Cardiovascular Adaptation to Partial Heart-Lung Bypass

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Previous experiments indicated that during partial heart-lung bypass (also called partial perfusion), the cardiac output decreased as the extracorporeal flow increased. In those experiments, the arterial tree was perfused from the heart-lung machine, using gravity instead of a pump. With greater amounts of blood passing through the extracorporeal circuit, there seemed to be an increase of the blood content stored in the heart-lung machine. It was suspected that an increase in extracorporeal flow might be accompanied by a shift of some of the blood volume of the organism into the extracorporeal circuit. In other experiments, prolonged diminution of cardiac filling, by partial heart-lung bypass, did not decrease substantially the energy expenditure of the heart, as long as the aortic pressure and the body blood content were kept constant. Therefore, the thought arose that some of the benefit expected from partial heart-lung bypass might result from a decreased body blood volume. This hypothesis was quantitatively investigated under strictly controlled conditions, in which the relationships between the cardiac output, the extracorporeal blood flow, and the blood volume contained in the extracorporeal circuit could be examined.

Methods

Ten open-chest dogs, ranging from 20 to 30 Kg. in weight, anesthetized with 25 mg./Kg. of pentobarbital and heparinized with 3 mg./Kg., were used. The experiments were designed in such a manner that cardiac output and blood volume changes could be recorded directly in conjunction with phasic changes in blood pressure (fig. 1).

The cardiac output was directly recorded with a Shipley-Wilson rotameter(R), inserted into the thoracic aorta during a temporary aortic bypass. All the thoracic branches of the aorta, distal to the coronary arteries, were tied. Under these conditions, all blood ejected by the left ventricle, except the coronary flow, had to pass through the rotameter before being distributed to the periphery. The brain was perfused from the descending tube of the rotameter through a carotid artery. This arrangement provided a fairly constant head of pressure, since brain perfusion was secured by the extracorporeal flow from a constant level reservoir, regardless of the left ventricular output. At high extracorporeal flow, when cardiac output decreased to such an extent that the pressure in the aortic arch dropped below the pressure in the abdominal aorta, the rotameter became locked, and no cardiac output was recorded. In such instances, all blood ejected by the left ventricle passed through the coronary arteries.

The extracorporeal circuit is shown on the right part of figure 1. Central venous and right atrial blood was drained through a polyethylene catheter (French 20 to 26), inserted via a femoral vein. The degree of venous aspiration, as recorded by manometer no. 1, could be altered stepwise to vary the amount of venous blood drained. The blood level in the drainage reservoir was kept constant, by adjusting the rate of the pump to the amount of blood drained from the venous system. The pump also served to raise the blood from the level of the dog board to the gas-exchange device (plastic bag oxygenator of Salisbury or Abbot-Hyman Pulmo-Pak®), suspended between 110 and 150 cm., above the heart level. From the gas-exchange device, the arterialized blood was infused by gravity into one or both femoral arteries. The hindrance to flow from the oxygenator into the animal depended mainly upon the bore of the arterial cannula and the blood hematocrit. The pressure needed to overcome the resistance in the arterial line ranged from 15 to 60 cm. of water, according to the flow rate.

To record continuously the blood content of the extracorporeal circulation, the oxygenator bag was
suspended, through a system of fulcrum and ball bearing pulleys, to the platform of a scale (Toledo 4030), as symbolized in the upper right part of figure 1. A record was obtained by transmitting the movements of the platform to a suitable capsule air manometer (no. 2). The oxygenator bag was primed with 300 to 500 ml. of homologous blood.

The output of the pump (exclusive roller pump, Pemco) equaled the amount of blood drained from the venous system into the oxygenator. It also measured the arterial infusion rate from the extracorporeal circuit, when the volume of blood in the oxygenator remained constant, as indicated by the weight recording. The degree of venous aspiration was always modified, without changing the level of the gas-exchange device above the heart; therefore, temporary imbalance between filling and emptying of the oxygenator occurred when the extracorporeal flow rate was changed, until the hemodynamic adaptation of the organism provided a new balance between venous drainage and arterial infusion.

Intravascular pressures were recorded through rigid catheters, introduced into the left ventricle through the left atrium (no. 3), and into the aortic arch through a carotid artery (no. 4). The distal aortic pressure was obtained through a side arm of the rotameter (no. 5). Modified Gregg type manometers were used for intravascular pressures, whereas the airway pressure (no. 6) was recorded with a capsule manometer. The pressures, weight changes, and excursions of the rotameter (galvanometer G) were recorded optically on the 30-cm.-wide paper of a Waters-Conley camera.

Results

When part of the venous return was suddenly diverted into the extracorporeal circuit, the volume output of the left ventricle always decreased. This response began in the subsequent 2 or 3 heart beats and reached a steady state within 1 to 5 minutes. The extent of the decrease in aortic flow mainly depended upon the pressure at which the arterialized blood was infused into the arterial tree. By adjusting the oxygenator to various heights, and thereby obtaining different arterial infusion pressures, 2 types of experimental conditions could be distinguished: in one, blood was shifted from the extracorporeal circuit into the animal during the course of partial heart-lung bypass; and in another, the animal was partially exsanguinated into the extracorporeal circuit.

Blood Shifted into Animal

The first type of response occurred when the perfusion bag was set at a level exceeding 15 to 60 cm. H₂O, the distal aortic pressure at the time when the heart-lung bypass was first started. Then the amount of blood infused into the animal exceeded the quantity drained out of the venous system during the first minute of partial bypass. Therefore, the blood content of the extracorporeal circuit decreased. This is illustrated in figure 2 by an original record taken from a representative experiment. The break in the venous suction tracing indicates the beginning of the partial heart-lung bypass. At this moment, venous drainage was started by lowering the aspiration pressure in the drainage reservoir from zero to —5 cm. H₂O. This resulted in a flow of 290 ml./min. entering the extracorporeal circuit. Flow in the aortic arch (left ventricular output minus coronary flow) decreased within a few beats from 1,550 to 1,420 ml./min. Distal aortic pressures (A.d.), aortic arch pressure (A.p.), and left ventricular pressures (L.V.) remained essentially unchanged. However, immediately with the beginning of the heart-lung bypass, the blood content of the oxygenator bag decreased (45 Gm. within 25 seconds), as depicted by the decline of the wide horizontal tracing at the bottom of the record. This meant an equivalent gain in body blood volume.
Figure 2
Pressure, flow, and volume changes occurring at the start of partial heart-lung bypass when the arterial infusion pressure equals the control aortic pressure. Open-chest dog, 20.5 Kg. Tracings from top to bottom: time in seconds; venous suction in cm. H₂O; aortic flow (left ventricular output minus coronary flow) in ml/min.; airway pressure in cm. H₂O; distal aortic pressure in mm. Hg; proximal aortic pressure in mm. Hg; left ventricular pressure in mm. Hg; weight changes in gm. The minus sign on the weight scale refers to a decrease in weight of the bag oxygenator, hence, to an increase in body blood volume. (Discussion of data in text.)

One to 5 minutes of extracorporeal circulation were required before a steady blood volume in the oxygenator was achieved. Then, the amount of external venous drainage was equal to the pump flow, which, in turn, equaled the arterial infusion flow.

In all experiments characterized by a shift of blood from the extracorporeal circuit into the animal, the cardiac output decreased only slightly and in a proportion always less than the amount of venous blood drained from the body circulation. As a result, the total blood flow passing from the arterial system to the tissues (left ventricular output plus extracorporeal flow) was higher than the control cardiac output. The left ventricular and aortic pressures became stabilized at a value very close to the control values.

Blood Shifted into Extracorporeal Circuit
A very different response occurred when the arterial perfusion pressure equaled the aortic pressure before partial heart-lung bypass, as revealed by the absence of flow when the arterial line alone was opened. Then, the start of the extracorporeal circulation always resulted in a shift of blood from the body into the external circuit, as illustrated in figure 3. With the beginning of venous drainage towards the extracorporeal circuit at a flow rate of 300 ml/min. (break in venous suction tracing), the aortic arch flow started to decrease immediately and fell, within 25 seconds, from a mean flow of 1,580 to about 500 ml/min. During the same period, the systolic values for the distal aortic pressure (A₀.d.), aortic arch pressure (A₀.p.), and left ventricular pressure (L.V.) decreased by about 25 per cent. In this circuit, the diastolic values for the distal aortic pressure were prevented from falling very low by the gravity infusion system (in the femoral arteries). There was no measurable change in left ventricular diastolic pressure. Immediately upon onset of the par-
Figure 4
Pressure, flow, and volume changes produced by a sudden increase in venous suction during partial heart-lung bypass. Tracings from the same animal as in figures 2 and 3. (Discussion of data in text.)

In all experiments in which the animals were partly exsanguinated at the beginning of partial perfusion by the temporary imbalance of external venous drainage and arterial infusion, the aortic arch flow decreased progressively, until the distribution of blood volume between extracorporeal and intracorporeal circuits stabilized. After this steady state was reached, the decrease in cardiac output always exceeded the amount of volume flow carried by the extracorporeal circuit. Therefore, the total perfusion of the tissues (cardiac output plus extracorporeal flow) was reduced below the control value. The left ventricular and aortic arch pressures decreased consistently, but by far less than could be expected on the basis of the reduction in left ventricular output. They could be maintained within safe limits, even when the aortic arch flow was diminished to less than 25 per cent of the control value.

The same relationship between body blood volume and aortic arch flow, observed at the start of partial heart-lung bypass, also was noted every time the extracorporeal flow was suddenly augmented by an increase of the venous suction, as illustrated in figure 4. This record was taken from the same animal as the tracings shown in figures 2 and 3. The left part of the record shows an aortic arch flow of 1,060 ml./min. in the presence of an extracorporeal flow of 390 ml./min. With a sudden increase of venous suction from -6 to -17 cm.H₂O, the amount of blood drained into the external circuit increased to 650 ml./min. Venous return to the right heart became less. As a result, the aortic arch flow decreased within 32 seconds to 450 ml./min., and the aortic arch pressure (Ao.p.) decreased by about 35 per cent. The decrease was less marked for the distal aortic pressure, because the continuous gravity infusion in the femoral artery tended to maintain the diastolic value, hence, resulting in a narrowing of the pulse pressure when the extracorporeal flow was increased. The left ventricular systolic pressure declined from 74 to 48 mm.Hg, whereas the left ventricular diastolic pressure was not measurably altered. That the weight tracing in the left part of the record is horizontal indicates that extracorporeal and intracorporeal flow had obviously reached a steady state of adjustment during the control period. At this stage, 40 ml. had already been exsanguinated from the organism into the oxygenator bag, as compared with the state before the beginning of any heart-lung bypass (0 on scale). With the sudden increase in extracorporeal flow, additional blood was shifted from the body into the bag, as indicated by the rise of the wide tracing from 40 to 115 Gm. within 32 seconds. A new steady state (not depicted in the record) was reached after 2 minutes, with a shift of 300 ml. of blood from the animal into the extracorporeal circuit.

When the extracorporeal flow was decreased from a high to a lower rate, the reverse of the above described changes occurred: Blood, accumulated in the oxygenator bag, ran back into the organism, aortic arch flow increased, and left ventricular as well as aortic pressure rose.
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The relationship between extracorporeal flow, body blood content, and cardiac output was consistent in all experiments. Figures 2 to 4 depict the acute changes occurring when the body blood content suddenly was altered by manipulations in the extracorporeal circuit. The data, pertinent to the relationship of extracorporeal infusion flow and cardiac output, were obtained after the body blood content reached a steady state. They are plotted in figures 5 and 6. In figure 5, both the aortic arch flow and the extracorporeal flow are expressed in per cent of the control cardiac output (aortic arch flow before the start of partial heart-lung bypass). The data would fit the diagonal line, if the amount of increase in extracorporeal flow and the amount of decrease in cardiac output were exactly the same. This obviously was not the case. In the experiments in which the body blood content increased (as symbolized by crosses), the aortic arch flow decreased but little. Contrasting to this, aortic arch flow decreased very much when blood shifted from the animal into the extracorporeal circuit, as symbolized by the dots. The separation of the crosses and dots by the diagonal line indicates that the relation between extracorporeal flow changes and aortic flow changes depends mainly upon the direction of the blood shift.

Furthermore, the amount of blood shifted to or from the animal’s vascular bed directly affected the left ventricular output for any given extracorporeal flow rate. In figure 6, the total tissue perfusion flow (aortic arch flow plus extracorporeal flow) is plotted versus the volume of blood transferred from the body circulation into the extracorporeal circuit, or conversely. The data indicate that whenever the dog gains blood during the partial heart-lung bypass, the total tissue perfusion flow exceeds the aortic arch flow before the beginning of the bypass. Whenever the dog loses blood into the external circuit, the total tissue perfusion is decreased. There is an approximately linear relationship between the animal’s blood volume changes and total perfusion flow. The total tissue perfusion is increased by about 15 per cent when the body blood content exceeds the control value by 100 ml., whereas, the total tissue perfusion reaches only 50 per cent of the control value when the animal has lost 400 ml. of blood in the external circuit.

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Discussion

These experiments indicate that the body blood volume is the main determinant of cardiac output during partial heart-lung bypass, with the gravity infusion method. If the arterial infusion pressure head is not set in excess of the aortic pressure, the start of the bypass procedure will be characterized by a loss of blood from the organism into the extracorporeal circuit, until the decrease in systemic arterial pressure equals the pressure gradient across the arterial infusion line.

It can be assumed that the decrease in body blood content occurs predominantly on the systemic venous side of the circulation and in the pulmonary bed, since the capacity of the arterial bed is rather small, and the systemic arteries are filled at about normal pressures by the combined flow from the left ventricular discharge and the extracorporeal circuit. The sequence of events would be as follows: Hypovolemia in the systemic veins diminishes venous return to the right ventricle, and, when right ventricular output is reduced, the pulmonary flow declines, in turn decreasing left ventricular discharge. With the partial perfusion procedure, the venous return can be easily modified by shifting blood from the body to the extracorporeal circuit. This means that cardiac output can be regulated artificially by changing the blood volume within the extracorporeal circuit, the procedure being easily reversible.

There is also a direct relationship between the total body tissue perfusion (aortic arch flow plus extracorporeal flow) and the body blood content. When the body blood content is maintained, as it was before bypass, the total body tissue perfusion is close to the control cardiac output. This can be concluded from figure 6 where the experimental points approximately fit a diagonal which would pass close to the intersection of the "100 per cent" flow line with the "0 ml." volume line. When the animal loses blood by the procedure (arrow to the right), total tissue perfusion is decreased. When the dog gains blood (arrow to the left), there is a greater tissue perfusion than that measured under control conditions.

However, a generalization of these statements should be somewhat restricted, because the results were obtained in open-chest preparations, and the measured aortic arch flow did not include the coronary flow. Additional information, therefore, would be desirable from experiments on closed-chest animals with total cardiac output measurements.

Looked upon from the viewpoint of the benefit of the partial heart-lung bypass for the circulation, it appears that artificial regulation of the body blood volume is an important factor. There is an obvious parallel between the exsanguination of the organism into the extracorporeal circuit and the classical phlebotomy, or similar maneuvers for reducing the circulating blood volume. However, a body blood volume reduction by partial cardiopulmonary bypass would offer several advantages: (1) an easy and reversible adjustment of the degree of exsanguination, with a participation of the displaced blood in the perfusion of body tissues; (2) the maintenance of myocardial and body tissue perfusion at near normal arterial pressures over a wide range of exsanguination; (3) some reduction of the work load of the heart, since cardiac output is decreased.

The findings reported here are, principally, in agreement with the observations of others in total heart-lung bypass. These authors found that the body blood volume is a function of the extracorporeal flow rate, as long as the venous pressure is kept constant. Their observations indicate that, in acute experiments, vasoemotion is not predominant in affecting the body blood volume. Our partial bypass experiments, also of the acute type, similarly show a direct dependence of the organism's blood content upon the extracorporeal flow rates. However, the existence of such relations in acute experiments does not rule out that during longer periods of heart-lung bypass, vasoemotion might become an important factor in affecting the body blood volume.

Summary

Partial heart-lung bypass was performed in open-chest dogs, using the gravity arterial inf-
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fusion technique. Arterial infusion pressure, venous suction and pressures in the left ventricle, aortic arch, and airways were phasically recorded. The mean flow in the aortic arch and the blood content of the extracorporeal circuit were continuously recorded. According to the height of the bag oxygenator above the heart level, partial heart-lung bypass resulted in a shift of blood either from the extracorporeal circuit into the animal or vice versa. When the body blood volume was increased by the bypass procedure, the cardiac output decreased only slightly. When the body blood volume was diminished by the bypass procedure, the cardiac output dropped markedly. It was found that when the systemic arterial pressure was maintained at approximately normal levels, independent of cardiac output, the change in cardiac output was proportional to the change in the body blood volume.

**Summario in Interlingua**

Circuizione partial de corde e pulmon esseva effectuata in canes a thorace aperto per medio del techniea de infusion arterial sub le fortia del gravitate. Le tension del infusion arterial, le suction venose, e le tensiones del ventriculo sinistre, del arco aortic, e del vías aorae esseva registrata pliasicamente. Le fluxo medic in le arco aortic e le contento de sanguine del circuito extracorporee esseva registrate continue. In dependentia del altor del sacco oxygenatori su pra le nivello del corde, le circuizione partial de corde e pulmon resultava in un displaciamiento de sanguine ab le circuito extracorporeo ad le animal o ab le animal ad le circuito extracorporeo. Quando le volumine de sanguine del corpore esseva augmentate per la manœuvre del circuizione, le rendimento cardiac esseva solamente per leve gradi. Quando le volumine de sanguine del corpore esseva reducute per le manœuvre del circuizione, le rendimento cardiac descresceva marcamente. Esseva trovate que quando le tension systemico-arterial esseva mantenite a aproximativamente normal nivellos (in independencia del rendimento cardiac), le alteration del rendimento cardiac esseva proportional al alteration del volumine de sanguine in le corpore.

**References**

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