They also related the states of "compensated and non-compensated shock" to compensatory arteriolar vasospasm of the kidneys, gastrointestinal tract, skeletal muscles and skin, thus allowing the limited circulating blood volume to be shunted to those more vital areas essential for the maintenance of life and least able to withstand ischemia (such as the brain and the heart). Our measurements of regional flows to the abdominal viscera, (Tables 1, 2) confirm these effects; namely, that when the coronary and carotid artery flows were even higher than pre-pump controls the renal and mesenteric flows were very low in the shock states experimentally produced. Morris et al. have shown that a perfusion rate of 35 ml./kg. of body weight supports an aortic pressure (35 to 60 mm.Hg) sufficient to allow renal function in cardiopulmonary bypass with pump oxygenator in patients undergoing aortic aneurysmal surgery. The pulsatile perfusion rates in our experiments approximated the 35 ml./kg. of body weight, but we made no attempt to increase or even maintain circulatory volume. The study of these and other factors in the treatment of severe shock states with veno-arterial pulsatile partial bypass, as well as more prolonged and repetitive daily pumping is now being undertaken.

Conclusions

A method is described for circulatory assist utilizing the Simas computerized pulsatile postsystolic augmentation system adapted and modified for veno-arterial pumping with an oxygenator-heat-exchanger. This veno-arterial circulatory assist system has been compared with arterio-arterial pumping in 74 dogs.

In shock states the benefits to regional flows and particularly to the coronary and carotid flows are much higher for the veno-arterial system.

In 27 dogs pumped during one hour's ventricular fibrillation, coronary flows could not be adequately maintained with A-A pumping, but with V-A pumping coronary flow was restored to pre-pump or higher levels (normal sinus rhythm) and the mean value was two and one-half times the control values. The myocardium was readily converted from ventricular fibrillation to sinus rhythm by cardioversion.

Clinical applications are discussed and therapeutic trials in selected cases with shock states as well as ventricular fibrillation appear to be warranted.