The Effects of Right Heart Bypass on Acute Ventricular Failure with and without Ventricular Fibrillation

Hans H. J. Zwart, M.D., Alex C. Kralios, M.D., and Willem J. Kolff, M.D.

A technique was developed for closed-chest bypass of the right ventricle. Blood is removed from the right atrium and returned into the pulmonary artery. The blood return cannula can be inserted without x-ray equipment. The maximum flow through the system is ten liters per minute. Acute right ventricular failure produced by embolization of pulmonary arteries with starch could be treated promptly and repeatedly with the bypass. In six out of eight failure periods, the right ventricle had recovered after only five minutes of bypass. Progressive decrease of the arterial oxygen saturation, inherent with diffuse pulmonary embolization, could not be reversed. During ventricular fibrillation, while the circulation was maintained with closed-chest left ventricular bypass (transarterial), right heart bypass could not substitute right heart function. The reasons for this failure were incompetence of the pulmonary artery and tricuspid valves and increase of pulmonary arterial resistance.

The development of cardiocirculatory assist devices has been almost exclusively directed towards improvement of left ventricular function. Although left-sided heart failure indeed constitutes the main defect in most cases of circulatory collapse, there remains ample reason to consider treatment of right ventricular failure with mechanical means. Acute intractable right heart failure can occur in combination with left ventricular failure or independently caused by pulmonary embolism, pulmonary hypertension or volume overload.

Recently it has been demonstrated that balloon counterpulsation in the pulmonary artery can improve right ventricular function and thereby the entire circulation. The present study evaluates the effects of right ventricular bypass on right ventricular failure. It was anticipated that with a bypass, extreme states of circulatory collapse such as occur during paroxysmal ventricular tachycardia, ventricular fibrillation and asystole could still be treated. Acute right ventricular failure was produced by embolization of the pulmonary artery with starch or by induction of ventricular fibrillation.

**Materials and Methods**

Twelve Columbia sheep weighing 45 to 55 kg, were fasted for 48 hours and anesthetized with sodium methohexital 200 to 300 mg and scopolamine 1 to 2 mg intravenously. Following endotracheal intubation, respiration was controlled with an Engstrom respirator (150 MIVAB), room air 70 percent and oxygen 30 percent, frequency 16 per minute, tidal volume 800 ml. Anesthesia was continued with halothane.

The right ventricle (RV) was bypassed with cannulas inserted via the external jugular veins and passed down into the right atrium (RA) and pulmonary artery (PA) (Fig 1, 2). The cannulas were connected with a ⅛" ID six foot Silastic tube which in turn was mounted in an occlusive calibrated roller pump. Blood was removed from the RA and returned into the PA. Details on the cannulation technique are presented under the section, Results.

Experiments were divided in three groups.

**Group 1** (three sheep): Cannula techniques for closed-chest right ventricular bypass (RVB) were developed. The pulmonary artery was embolized with starch until right ventricular (RV) failure occurred. Some pilot experiments were performed with the bypass but the sheep were essentially left untreated and served as controls.

**Group 2** (three sheep): Failure was produced with corn starch embolization of pulmonary arteries. The effects of RVB before and during RV failure were studied.

*From the Division of Artificial Organs and Institute for Biomedical Engineering, University of Utah, Salt Lake City. This work was supported by The John A. Hartford Foundation, The Max C. Fleischmann Foundation, The Christina Foundation, and The Lad L. and Mary Hercik Fund. Reprint requests: Dr. Zwart, University of Utah Medical Center, Salt Lake City 84112.*
Group 3 (six sheep): The effects of RVB were determined before and during ventricular fibrillation.

The pulmonary arteries were embolized with a 10 percent suspension of starch in 0.9 percent saline. The mean diameter of swollen starch grains is 14.4 ± 0.6 micron. An initial dosage of 5 ml of the suspension was given intravenously. Additional injections of 2 ml were administered at intervals of ten minutes until RV failure occurred.

Ventricular fibrillation was produced with a 6 V DC current applied directly to the heart with needle electrodes. During ventricular fibrillation the circulation was maintained with left ventricular bypass (LVB). Blood was removed from the left ventricle (LV) with a 45 cm long, 6 mm OD, 0.3 mm wall-thickness flexible cannula which was inserted via the right carotid artery past the aortic valve. The blood was returned with an occlusive calibrated roller pump into a femoral artery. This bypass has been described in detail previously. It can be operated equally well in open and closed chest animals (Fig 3).

Bypass flows were calculated from the rpm of the roller pumps. Prior to bypass the sheep were heparinized (2 mg per kilogram body weight). The arterial and right atrial pressure (AP and RAP) were measured in all sheep with catheters inserted via a femoral artery and vein. In group 2, pulmonary arterial pressure (PAP) was measured from the RVB blood return cannula in between bypass periods. In three sheep of group 3, the right ventricular pressure (RVP), PAP, and left ventricular pressure (LVP) were measured with Sanborn transducers (Sanborn Company, Waltham, Massachusetts) and recorded together with lead aVF of the ECG on an eight channel Sanborn recorder.

The hematocrit, oxygen saturation (American Optical Oximeter) and the pH (Radiometer, Copenhagen) of arterial blood were measured at regular intervals. The esophageal temperature and the end-respiratory pressure were recorded.

Surgical procedures were carried out under clean conditions. In the three latter sheep of group 3, the chest was opened through the fifth IC space on the right side. The experiments had an average duration of four hours (range 2 to 6). At termination of the experiments, the sheep were killed and autopsy was performed.

RESULTS

Cannulation Techniques (group 1): Two techniques were developed for closed-chest RVB. In one (Fig 1) a double lumen cannula was used, consisting of an inner tube: 7.0 OD, 5.5 mm ID, 45 cm long of Tygon, and an outer Silastic tube: 12.0 OD, 10.0 mm ID, 16 cm long. The cannula was inserted via the right external jugular vein. Manipulation of the inner cannula into the PA is illustrated in Figure 4. For another RVB cannulation technique, separate blood outflow and return cannulas were used (Fig 2). The outflow cannula (Bardic 32-34) was inserted into the RA via the left external jugular vein. The blood return cannula (Tygon tube, 12.0 OD, 10.0 mm ID, 45 cm long) was inserted into the PA via the right external jugular vein.

Both cannulation techniques were easily mastered after some practice, and no x-ray equipment was necessary. During manipulation in the RV, some premature ventricular contractions were observed but once in position, the cannulas did not cause arrhythmias. The maximum capacity of the
EFFECTS OF RIGHT HEART BYPASS

Figure 4. Technique for insertion of double lumen right heart bypass cannula. (A)—Tip of blood return cannula curled up in blood outflow cannula. The cannulas are inserted into right atrium. (B)—Cannulas enter right ventricle (RV) because the combined tip is too bulky to pass down vena cava inferior. (C)—Outer cannula withdrawn, tip of blood return cannula curled up in RV. (D)—Blood return cannula advanced until tip is in pulmonary artery. Position of cannula tip is determined with pressure recording.

The first circuit was 5.5 L/min (water 22°C, input pressure 5 cm H₂O, outflow pressure 50 mm Hg). The maximum capacity of the second system was 10 L/min. If a catheter was inserted into the pulmonary artery for diagnostic purposes, the blood return cannula could be passed down using the catheter as a guide. No special cannulation technique was then necessary. After a mean dosage of 0.4 ml per kg body weight of starch suspension, RV failure occurred and the sheep died from systemic shock and arterial desaturation. At autopsy, no abnormalities were observed that could be related to the cannulas.

Pulmonary Artery Embolization (group 2): The two-cannula system was used for closed-chest RVB (Fig 2). Before embolization, mean RAP was below 6 mm Hg. RVB could be operated at flows of only 0.4-1.2 L/min (mean 0.8). During bypass RAP fell to a mean of 2 mm Hg, all other hemodynamic parameters remained unchanged.

After each starch embolization, PAP increased and AP decreased, but initially returned spontaneously to control values within five minutes. Later PAP remained at a slightly higher level after each consecutive embolization. RV failure occurred eight times after 22 to 64 ml (mean 0.9 ml per kilogram of body weight) of starch suspension were injected. Failure was characterized by a sudden decrease of PAP (2 to 40, mean 13.2 mm Hg) and AP (20 to 50, mean 30.5 mm Hg) and an increase of RAP (10 to 25, mean 19.1 mm Hg) (Table 1). RVB was started if recovery did not take place during the next five minutes. In all instances the failure could be reversed promptly with the bypass: PAP (1 to 22, mean 6.7 mm Hg) and AP increased (18 to 70, mean 43.1 mm Hg), RAP decreased (12 to 25, mean 19 mm Hg) (Fig 5). The mean RVB flow was 3.9 L/min (range 2.7 to 5.2). The bypass was discontinued after five minutes. The hemodynamic improvements remained stable thereafter at the first. RV failure in all sheep. Starch embolization was then continued until failure occurred again. It could be treated similarly in sheep 5 and 6. In sheep 4 failure was reversed during bypass but recurred after the bypass was discontinued. In sheep 5 and 6 a third RV failure period, produced with further embolization, could be treated effectively. Sheep 5 survived until 80 minutes thereafter when it died from recurring RV failure with shock and arterial desaturation.

At the time of the first RV failure, the oxygen saturation was low in sheep 4 and 6 (85 percent and 93 percent). At each next RV failure the oxygen saturation had decreased further in all sheep. After five minutes of RVB, the saturation had decreased further in five RV failure periods (5 to 12, mean 8 percent) and increased in three (2 to 5, mean 3 percent).

The end-inspiratory pressure at the time of the first RV failure had increased in all instances (6 to 16, mean 12 cm H₂O). A further rise was invariably observed at the next failure (4 to 9, mean 7 cm H₂O). After five minutes of RVB, the pressure had decreased in all cases (2 to 14, mean 8 cm H₂O). The esophageal temperature remained between 38.2 and 39.4°C. The hematocrit dropped during RVB (1 to 6, mean 4 percent). At autopsy, no gross abnormalities were found in the hearts; pulmonary edema was observed in sheep 6.

Ventricular Fibrillation (group 3): In the first three sheep (7, 8, 9) the double lumen cannula (Fig 1) was used for RVB and the chest remained closed. Before ventricular fibrillation was induced, mean LVB flow was 3.2 L/min, mean AP 72 and RAP 7 mm Hg (Table 2). RVB did not effect these values, flow ranged from 0 to 0.9 L/min. During fibrillation LVB flow and AP had decreased to a mean of 2.4 and 40, RAP had increased to 21 mm
Pressure tracings and ECG obtained from pilot experiment of group 1. Pulmonary arteries were embolized with 52 ml of 10 percent starch suspension in open-chest sheep. RA (right atrial), RV (right venricular), PA (pulmonary artery), AP (arterial) pressure in mm Hg. Paper speed 0.25 and 25 mm per second. Failure of right ventricle is indicated when RAP increases and PAP and AP decrease. At arrow, right ventricular bypass is started. RAP and RVP fall to atmospheric, PAP and AP increase. Condition remains stable after bypass is stopped (note sudden return to normal of RV pressure).

Hg. After RVB was started (mean flow 4.2) RAP decreased to 14 but AP and LVB flow did not change significantly.

In sheep 10, 11 and 12, the two cannula system (Fig 2) was used and the chest was opened. During ventricular fibrillation, similar changes occurred when RVB was started (Table 3). RVP changed significantly in sheep 12 only; it dropped from 10 mm Hg to atmospheric pressure. PAP increased from a mean of 13 to 20 mm Hg. The pulmonary arterial resistance increased 100 percent to 300 percent. LVP could be kept around atmospheric pressure. Mean RVB flow was 3.8 and LVB 2.4 L/min.

If the pulmonary artery was tied around the RVB blood return cannula, RVP dropped from a mean of 18 to 5 mm Hg, and RVB flow decreased from a mean of 4.4 to 2.9 L/min in sheep 10 and 11 (Table 3).

The mean hematocrit of all sheep in this group was 31 percent (28 to 33), mean pH was 7.58 (7.54 to 7.68) and oxygen saturation 93 percent (88 to 99). The mean end-inspiratory pressure was 26 cm H2O (22 to 34), the rectal temperature remained

<table>
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<tr>
<th>Stages</th>
<th>RAP</th>
<th>PAP</th>
<th>AP</th>
<th>Arterial O2 Saturation</th>
<th>End-inspiratory Pressure</th>
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<td>Control</td>
<td>1.4</td>
<td>19/10</td>
<td>90/76</td>
<td>93</td>
<td>26</td>
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<tr>
<td>Five minutes prior to RV failure</td>
<td>1.9</td>
<td>43/28</td>
<td>69/46</td>
<td>76</td>
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<td>30/20</td>
<td>31/23</td>
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<td>51</td>
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<td>RVB mean flow 3.9 L/min</td>
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<td>—</td>
<td>94/50</td>
<td>80</td>
<td>40</td>
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<tr>
<td>RV failure reversed (6 cases)</td>
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<td>39/25</td>
<td>83/54</td>
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<td>RV failure recurs (2 cases)</td>
<td>17.5</td>
<td>30/14</td>
<td>37/22</td>
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within 38.6 to 39.9°C. The induction of ventricular fibrillation and the start of RVB did not effect any of these values significantly. Defibrillation could be readily achieved after a mean of 36 minutes (24 to 57).

At autopsy, no gross abnormalities were found in heart and lungs.

**COMMENTS**

Cannulation for RVB without thoracotomy was mastered after experience was gained on the first three sheep. RVB was not complicated with arrhythmias or damage to the right side of the heart or pulmonary artery. The double lumen cannula had the advantage that only one vein needs to be dissected, but the capacity of the two cannula bypass was higher (10 L/min).

Pulmonary embolization is a convenient method for the production of acute right ventricular failure. Failure is characterized by a rise of RAP, a decrease of PAP and pulmonary flow and in later stages, by a decrease of AP. Once RV failure occurs, recovery is unlikely and the animals die shortly thereafter. The three untreated sheep of group 1 did not recover from RV failure. There is a correlation between PAP and arterial oxygen saturation: as more emboli are injected and as the pressure rises, the saturation declines. Initially, desaturation can be treated with 100 percent oxygen, but after some 30 minutes, anoxemia recurs.

The cardiopulmonary effects observed in the sheep of group 2 are in confirmation with these findings. RV failure could promptly and invariably be relieved with RVB; PAP and AP increased. In six out of eight failure periods studied, the right ventricle had recovered after only five minutes of bypass: PAP and AP were maintained near the preassist level and RAP remained low after the assist was stopped. Sheep 8 survived three successfully treated right ventricular failure periods for 80 minutes. The arterial oxygen saturation could not be increased with RVB. The end-inspiratory pressure decreased during bypass.

The effect of RVB on acute RV failure was

**Table 2**—Right atrial (RAP) and arterial pressure (AP) (mm Hg) and bypass flows (L/min), before ventricular fibrillation (Stage A) with left ventricular bypass (LVB) alone or in combination with right ventricular bypass (RVB), and during ventricular fibrillation without RVB in operation (Stage B), and with RVB in operation (Stage C) (group 3, first three sheep).

<table>
<thead>
<tr>
<th>Sheep</th>
<th>Stage</th>
<th>Mean RAP</th>
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<th>Flow RVB</th>
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<td>7</td>
<td>A</td>
<td>5-2</td>
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<td>50</td>
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<td>C</td>
<td>10</td>
<td>40</td>
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<tr>
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<td>A</td>
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<td>30</td>
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<td>C</td>
<td>16</td>
<td>30</td>
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<td>A</td>
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<tr>
<td></td>
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<td>22</td>
<td>40</td>
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<tr>
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<td>C</td>
<td>15</td>
<td>45</td>
<td>2.1</td>
<td>2.6</td>
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beneficial in all cases. Similar results were reported with the use of balloon counterpulsation in the pulmonary artery of sheep. Acute RV failure was produced in seven instances by embolization of the pulmonary arteries with a starch suspension of the same concentration. However, only 0.3 ml per kilogram of body weight of suspension was injected in these cases as compared to a mean of 0.9 ml in the present experiments. A second RV failure period in the same sheep could be treated in one case with balloon pumping, whereas with RVB three second and two third failure periods could be reversed. In comparison, RVB is a more powerful mechanical assist than balloon counterpulsation. The arterial oxygen saturation did not fall below normal in the incompetent. After the pulmonary artery was tied around the thoracic aorta, the pulmonary pressure difference between right and left atrium. This balloon would also facilitate positioning of the cannula. 

The occurrence of valve incompetence during ventricular fibrillation in the majority of the cases (five out of six sheep) has important implications for the technique of RVB: some means has to be provided to prevent backflow from the pulmonary artery. The easiest solution is to attach a balloon near the tip of the RVB blood return cannula, which, if inflated, would occlude the pulmonary artery. This balloon would also facilitate positioning of the cannula. The incidence of pulmonary artery resistance during RVB was an unexpected finding. In normal humans and dogs, no change occurs in pulmonary artery pressure during exercise when the cardiac output increases 200 percent to 300 percent. During ventricular fibrillation there is complete failure of the RV. The circulation can be maintained with LVB alone but the flow is 30 percent to 50 percent lower than with a beating right ventricle. The pulmonary flow is determined by the pressure difference between right and left atrium. In this preparation, effectiveness of RVB would be reflected in a return of LVB flow and RA pressure to prefibrillation levels. In the first three sheep of group 3, RVB could not substitute RV function, LVB flow did not increase, and RAP fell only slightly. In the next three sheep it became clear why: pulmonary artery resistance increased with RVB and the pulmonary and tricuspid valves were incompetent. After the pulmonary artery was tied around the RVB blood return cannula, RVB flow and RVP fell, especially in two sheep.

The most important finding of this study is the fact that otherwise deadly right heart failure by repeated pulmonary embolism can be reversed by a brief period of right ventricular bypass.

REFERENCES

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