Effects of Aortic Balloon Pumping during Cardiopulmonary Bypass on Myocardial Perfusion, Metabolism, and Contractility*


This study was undertaken to determine if the production of pulsatile flow by the intra-aortic balloon pump during cardiopulmonary bypass has any beneficial effect on coronary flow, regional myocardial flow, myocardial metabolism, and left ventricular function. Thirty-six conditioned dogs were subjected to one hour of total normothermic cardiopulmonary bypass. They were divided into the following five groups: (1) controls, beating heart and femoral inflow; (2) balloon, beating heart, and femoral inflow; (3) balloon, beating heart, and aortic inflow; (4) control, fibrillating heart and femoral inflow; and (5) balloon, fibrillating heart, and femoral inflow.

The use of pulsatile flow during cardiopulmonary bypass has been advocated by several authors, with variable findings. Trinkle et al.\(^1\) noted a lower systemic vascular resistance, a lower transfusion volume, a higher arterial pH, lower arterial lactate, and greater venous oxygen saturation with pulsatile flow, as compared to nonpulsatile flow. Jacobs et al.\(^2\) also noted a lesser increase in systemic vascular resistance, less volume requirement, lower serum lactate levels, a lesser decrease in creatinine clearance, and higher urinary output with pulsatile flow. Shepard and Kirkin\(^3\) found greater oxygen consumption, lower peripheral resistance, and less acidosis using pulsatile flow. Wakabayashi et al.\(^4\) evaluated the effects of pulsatile vs. nonpulsatile coronary perfusion in the fibrillating heart on cardiopulmonary bypass and found little difference in myocardial oxygen consumption and coronary vascular resistance; however, regional myocardial flow and myocardial metabolism were not evaluated.

In 1974, Pappas\(^5\) reported the use of the intra-aortic balloon pump to produce pulsatile flow during cardiopulmonary bypass. This technique was particularly attractive because of its simplicity, the lack of any adjustments in the routine setup for bypass, and the fact that the balloon could be left on at the end of bypass and thus assist the left ventricle. In a later report, Pappas et al.\(^6\) noted improved left ventricular ejection fractions and lower lactate levels in the coronary sinus of those patients in whom pulsatile flow had been employed.

The effects on the coronary blood flow and regional myocardial flow as a result of pulsatile cardiopulmonary bypass using this simple technique have not been investigated. In addition, the myocardial metabolic effects and left ventricular function have not been evaluated in an experimentally controlled setting. It was therefore elected to perform the following study in animals.

**Materials and Methods**

Thirty-six conditioned mongrel dogs weighing 15 to 30 kg (33 to 66 lb) were anesthetized with chloralose (100 mg/kg of body weight) and morphine sulfate (0.75 mg/kg) administered intravenously. Following intubation, the dogs were connected to a volume respirator (Harvard) with supplemental oxygen. The superior vena cava via the external jugular vein and the left carotid artery were cannulated and connected to strain gauges (Statham) and a recorder (Beckman RM 411) for monitoring of arterial and central venous pressures. A median sternotomy was performed, the azygos...
vein was ligated, and tapes were placed around the inferior and superior vena cavae and the pulmonary artery. A catheter was inserted into the left ventricular cavity through the apex, for recording left ventricular pressures and the maximum first differential of the left ventricular pressure (\(dp/dt\) max). Catheters were inserted into the left atrium for injection of microspheres and into the coronary sinus via the right atrium for sampling.

The animals were given heparin (3 mg/kg) intravenously, and the right femoral artery was cannulated for inflow from the cardiopulmonary bypass pump. The inferior vena cava was cannulated through the right femoral vein and the superior vena cava via an external jugular vein for flow to the pump (Fig 1). Total normothermic cardiopulmonary bypass was then instituted for one hour at 80 ml/kg/min using a modular roller pump (Sarns) and a pediatric bubble oxygenator (Bentley), which was primed with D5 PlasmaLyte (20 ml/kg) and the remainder with fresh, buffered heparinized blood. A cannula was inserted into the right ventricle for gravity drainage into the pump through a measuring container. The left ventricle was also cannulated and connected to gentle suction, with return to the pump. Total bypass was obtained by occluding both vena cavae at the atrial junction with the umbilical tapes, and the right side of the heart was then excluded by tightening the pulmonary arterial tape. Flow through the right ventricular catheter was then measured as coronary sinus flow.

Arterial, central venous, and left ventricular pressures; left ventricular \(dp/dt\); cardiac output (dye dilution); pH, oxygen pressure, carbon dioxide tension, and lactate levels of arterial blood and blood from the coronary sinus; myocardial levels of lactate and adenosine triphosphate (ATP); and total and regional myocardial blood flow were measured before bypass, at 10, 30, and 60 minutes on bypass, and for one hour after bypass. Specimens of left ventricular tissue for measurement of lactate and ATP were obtained by needle biopsy and were immediately frozen in liquid nitrogen (-183°C). Chemical analysis was performed using the method of Lowry and Passoneau.

Total and regional myocardial blood flow was measured by injecting 400,000 to 800,000 radioactive microspheres measuring 15\(\mu\) ± 5\(\mu\) in diameter (3M Co.), which were labeled with \(^{125}\)iodine, \(^{113}\)cesium, \(^{85}\)strontium, and \(^{45}\)scandium, into the left atrium for determination before and after bypass and into the pump inflow line during bypass. At the end of the experiment, the animals were killed, and the heart was excised and weighed. The left ventricle was divided into endocardial, middle, and epicardial layers, the septum into left and right layers, and the right ventricle into inner and outer layers. The tissue was placed in vials, weighed, and counted in a gamma scintillation counter (Packard). Twenty-second reference samples of arterial blood were drawn from a carotid artery at a constant rate for two minutes during each injection of microspheres and counted. The overlap of isotopes was subtracted by a computer, and the flow was calculated using the following formula: coronary blood flow (in ml/100 gm/min) = (reference flow/reference counts) \(\times\) (corrected tissue counts/tissue weight) \(\times\) 100. The sequential regional distribution of coronary flow at each interval of time was thus calculated, a different isotopic tag having been used for each injection.

Myocardial consumption of oxygen was calculated using

**Figure 1.** Method of bypass. Both cava are drained by gravity, with inflow via femoral artery. Tapes around both cava and pulmonary artery isolate right atrium and ventricle, enabling right ventricular drainage to be measured as coronary sinus flow. Note placement of intra-aortic balloon just distal to arch vessels. SVC, superior vena cava; and IVC, inferior vena cava.
myocardial flow as determined by the microspheres and the arterial-coronary sinus oxygen difference. The data were analyzed using Student's t-test.

The animals were divided into the following five groups: (1) group 1 (controls, beating heart and femoral inflow), eight dogs; (2) group 2 (balloon, beating heart, and femoral inflow), ten dogs; (3) group 3 (balloon, beating heart, and aortic inflow), six dogs; (4) group 4 (control, fibrillating heart and femoral inflow), six dogs; and (5) group 5 (balloon, fibrillating heart, and femoral inflow), six dogs. In groups 4 and 5, the ventricles were fibrillated with a brief period of alternating-current electrical stimulus and were then allowed to spontaneously fibrillate until after the 60-minute samples and readings were obtained. The ventricles were then defibrillated by direct current prior to discontinuing bypass. In groups 2, 3, and 5, intra-aortic balloons (12 ml) were inserted into the descending thoracic aorta just distal to the left brachial-cephalic artery (Fig 1) via the left femoral artery immediately after obtaining ten-minute samples and readings on bypass. The balloons were connected to an aortic balloon console (AVCO) and were triggered by the animals electrically in groups 2 and 3, so that inflation occurred during diastole. The balloon console was triggered by an outside stimulus at a rate of 90 in group 5. The pulsatile flow thus created by the aortic balloon pump was maintained for 50 minutes through the recording of the samples and pressures for 60 minutes on bypass.

Coronary sinus flows (drainage from right ventricular catheter) were measured at 10, 30, and 60 minutes of bypass and also after balloon pumping ceased (ie, pulsatile flow discontinued) and again after the balloon was removed.

**RESULTS**

**Total Coronary Flow**

Total coronary flow increased from 67 ± 9 ml/100 gm/min (± SE) prior to bypass to 72 ± 18 ml/100 gm/min while on bypass in the beating control group. There was no significant difference in the balloon-treated group with inflow via the femoral artery, the flows being 48 ± 8 and 74 ± 11 ml/100 gm/min at 10 and 30 minutes of bypass, respectively. There was a modest increase in flow at 30 minutes of bypass in the balloon-treated group with inflow via the aorta, the flow being 98 ± 19 ml/100 gm/min, as compared to 72 ± 10 ml/100 gm/min in the control group. Total coronary flow increased in the fibrillating control group from 82 ± 13 ml/100 gm/min before bypass to 131 ± 12 ml/100 gm/min after 30 minutes on bypass. There was little difference when the balloon was added, the flow being 107 ± 21 and 113 ± 7 ml/100 gm/min while on bypass.

**Left Ventricular Flow**

Left ventricular flow (Fig 2) decreased from a value before bypass of 70 ± 9 ml/100 gm/min to 69 ± 15 and 64 ± 10 ml/100 gm/min at 10 and 30 minutes of bypass, respectively, in the beating-heart control group. The values for flow were 38 and 76 ml/100 gm/min at 10 and 30 minutes of bypass, respectively, in the beating-heart control group. There was no significant difference in the data obtained in the beating groups (Fig 2) while on bypass; in group 2, values for group 2; and in group 4, values for group 4.

**Left Ventricular Endocardial-Epicardial Flow Ratio**

Values for the left ventricular endocardial-epicardial flow ratio (Fig 3) before bypass and at 10 and 30 minutes on bypass were, respectively, 1.16 ± 0.07, 1.22 ± 0.10, and 1.10 ± 0.06 for group 1; were 1.26 ± 0.04, 1.28 ± 0.08, and 1.19 ± 0.07 for group 2; and were 1.15 ± 0.10, 1.50 ± 0.22, and 1.51 ± 0.07 for group 3.
respectively, 1.05 on bypass for the fibrillating control group were, respectively, 1.05 ± 0.08, 1.24 ± 0.19, and 1.12 ± 0.10 and for the fibrillating balloon-treated group were 1.23 ± 0.14, 0.98 ± 0.17, and 0.93 ± 0.19 (not significantly different).

Coronary Sinus Flow

Coronary sinus flow (Fig 4) measured at 10, 30, and 60 minutes of bypass remained relatively constant at 90 ± 10 ml/100 gm/min in control group 1. There was little change in group 2, with flows of 74 ± 12 ml/100 gm/min at ten minutes, 86 ± 12 ml/100 gm/min at 30 minutes, and 93 ± 13 ml/100 gm/min at one hour on bypass; however, there was considerable increase in flow in group 3 (balloon, beating heart with aortic inflow), with flows of 83 ± 8 ml/100 gm/min at ten minutes, 123 ± 19 ml/100 gm/min (P < 0.13) at 30 minutes, and 125 ± 27 ml/100 gm/min (P < 0.14) at 60 minutes on bypass. Coronary sinus flow in both of the fibrillating groups was higher, but there was no significant difference between them. Flows before bypass and at 10 and 30 minutes on bypass were 131 ± 16, 129 ± 16, and 142 ± 17 ml/100 gm/min, respectively, in group 4 and were 136 ± 16, 108 ± 11, and 110 ± 17 ml/100 gm/min, respectively, in group 5. It is interesting that when the balloon was turned off in groups 2, 3, and 5, there was no decrease in flow. In group 3, when the balloon was turned off, the coronary sinus flow was 133 ± 32 ml/100 gm/min. It decreased to 107 ± 21 ml/100 gm/min when the balloon was removed, indicating that the collapsed balloon caused resistance to flow in the descending aorta.

Oxygen Consumption

Oxygen consumption decreased somewhat in the beating-heart groups, without any significant difference occurring between groups. Prior to bypass, the oxygen consumption in group 1 was 6.0 ± 1.1 ml/100 gm/min. This decreased to 4.7 ± 1.0 ml/100 gm/min at ten minutes and 4.4 ± 1.1 ml/100 gm/min at 30 minutes and rose to 11.2 ± 3.7 ml/100 gm/min at one hour after bypass. Corresponding values in group 2 were 7.6 ± 1.8, 3.0 ± 0.5, 4.5 ± 0.5, and 8.8 ± 1.4 ml/100 gm/min and in group 3 were 6.6 ± 1.4, 2.2 ± 0.8, 3.3 ± 1.1, and 6.3 ± 1.7 ml/100 gm/min. Oxygen consumption was higher in the fibrillating hearts, being 6.6 ± 1.7 and 13.0 ± 5.0 ml/100 gm/min at 10 and 30 minutes of bypass in group 4 and 5.9 ± 3.7 and 7.4 ± 1.8 ml/100 gm/min in group 5.

Lactate Levels in Coronary Sinus

The lactate level in the coronary sinus in group 1 was 2.50μmol/ml ± 0.29μmol/ml. It increased to a high of 4.89μmol/ml ± 0.68μmol/ml on bypass. In group 2, the level before bypass was 1.81μmol/ml ± 0.34μmol/ml, and the highest value during bypass was 5.28μmol/ml ± 0.74μmol/ml. In group 3, the lactate level in the coronary sinus rose from 1.98μ-
mol/ml ± 0.45μmol/ml to 7.48μmol/ml ± 2.01μmol/ml on bypass, in group 4 from 2.23μmol/ml ± 0.47μmol/ml to 8.24μmol/ml ± 1.08μmol/ml, and in group 5 from 2.77μmol/ml ± 0.89μmol/ml to 8.65μmol/ml ± 1.00μmol/ml. There were no statistically significant differences between the balloon-treated groups and their respective controls.

Myocardial Lactate Level

In group 1, the myocardial lactate level rose from a level of 4.60μmol/gm ± 0.82μmol/gm before bypass to 5.70μmol/gm ± 0.46μmol/gm on bypass and 8.80μmol/gm ± 0.75μmol/gm one hour after bypass. Corresponding values were 5.30μmol/gm ± 0.34μmol/gm, 6.80μmol/gm ± 0.33μmol/gm, and 6.48μmol/gm ± 0.14μmol/gm in group 2 and were 3.98μmol/gm ± 0.47μmol/gm, 7.91μmol/gm ± 0.80μmol/gm, and 5.86μmol/gm ± 0.87μmol/gm in group 3. In the fibrillating control group, the lactate level before bypass was 4.00μmol/gm ± 1.00μmol/gm, with a high of 7.55μmol/gm ± 0.05μmol/gm on bypass, and was 6.44μmol/gm ± 1.69μmol/gm one hour afterwards. In group 5, corresponding values were 4.55μmol/gm ± 1.04μmol/gm, 8.73μmol/gm ± 0.35μmol/gm, and 6.79μmol/gm ± 0.67μmol/gm. No statistically significant difference occurred between balloon-treated groups and their respective controls.

Myocardial ATP Level

The myocardial ATP level was 5.83μmol/gm ± 0.02μmol/gm prior to bypass in group 1; it decreased to 4.82μmol/gm ± 0.31μmol/gm after one hour of bypass and was 4.70μmol/gm ± 0.50μmol/gm one hour after completion of bypass. Corresponding values were 6.83μmol/gm ± 0.31μmol/gm, 6.02μmol/gm ± 0.28μmol/gm, and 4.88μmol/gm ± 0.28μmol/gm in group 2 and were 6.39μmol/gm ± 0.26μmol/gm, 5.85μmol/gm ± 1.73μmol/gm, and 5.03μmol/gm ± 0.38μmol/gm in group 3. The level of ATP before bypass in group 4 was 6.43μmol/gm ± 0.79μmol/gm, decreasing to 5.73μmol/gm ± 0.40μmol/gm at one hour of bypass and to 5.30μmol/gm ± 0.50μmol/gm one hour after completion of bypass. Corresponding values in group 5 were 6.08μmol/gm ± 0.31μmol/gm, 5.63μmol/gm ± 0.70μmol/gm, and 3.98μmol/gm ± 0.69μmol/gm. All groups therefore showed slight depletion of stores of ATP during the experiment, with no significant differences between groups.

Mean Arterial Blood Pressure

Mean pressure prior to bypass in group 1 was 118 ± 11 mm Hg. It ranged from 81 ± 5 to 88 ± 8 mm Hg during bypass and from 104 ± 7 to 105 ± 8 mm Hg afterwards. The values in group 2 were 148 ± 3 mm Hg prior to bypass, 82 ± 8 to 95 ± 9 mm Hg during bypass, and 112 ± 8 to 117 ± 9 mm Hg afterwards. The mean pressures in group 3 were 110 ± 10 mm Hg before, 74 ± 10 to 119 ± 6 mm Hg during, and 83 ± 5 to 94 ± 8 mm Hg after bypass. The arterial pressure, as measured in the carotid artery, therefore increased during bypass in the balloon-treated group with inflow via the aorta, whereas there was no difference between the control and balloon-treated groups with femoral arterial perfusion. In group 4, arterial pressure prior to bypass was 120 ± 11 mm Hg; it ranged from 52 ± 4 to 57 ± 6

![Figure 5. Arterial pressure tracing of balloon-treated beating-heart animal. Note pulsatile pressure of 100/60 mm Hg produced by intra-aortic balloon.](http://journal.publications.chestnet.org/pdfaccess.ashx?url=/data/journals/chest/21016/ on 06/26/2017)
mm Hg during bypass and from 84 ± 5 to 91 ± 13 mm Hg after bypass. The values in group 5 were 118 ± 10 mm Hg before, 68 ± 15 to 86 ± 20 mm Hg during, and 79 ± 5 to 81 ± 5 mm Hg after bypass.

**Systolic and Diastolic Arterial Pressures in Pulsatile Groups**

The systolic and diastolic pressures (Fig 5) during balloon pumping at 10, 30, and 60 minutes of bypass, respectively, were 102 ± 9/81 ± 9, 101 ± 10/78 ± 7, and 109 ± 8/81 ± 7 mm Hg in group 2, were 94 ± 14/74 ± 9, 128 ± 7/99 ± 8, and 133 ± 6/107 ± 6 mm Hg in group 3, and were 92 ± 12/64 ± 10, 90 ± 11/60 ± 11, and 90 ± 14/63 ± 13 mm Hg in group 5.

**Cardiac Output**

The cardiac output in group 1 was 130 ± 16 ml/kg/min prior to bypass and was 98 ± 13 ml/kg/min at one hour after bypass. Corresponding values in group 2 were 125 ± 8 and 92 ± 5 ml/kg/min, in group 3 were 110 ± 23 and 70 ± 5 ml/kg/min, in group 4 were 130 ± 25 and 70 ± 10 ml/kg/min, and in group 5 were 110 ± 16 and 67 ± 14 ml/kg/min. There was no significant difference in cardiac output between the groups following bypass.

**Left Ventricular dp/dt**

Left ventricular dp/dt in group 1 was 1,880 ± 196 mm Hg/sec prior to bypass and was 1,600 ± 181 and 1,800 ± 264 mm Hg/sec at 30 and 60 minutes after completion of bypass. In group 2, the dp/dt was 1,748 ± 214 mm Hg/sec prior to bypass and was 1,389 ± 145 and 1,431 ± 194 mm Hg/sec afterwards (30 and 60 minutes after). In group 3, left ventricular dp/dt was 1,835 ± 419 mm Hg/sec prior to bypass and was 1,632 ± 275 and 1,456 ± 191 mm Hg/sec at 30 and 60 minutes after bypass. Corresponding values in group 4 were 1,988 ± 106, 1,411 ± 120, and 1,120 ± 156 mm Hg/sec and in group 5 were 2,110 ± 206, 1,388 ± 62, and 1,538 ± 144 mm Hg/sec. All groups therefore demonstrated a moderate decrease in left ventricular dp/dt following bypass, but there were no significant differences between groups.

**Coronary Vascular Resistance**

Resistance in the beating-heart groups remained relatively constant from before bypass through bypass, with values in group 1 being 1.28 ± 0.19 mm Hg/ml/100 gm/min prior to bypass, 1.29 ± 0.26 and 1.32 ± 0.30 mm Hg/ml/100 gm/min during bypass, and 0.93 ± 0.33 mm Hg/ml/100 gm/min at one hour after bypass. In group 2, the corresponding values were 1.88 ± 0.46, 2.15 ± 0.37, 1.39 ± 0.22, and 0.77 ± 0.24 mm Hg/ml/100 gm/min and in group 3 were 1.79 ± 0.41, 1.06 ± 0.23, 1.24 ± 0.29, and 0.68 ± 0.21 mm Hg/ml/100 gm/min. The fibrillating groups revealed a decrease in resistance during and after bypass, with the corresponding values for resistance in group 4 being 1.38 ± 0.33, 0.61 ± 0.15, 0.42 ± 0.7, and 0.53 ± 0.04 mm Hg/ml/100 gm/min. In group 5, the corresponding values were 1.54 ± 0.31, 0.36 ± 0.11, 0.47 ± 0.13, and 0.29 ± 0.05 mm Hg/ml/100 gm/min (P < 0.005), thus revealing a significant coronary vasodilatation after bypass in group 5.

**DISCUSSION**

The need for pulsatile flow during cardiopulmonary bypass has been controversial because of inconsistent data concerning its benefits and because of the complicated nature of most pulsatile flow systems. Trinkle and his colleagues investigated a diaphragmatic type of pulsatile pump, with cardiac valves controlling inflow and outflow. Both clinically and experimentally, these investigators found a lower peripheral vascular resistance, lower required transfusion volume, a higher pH, lower blood lactate level, and high venous oxygen saturation with pulsatile flow. Jacobs et al. described a pulsatile system employing a roller pump which was driven by the amplified output of a triangular wave-form generator. These workers found that the peripheral vascular resistance was less in their pulsatile group, less volume replacement was needed, and serum lactate levels were lower. A larger urinary output and greater creatinine clearance were noted in the animals receiving pulsatile flow. The importance of the character of the pulse wave form was emphasized, particularly the sharp upstroke.

Using a roller pump modified to produce pulsatile flow by stopping and starting, Shepard and Kirklin found increased oxygen consumption, a lower peripheral resistance, and a higher pH in their pulsatile group, as compared to the nonpulsatile animals; however, these investigators found no difference in excess lactate and catecholamine levels and noted a greater incidence of pulmonary dysfunction after bypass in the pulsatile group. Wakabayashi and colleagues investigated the effect of pulsatile coronary perfusion on coronary resistance and myocardial oxygen consumption. They found that there was no significant difference in myocardial oxygen consumption or coronary vascular resistance, although the oxygen consumption was slightly higher in the nonpulsatile group.

In 1974, Pappas published the technique of using the intra-aortic balloon during cardiopulmonary by-
pass to produce pulsatile flow. This method was particularly attractive because it was simple and did not involve changing the usual techniques of cardiopulmonary bypass. In 1975, Pappas and his colleagues reported the findings from 56 patients in whom this technique was utilized. These investigators noted that there was less derangement of myocardial metabolism in the pulsatile group, as evidenced by a lower level in the coronary sinus, less extraction of lactate, and less production of excess lactate. In addition, the left ventricular ejection fraction increased after surgery in the balloon-treated group, whereas it decreased in the control group.

In our study, an increase in coronary flow was seen only in group 3 (the animals with bypass inflow via the ascending aorta who received balloon pumping) and in both fibrillating groups. The total coronary flow in group 3 was 98 ml/100 gm/min, compared to a control value of 72 ml/100 gm/min at 30 minutes of bypass. The respective left ventricular flows were 95 and 64 ml/100 gm/min (P < 0.14). The left ventricular endocardial-to-epicardial flow ratio was also significantly elevated at 30 minutes in group 3, as compared to group 1 (1.51 to 1.08; P < 0.0009), although the ratio was also elevated in group 3 at ten minutes of bypass, prior to pulsatile flow. Coronary sinus flow also was higher in group 3 at 30 and 60 minutes, as compared to group 1. These improvements in flow were not seen in the balloon-treated dogs who received pump inflow via the femoral artery, nor were the improvements noted in the fibrillating balloon-treated group. Of concern is the fact that there was no decrease in coronary sinus flow in any of the balloon-treated groups when the balloon was turned off, thus causing one to wonder if the increased flow observed in group 3 was due to pulsatile flow or increased resistance in the descending aorta secondary to the presence of the balloon. Coronary sinus flow did decrease 25 ml/100 gm/min when the empty balloon was removed from the group with aortic flow, indicating that part of the increase in flow in this group may have been due to increased resistance from the balloon. The blood pressure, as measured in the carotid artery, was also somewhat higher in this group, again possibly due to resistance in the aorta. It was elected to perform the experiments at a constant flow rate, rather than at a constant blood pressure, since this is the usual method employed clinically and also because we wanted to observe the effects of the balloon on blood pressure and vascular resistance under these circumstances; however, this does add an additional variable which, if maintained constant, might have altered the coronary flows somewhat (ie, decreased the coronary flow in group 3). No other significant differences between balloon-treated groups and their respective control groups were noted in the data on flow.

Myocardial consumption of oxygen, the pH and lactate level of blood from the coronary sinus, the myocardial lactate level, and the myocardial ATP level were similar in balloon-treated and control groups. Cardiac output one hour after bypass was very similar in all five groups. Left ventricular dp/dt decreased somewhat in both balloon-treated beating groups, as compared to the control beating group, which showed no deterioration one hour after bypass. Both fibrillating groups showed a moderate decrease in left ventricular dp/dt one hour after bypass; however, none of these differences was significant.

The general lack of improvement in metabolism and left ventricular contractility in the balloon-treated pulsatile groups, as compared to nonpulsatile, is contradictory to the findings of Pappas et al; however, it must be emphasized that our experiments were performed in dogs with normal hearts, whereas the work of Pappas et al was largely done on patients with occlusive coronary arterial disease, many of whom were considered at high risk. Watson et al, Powell et al, Goldfarb et al, and Gill et al found little improvement in flow, metabolism, or contractility in nonischemic normotensive situations with balloon pumping. Previous reports concerning pulsatile cardiopulmonary bypass using other techniques have demonstrated conflicting data and opinions; for example, Wakabayashi et al reported a higher myocardial oxygen consumption and a lower coronary vascular resistance in their nonpulsatile groups, although these were not of statistical significance.

Other factors which could have affected the results are related to the method of production of the pulsatile flow. Arterial pressures were 101-102/70-81 mm Hg in group 2, 116-140/87-110 mm Hg in group 3, and 98-102/66-70 mm Hg in group 5. These would seem to be adequate pulse pressures; however, the contour was not quite the same as the normal wave form and may have had a slower upstroke. Also of concern is whether the balloon partially obstructed aortic flow, which may have occurred in group 3, although the 12-ml balloon appeared to be an appropriate size, as judged by palpation of the descending aorta around it. This did not appear to be a factor in groups 2 and 5, since arterial pressure and microsphere reference samples reflected a normal pressure and flow, and these were obtained from a carotid artery in animals perfused through the femoral artery. It would appear from our data that if the balloon is used during cardiopulmonary bypass,
it should be used with aortic inflow from the pump, rather than femoral inflow.

In summary, aortic balloon pumping during cardiopulmonary bypass in the normal canine heart increased coronary flow and the endocardial-to-epicardial flow ratio when the pump was via the aorta, with the endocardial flow being increased very significantly. Of concern is that part of this improved myocardial flow may be due to passive resistance of flow in the descending aorta, rather than the pulsatile flow created. No differences in myocardial flow were seen in balloon-treated groups with beating or fibrillating hearts when inflow was via the femoral artery. No improvement in myocardial metabolism or left ventricular contractility was noted in the groups with pulsatile flow; however, it must be emphasized that these experiments were performed in normal hearts and that there may be benefit from this technique when employed in patients with coronary obstructive disease.

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REFERENCES