The Influence of Cardio-Pulmonary Bypass with Cardiac Arrest and Right Ventriculotomy on Myocardial Contractile Force *

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THE INCREASED USE of cardiac-pulmonary bypass with cardioplegia and ventriculotomy has developed a need for evaluating the influence of these procedures on cardiac function. Despite the diminution in the stroke work and volume, during bypass, an apparent vigorous contraction of the heart continues. The force of contraction of the myocardium is a fundamental factor in the production of stroke work. As Cotten et al. have pointed out, there are several instances when changes in stroke work are not accompanied by changes in the force of contraction of the heart muscle.[4] One of these occurs with occlusion of the venae cavae. Under this condition of reduced venous return, the stroke work is markedly diminished by the reduction in stroke volume. For the above reasons, it was decided to measure in the dog, the force of contraction of the myocardium during cardio-pulmonary bypass with potassium induced arrest and right ventriculotomy. In addition, direct measurements of contractility were obtained in patients undergoing operation for correction of congenital cardiac abnormalities.

Methods

Mongrel dogs weighing between 12 and 16 kilograms were used in these studies.

Intravenous pentothal was used for anesthesia. There was no other pre-medication. Digitalis was not used. The basic principles for cardio-pulmonary bypass as reported by DeWall et al. were generally followed.[6] The procedures were carried out through a right thoracotomy in the fourth intercostal space. The venous cannulae were introduced into the superior and inferior venae cavae through incisions in the right atrial appendage. The arterial cannula was placed in the right carotid artery. A DeWall type bubble oxygenator (Brunswick Model) and Sigmamotor pump apparatus were used. Polyethylene catheters were placed in the femoral artery for direct measurement of arterial blood pressure by Statham pressure transducers.

Right ventricular contractile force was measured with a Walton-Brodie strain gauge arch.[1] The two feet of the arch were attached to the myocardium by sutures. The strip of muscle between the two sutures was stretched by approximately 35 per cent of its initial diastolic length. Therefore, the initial length and tension of the strip of muscle under measurement were fixed. The arch represented one arm of a Wheatstone bridge in a Sanborn carrier wave preamplifier. The amplitude of the recording was proportional to the force applied by the myocardium between the two feet of the arch. A detailed description of the arch and the factors affecting these recordings have been published.[2-4]

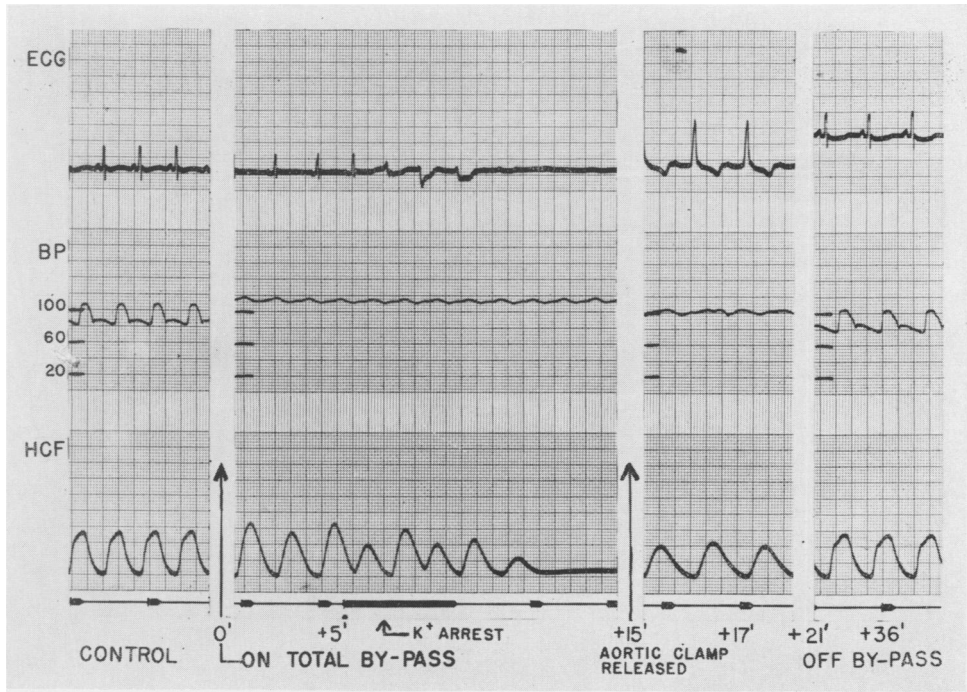During the procedures, ventricular con-

FIGURE 1.

tractile force, arterial pressure, electro-cardiograms, and in some cases right intra-ventricular pressure and in other cases venous pressure were recorded simultaneously on a four channel Sanborn Polyviso recorder (Model 150). Following the completion of these procedures, the strain gauge arch was left attached to the heart in four dogs. The lead wires were brought out of the chest and the incision closed. This permitted recordings of contractility from the conscious animals on a series of post-operative days.

Ventricular contractile force, arterial pressure, electrocardiograms, and in three cases venous pressure were recorded in ten patients undergoing by-pass operations for the correction of various congenital abnormalities. Nine of the ten patients had Digitalis pre-operatively. The procedures were generally the same as those outlined for the dog except the incision used was an anterior bilateral transverse thoracotomy and the arterial cannula was placed in the distal abdominal aorta through a femoral arteriotomy. Arterial blood pressure was recorded from the brachial artery.

Results

The changes obtained in a dog subjected to cardio-pulmonary by-pass with cardiac arrest and right ventriculotomy are illustrated in Figure 1, and are representative of those obtained in 14 dogs. The control segment was obtained from a five minute stable period before starting the by-pass. The electrocardiogram was considered normal in each case at this time. The arterial pressure was 110/80 in this animal. However, in the group the systolic pressure ranged between 100 and 140 mm. of Hg and the diastolic pressure ranged between 65 and 95 mm. of Hg. The contractile force recording was 13 mm. in amplitude representing a force of approximately 35 grams. The control contractile force averaged 40 grams. At zero minutes, the extra-corporeal perfusion was started and the vena caval
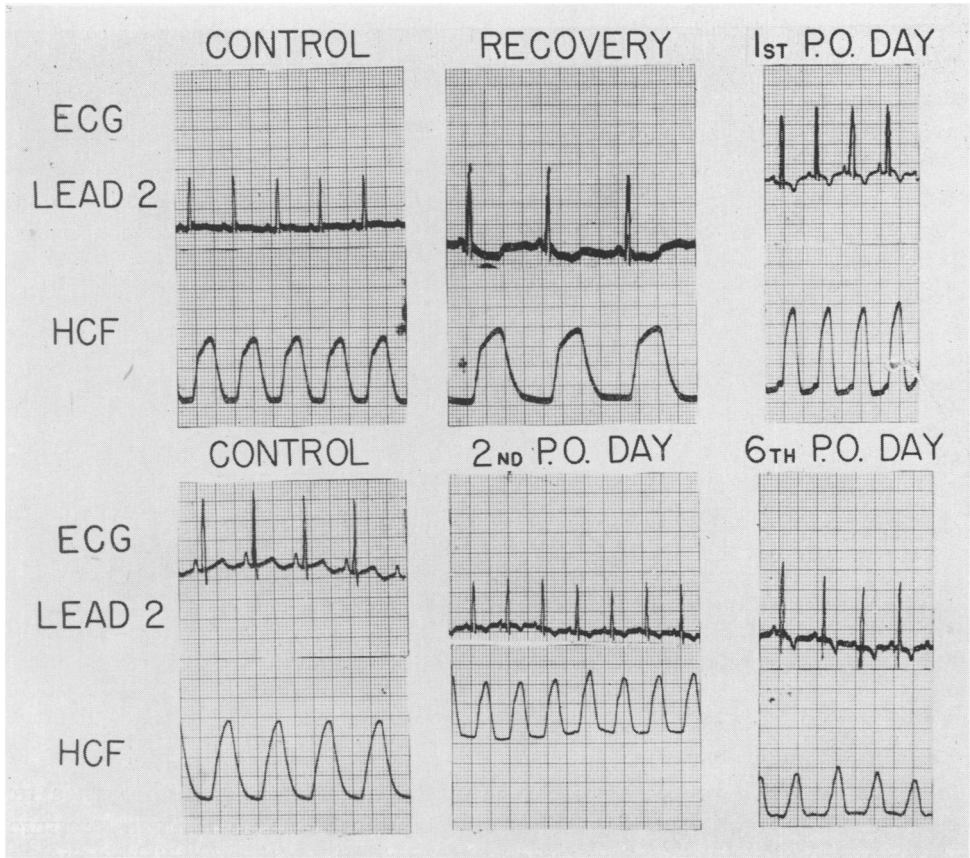
FIGURE 2.

inflow occluded. The perfusion flow rate used in this case was 35 cc./Kg./min. as it was in nine of these experiments. In two experiments a flow rate of 40 cc./Kg./min. was used and in three experiments 50 cc./Kg./min. was used. In a previous series of experiments, flow rates above 30 cc./Kg./min. were found to be necessary to maintain cardiac contractility at control levels during 20 minutes of bypass.[7] After five minutes of perfusion at the 35 cc./Kg./min. flow rate, there was no change in the electrocardiogram or the ventricular contractile force in this illustration. The average change in contractile force which occurred during this five minute interval was − 7.2 per cent (S.E. ± 5.53). The arterial pressure was a function of the perfusion and showed no change with each systole.

The arterial pressure averaged 80 mm. of Hg with a range between 55 mm. of Hg and 110 mm. of Hg in these experiments. The ascending aorta was clamped. Cardiac arrest was induced by an injection of 10 to 12 cc. of a 2.5 per cent solution of potassium citrate. After ten minutes of cardioplegia (plus 15 minutes in Fig. 1), the aortic clamp was released. At plus 17 minutes, the force of contraction returned to approximately 70 per cent of the control amplitude. The electrocardiogram showed an AV nodal rhythm. After release of the aortic clamp, the time for the resumption of a heart beat varied from one to four minutes. Usually within five minutes the contractile force had returned to within 75 per cent of control, and the heart rate was near 70 beats per minute. The superior

and inferior caval occluding tapes were released and the extra-corporeal perfusion was stopped at plus 21 minutes. The time of removal of the occluding tapes varied depending on the contractile force recordings. When the force had returned to 80 per cent of control the tapes were removed. The total by-pass time varied between 18 and 24 minutes in the group. At 36 minutes, the electrocardiogram returned to normal in this case; however, in some cases partial AV block and ST segment changes were observed. The arterial pressure was 105/56. The contractile force returned to the pre-bypass control level. The average contractile force after bypass was 4.0 per cent (S.E. ± 6.08) above the control recording.

The typical recordings obtained from two dogs post-operatively are illustrated in Figure 2. The inversion of the T wave was the most conspicuous change in the electrocardiogram. The partial AV block and ST segment changes often noted immediately post-operatively were generally absent on the first postoperative day. The T wave inversion is nonspecific in lead 2 of the dog and may be largely due to positional changes. The contour of the contractile force curve showed little change in the series of recordings obtained through the sixth postoperative day. There was generally some reduction in the amplitude of the recordings. However, it was felt that this was largely due to loosening of the sutures caused in part by pressure necrosis. This reduction in force is a usual finding in dogs prepared for these measurements in other experiments not utilizing cardiac bypass, and that have not been subjected to cardiac arrest or ventriculotomy.

In the dog under conditions of cardio-pulmonary bypass, hypervolemia elicited a fall in myocardial contractility. In three animals, rapid over-transfusion of as little as 100 cc. of blood was accompanied by a decrease in contractility of near 20 per cent. This change in contractile force was not related to changes in intracardiac volume since the venous return was occluded. Withdrawal of the 100 cc. of blood resulted in an immediate increase in contractile force to approximately control levels.

The results obtained in four dogs in which irreversible ventricular fibrillation occurred are not included in average changes in contractile force. It is interesting that in three of these cases the contractile force returned to near control levels immediately after release of the aortic clamp, but the heart rate slowed and the amplitude of contraction decreased after approximately 30 to 45 seconds of strong beats. This reduced rate was generally accompanied by an electrocardiographic pattern of AV nodal block. Further studies of these changes are being carried out.

The changes in arterial pressure and myocardial contractility obtained in a patient at the time of operation for correction of intraventricular septal defect and infundibular stenosis are shown in Figure 3. The arterial pressure for all ten cases pre-bypass was in the range of 120/70 mm. of Hg as shown in this case. The contractile force was generally in the range of 40 grams as represented by the 15 mm. amplitude of the recording in this illustration. The perfusion flow rates ranged from 35 cc./Kg./min. to 80 cc./Kg./min. In this case the perfusion rate was initially 35 cc./Kg./min. but the flow rate was increased to 50 cc./Kg./min. as dictated by the fall in contractility at the lower flow rate. The average change in contractile force which occurred initially was − 19.9 per cent (S.E. ± 8.6). It is interesting that the increase in flow rate produced no change in the recorded arterial blood pressure. This was not a consistent finding, but no linear relationship could be found between perfusion rate and arterial pressure. The total time of cardioplegia varied from 12 to 21 minutes. The total time of bypass ranged from 19 to 41 minutes. Usually within two minutes after release of the aortic clamp regular contractions were recorded. However, these
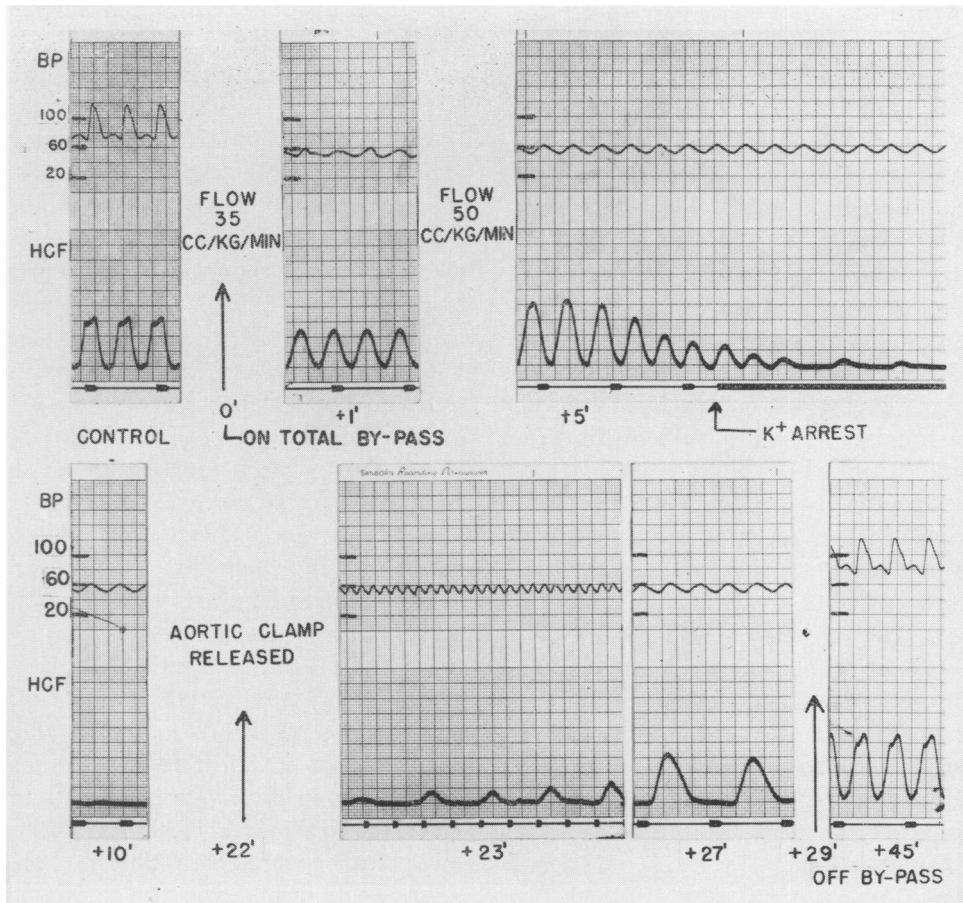
FIGURE 3.

initial beats were weak and the curves were dome shaped with a prolonged relaxation phase. This type of curve was believed to represent acute failure probably related to a metabolic or chemical imbalance of the myocardium. With adequate coronary perfusion this change lasted for only a few minutes. Within ten minutes the contractile force had generally returned to near control levels. Immediately after bypass the average result in eight cases showed a − 9.8 per cent (S.E. ± 10.95) change in contractile force from the pre-bypass control.

Ventricular fibrillation was encountered in four cases. In three of these cases the fibrillation was reversed chemically. The contractile force returned to near normal levels in two of these cases. In one case, the arch was dislocated. In the fourth case, attempts to reverse the fibrillation were unsuccessful.

In one patient at the onset of bypass a marked increase in contractile force occurred followed by an alternation in the amplitude of contraction. Following completion of the procedure this patient had an increase of 38 per cent above control contractile force. This change was possibly related to a sympatho-adrenal discharge.

Discussion

Wiggers has predicted that a total assessment of the factors regulating myocardial contractility is not likely to succeed from

analysis of hemodynamic data alone since multiple factors may separately influence intrinsic myocardial contractility.[13] The classical measurements of stroke work, stroke volume and cardiac output are of little assistance in the evaluation of cardiac function during the artificial conditions imposed by cardio-pulmonary bypass. Recognizably there is some reduction in total cardiac force, in accordance with Starling's law, produced by the reduction in initial tension which accompanies vena caval occlusion. With a fixed initial tension and length imposed by the strain gauge arch, and under the conditions of these experiments, the measured changes in contractility of the myocardium of the dog were minimal. These findings and those of other experiments tend to emphasize the importance of metabolic, neurogenic and humoral factors in the regulation of intrinsic myocardial contractility.[2, 5, 7, 14] With adequate total body perfusion (35 to 50 cc./Kg./min.) there is little impairment of cardiac function following recovery from cardioplegia and ventriculotomy. The minimal changes in myocardial contractility elicited by these procedures would indicate the heart is still capable of doing the same amount of work following completion of the operation.

These findings are in essential agreement with those of Stirling, Stanley and Lillehei who showed no significant deterioration in the ventricular function curves after total body perfusion at varying flow rates from 35 to 90 cc./Kg./min.[10] Read, Johnson and Kuida have reported that the percentage of total body perfusion which passes through the coronary arteries increases as the flow rate decreases.[9] The interpretation drawn from their data was that 35 to 50 cc./Kg./min. perfusion rates should be adequate to maintain sufficient coronary flow. The results also agree with the findings of Welch et al. who reported that myocardial oxygen consumption was more closely related to the total tension developed by the myocardium than to the cardiac work or output.[12]

In the patients with abnormal hemodynamics prior to operation, the results were variable. A reduction in contractility was observed during the short interval of bypass prior to arrest, and there was a reduction of as much as 40 per cent following the correction of the defect. In most instances there occurred a visible reduction in cardiac size in these patients. This reduction in heart size and the concomitant shortening in fiber length would increase the efficiency of contraction of the myocardium. This increase in efficiency of the fibers not under measurement could have a resultant effect on the recordings of contractile force. Cotten has shown that with marked changes in heart size, some change in measured myocardial contractility, by the strain gauge arch method, could be expected to occur.[2-4] This influence of the surrounding muscle fibers on the measurements of the force of contraction are usually not greater than 25 per cent of the control recording.

Another possible explanation of the variation in the human recordings may be related to metabolic changes that can occur with cardiac bypass. Metabolic acidosis is a common finding with low total body perfusion rates. Preliminary studies with lactic acid show that this agent decreases myocardial contractility. The results of McClure have shown that decreasing hepatic circulation could result in a reduction of pH of 0.018 with each complete circuit of the circulating blood.[8] Weil et al. have shown a reduction in the responsiveness of the vascular bed to arterenol during periods of reduced pH.[11] Unreported studies from this laboratory have also shown that lactic acid reduces the responsiveness of myocardial contractility to arterenol. This reduction in the responsiveness of the myocardium to the sympathetic hormone could account for some of the reduction in contractile force observed following bypass.

The fairly high incidence of ventricular fibrillation observed in this study is believed to be largely due to the potassium arrest. In a previous study with low flow rates and during periods of "azygos vein flow" relatively few incidences of ventricular fibrillation occurred.[7] The metabolic derangement caused by the potassium injection was believed to be largely responsible for the observation of transient apparent acute failure in the immediate post-arrest period. Further studies are being carried out to evaluate the influence of these metabolic derangements on myocardial conduction and contractility.

Summary

The influence of cardiac bypass with potassium induced arrest and right ventriculotomy was studied in 14 dogs and ten patients. Direct measurements of myocardial contractility in these studies indicate that the heart is still capable of doing the same amount of work following recovery from cardioplegia and ventriculotomy. Evidence is presented which emphasizes the importance of metabolic, neurogenic, and humoral factors in the regulation of myocardial contractility.

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