THE PREVENTION OF SHOCK FOLLOWING EXTRACORPOREAL CIRCULATION AND HYPOTHERMIA*

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THE TITLE of this paper promises more than it keeps. We cannot define "shock": its treatment is to some extent controversial as we know very little about the changes produced by extracorporeal circulation and less about hypothermia. This presentation is nothing but another variation of the old theme: "How to keep the patient alive" or "How to get away with it."

Extracorporeal circulation and hypothermia are two of the most formidable procedures to which patients are regularly submitted. It certainly would have been in order to investigate thoroughly the many rather complicated aspects before employing them clinically. However, the pressing needs of the patients have led to an early and successful clinical application. Although a good deal of work has been done during recent years our knowledge is still very limited and we are really only beginning to understand these processes. The surgeons and their associates, the anaesthesiologists, have entered the experimental field comparatively recently. It is a great disadvantage that so few physiologists, biochemists, and other basic scientists take an active part in the investigation of these problems.

At the Winnipeg Children's Hospital and at the Winnipeg General Hospital, a Kay-Cross Disc Oxygenator is used for all clinical by-pass procedures as manufactured by Pemco. A Pemco heat exchanger is added when the operation is done under hypothermia. The blood is collected in the venous reservoir by gravity and two roller-type pumps are used as arterial pump and coronary sinus suction pump. Everybody knows that the heart-lung machines work well and it has been stated repeatedly that the running of these machines does not present any problems. It is futile to discuss the advantages and disadvantages of the various types of machines. They all work well if they are run properly. However, at the end of the procedure, the man in charge of the by-pass should not be content to turn off his machine, see that the patient's own heart is beating and excuse himself. In the development of shock something may happen which is not immediately apparent but which leads to the shock syndrome and perhaps to death. If this picture develops postoperatively and provided there is no obvious other explanation, such as evidence of myocardial infarction,¹ it must be assumed that the derangement has occurred during the by-pass. Evidently the operator of the machine is very interested in the events during the postoperative phase.

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The following breakdown is an attempt to classify the areas where changes may occur which eventually may lead to shock.

Extracorporeal Circulation

Operation and anaesthesia	Hypothermia
Massive transfusion	Blood flow
Pump, filters, tubing, etc.	Blood balance
Oxygenator	

Of course, postoperative shock can occur without by-pass or hypothermia. The massive transfusion has some inherent dangers which cannot be discussed in this paper. The mechanical parts of the heart-lung machines are always inferior to their living counterparts. The oxygenator may efficiently exchange oxygen and CO₂ but after a moment's reflection it will become evident that it cannot replace the intricate functions of a living lung. In this connection the status of the patient's own lungs during by-pass also has to be considered. Hypothermia is the part which is least understood and the last two items represent the two variables of each individual run.

For this audience there is no need to stress the importance of good anaesthesia, but a few facts regarding the anaesthesia in experimental animals should be pointed out. The experimental work in cardiovascular surgery is mainly done on dogs, and our present knowledge to a large extent is based on observations made on dogs. There are many differences between dogs and humans and great care has to be exercised when applying to patients conclusions based on dog experiments. For convenience sake the most popular anaesthesia for dogs is intravenous pentobarbital. This type of anaesthesia has little in common with modern clinical anaesthesia. Any time we look at results obtained in dogs under these circumstances we should remind ourselves that these results have been obtained in a hypoxic hypercapnic dog under pentobarbital anaesthesia, a situation quite different from a patient anaesthetized in the operating room.

For instance, the acute syndrome of apparently sudden death in the postoperative period following prolonged hypotension, as described by Kirklin, McGoon, Patrick, and Theye,² was frequently observed in dogs but not in human patients. The type of anaesthesia may be a contributory factor.

The problems involved in massive transfusions would merit a more detailed description but this is outside the scope of this paper. Several recent investigations have shown that the blood which is in the machine before by-pass has several undesirable properties. It has a low pH and a low sugar content. In the local organization the blood is collected during the previous day by the Red Cross and delivered to the hospitals where it is kept at a low temperature. The blood is preserved in siliconized bottles containing 20 mg. heparin in 30 c.c. saline per 500 c.c. blood. Since the low blood sugar and the low pH are caused by the metabolic activity of the erythrocytes, the blood is kept in the refrigerator as long as possible. It is added to the machine only a few minutes before by-pass. If the heat exchanger is used, the blood is not heated before being added to the machine and if the heat exchanger is not used it is warmed in a water bath to 25° C.-30° C. immediately prior to use. By keeping the period of time during which the blood is at or near body temperature to a minimum it is possible to avoid severe

alterations in the blood. In Table I our findings are compared with those reported in the literature.^{3, 4}

TABLE I
DATA IN THE BLOOD USED FOR EXTRACORPOREAL CIRCULATION PRIOR TO USE OBTAINED BY THREE INDEPENDENT GROUPS

	Heparinized blood stored 24 hours			
	Houston		Montreal	Winnipeg
	18 mg* SG† (4 units)	20 mg. PB‡ (11 units)	18 mg. PB (25 patients)	20 mg. SG (9 patients)
Plasma haemoglobin (mg.%)	20	40	—	35
pH	7.33	7.16	7.27	7.29
Glucose (mh.%)	50	65	—	51
pCO ₂ (mm. Hg)	—	—	47.3	40.9
Bicarbonate (mM./L.)	23	23	20 4	18.4

*Mg. of heparin per 500 ml. blood.
†SG = in siliconized glass bottle.
‡PB = in plastic bag.

For the purpose of this discussion, the heart-lung machine is divided into two parts—the oxygenator and the rest, consisting of pumps, reservoirs, filters, connectors, and tubing. The early workers in this field devoted much time and energy to investigations of the mechanical parts of the machines. In order to decrease the damaging effects of rough and wettable materials, the blood comes in direct contact only with plastics, latex, and siliconized highly polished metal. Excessive haemolysis occurs mainly in the coronary sinus suction system. The increased haemolysis is evidenced by an increase of plasma haemoglobin after prolonged periods of by-pass. Although in a clinical case it is impossible to differentiate between the effects of the coronary sinus suction and of the other parts of the machine, there is no doubt that the highest values were found in cases with a high flow through the coronary sinus suction, for a prolonged period of time. In this situation it may be better to lose some blood into the ordinary suction apparatus provided the surgeon's vision can still be maintained.

The liberated haemoglobin is bound to a plasma protein, the haptoglobin, up to a concentration of about 100 mg. per 100 gm.⁵ Only the free haemoglobin, that is the plasma haemoglobin in excess of 100 mg. per 100 gm. passes through the renal glomerulus and may lead to renal changes. Free haemoglobin is known to be a powerful vasoconstrictor. It is well known that the finding of a high plasma haemoglobin is associated with a high mortality, but it is difficult to establish a causal relationship since in these difficult and long cases other complications may be present as well.

All pumps produce a pulsatile flow, the characteristics of the pulsations being different in the various types of pumps. Some pumps apparently produce a rather high, short systolic peak which has led to the addition of various devices commonly referred to as depulsators. They usually consist of a membrane or an elastic tube which dampens the peak. With the two roller pumps used in our system, pressures exceeding the physiological range of systolic pressures do not

occur in the patient and we did not find it necessary to introduce depulsators. The rationale is as follows: high systolic pulse peak pressures during by-pass may lead to an excessive stimulation of the carotid body. At the end of the by-pass when the patient's own heart takes over again, this stimulation is terminated but the exhausted carotid body is unable to function properly and a period of hypotension follows. Although another Canadian team has found that in dogs post-operative hypotension did not occur any more following the introduction of a depulsator,⁶ a direct experimental proof of this attractive theory is lacking. None of the presently available pumps is ideal except perhaps the McCabe pump which can duplicate the pulse waves exactly, but their performance is adequate for short perfusions.

The same thing can be said regarding the oxygenators. Provided an oxygenator of the right size is used an adequate oxygenation of the blood can always be achieved. A few years ago the possible dangers of over-oxygenation attracted a great deal of attention, especially if there is a temperature gradient between oxygenator and patient. Since this problem could not be solved by experiments it became a matter of beliefs, and, as it often happens there are now two groups, the believers and the non-believers. Since the believers could not prove their point, one of their spokesmen resorted to a nice diplomatic trick. He pointed out that over-oxygenation must be assumed to be dangerous and therefore it would be up to the non-believers to prove that it is innocuous.⁷ Of course, this negative proof is much more difficult to furnish. This problem cannot be fully discussed here, suffice it to mention the practice of several groups to use fully oxygenated blood at a temperature of 10° C. or less to induce hypothermia with no ill effects.

The carbon dioxide brings up many rather complicated problems, especially if hypothermia is added to the by-pass. One of the main functions of the anaesthesiologist and of the pump operator is the prevention of alkalosis or acidosis. Derangements of the pH are important factors in the development of postoperative shock.

Whether or not slight and intraoperative changes of the acid-base balance are beneficial is still a controversial problem. Edmark⁷ advises the production of a temporary acidosis during hypothermia. Before describing the methods used by our group, I would like to present a small portion of the physiological background. A fall in pH can, of course, be due to a fall of the bicarbonate (metabolic acidosis) or a rise of the pCO₂ (respiratory acidosis). Under hypothermia the normal pH and the pCO₂ change and conversion factors and nomograms have been worked out in order to calculate corrected values. At the lower temperature, more CO₂ is dissolved and consequently the pCO₂ corresponding to the same total CO₂ is lower. However, all workers in this field agree that these factors are quite unreliable. During the last months our group has started to do serial determinations of arterial pH, pCO₂, and bicarbonate during open heart surgery. These determinations can be done expeditiously with the Astrup apparatus. At the present time we are unable to change the temperature of the water bath surrounding the electrode and interpretation of the values obtained at a lower temperature consequently is difficult. For the expression of the data the method described

by Brewin, Gould, Nashat, and Neil⁷ was adopted fully realizing, however, that some of the interpretations may be erroneous. If a blood sample is equilibrated with varying CO₂ tensions and the pH determinations are plotted against the CO₂ on semilogarithmic paper, the dots fall on a straight line and this line is independent of temperature. The line is shifted to the left side in acidosis and to the right in alkalosis. During by-pass and hypothermia, the pCO₂ may change due to a variety of reasons. Based on determinations of pH and pCO₂ in the same blood sample, this line has been constructed for each patient. Two representative examples are given in Figures 1 and 2.

Regarding blood flow there is not much to be added. Although low flow rates may be tolerated for short periods of time, the aim is to have a flow of at least 2.3 L./m²/min. The oxygen saturation of the venous blood is about 75 per cent or more during a perfusion at this rate, and the A-V difference, accordingly, is 25 per cent. At lower flow rates the A-V difference increases. If bloodstream cooling is used, it must be realized that large areas of the body mass are cooled slowly and remain at a temperature higher than the one recorded in the oesophagus. The oxygen requirements are therefore higher than those calculated on the basis of a single temperature reading. Whereas it is permissible to start the cooling on partial by-pass, it is necessary to complete the cooling period on total by-pass. During partial by-pass the upper parts of the body are perfused with warm blood pumped by the heart. The rectal temperature at this time may be lower than the oesophageal temperature. The brain probably is cooled adequately only during the period of total by-pass.

Finally, the question of blood balance. During and immediately after the by-pass a reasonably accurate blood balance must be maintained. All the reservoirs of the machine are calibrated and the operator knows at all times how much blood has been added to, or removed, from the patient's circulation. The blood loss is estimated by the conventional methods. As a final check at the end of the by-pass, the blood is drained from the machine and measured exactly. The amount of blood transfused can then be accurately calculated.

At the end of the operation the patient should have the physiological circulatory blood volume. This, however, may be different from the preoperative circulating blood volume in view of the surgical corrections which have been made. The weight of the patient is therefore of very limited value, inasmuch as weight changes do not reflect these alterations and also do not provide information regarding internal haemorrhage or fluid shifts between the various compartments.

From the practical standpoint the venous pressure determination provides the best index of the adequacy of the circulating blood volume.

Our experience has confirmed the impression of others that a moderate over-transfusion is beneficial. At the end of by-pass the patient is transfused until the venous pressure rises 2-5 cm. The majority of patients require only 200-300 c.c. which, incidentally, is the quantity of normal saline present in the machine blood. It is not an over-transfusion. Patients who underwent total correction of tetralogy of Fallot may require over-loading of 500 c.c. and more, which may lead to a temporary rise in venous pressure up to 20 cm. of water. As we have gained more experience we have been increasing the amount of blood transfused more

FIGURE 1. A 21-year-old male patient. Complete correction of tetralogy of Fallot. A. Oesophageal temperature, pH, pCO₂, and bicarbonate (uncorrected) plotted against time. Note the metabolic acidosis during by-pass and hypothermia with partial correction at the end of the operation and in the recovery room. Patient made an uneventful recovery. B. The pCO₂ and pH determined in the same blood sample are plotted on semilogarithmic paper.

A.

B.

FIGURE 2. A 36 year-old female patient. Cardiectomy for aneurysm of the sinus of Valsalva. A. Oesophageal temperature, uncorrected pH, $p\text{CO}_2$ and bicarbonate recorded from the beginning of the operation until patient arrived in recovery room. Note metabolic acidosis during by-pass and hypothermia with a further fall in bicarbonate when temperature returned to normal levels. At the arrow 40 mEq. of sodium bicarbonate were given intravenously resulting in a rise of the bicarbonate and pH. B. pH and $p\text{CO}_2$ plotted on semilogarithmic paper.

and more. I do not think we have ever caused harm by over-transfusion, but in several early cases we regretted that we had not given more blood. Should an over-transfusion actually take place, the heart dilates and the venous pressure rises. Since the patient is still connected to the machine via the venous catheters the excess blood volume can then be removed within a few seconds.

SUMMARY

The current thinking regarding the management of patients on the heart-lung machine, with or without hypothermia, has been reviewed. The following points appear to be of importance for a smooth postoperative phase and the prevention of shock: adequate flow; slight hypervolemia during and after by-pass and hypothermia; minimal use of coronary sinus suction; possible temporary acidosis during hypothermia. Some of our theories are based on facts, others are based on fantasies and will have to be reviewed again. The main problem is to provide enough oxygen to the living cells and to remove CO_2 without upsetting the acid-base balance and other physiological equilibria. The trouble is that we do not know what is physiological for a patient on total by-pass whose lungs are not perfused, whose major organs are at 25°C . and the rest of the body somewhere between 27°C . and 34°C .

Many problems have not been discussed, such as the value of the EEG, which usually shows severe changes at the beginning of partial by-pass. These problems are actively investigated in many centres and as time goes on we shall get a better understanding. I would like to close by quoting a remark which a member of the audience made to me some time ago following a similar presentation: "If you know so little about your subject it is surprising how much you can do."

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RÉSUMÉ

Nous avons passé en revue les opinions courantes sur les traitements des malades sous les machines cœur-poumon, avec ou sans hypothermie. Si l'on désire des suites opératoires sans incident et prévenir le choc, il faut surveiller les points suivants: un débit suffisant; une hypervolémie légère, pendant et après la dérivation et l'hypothermie; un emploi minimum du système de suction du sinus coronaire; une acidose temporaire possible durant l'hypothermie.

Un certain nombre de nos théories sont basées sur des faits, les autres sont fantaisistes et seront étudiées plus attentivement. Le problème essentiel est de procurer assez d'oxygène aux cellules vivantes et de faire éliminer le CO_2 sans troubler l'équilibre acide-base et les autres équilibres physiologiques. L'ennui provient du fait que nous ne savons pas ce qui est physiologique chez un

malade en dérivation totale dont les poumons ne sont plus perfusés, dont les principaux organes sont à 25° C., et le reste du corps quelque part entre 27° C. et 34° C.

Si un choc s'amorce au cours de la période postopératoire à la suite d'une dérivation, et qu'on ne trouve pas d'autres causes apparentes, tel un infarctus du myocarde, on peut présumer que le choc est attribuable à la circulation extra-corporelle. Il faut éviter que le sang se détériore au cours de la conservation.

Une grande quantité d'hémoglobine plasmatique libre semble nuisible; l'hémolyse survient surtout dans le système de succion du sinus coronaire.

Il est toujours possible d'oxygéner 100 per cent avec l'oxygénateur. Au cours de l'hypothermie, il n'est pas facile de préciser la concentration du CO₂. Tel que l'ont proposé Brewin, Gould, Nashat, et Neil, nous avons présenté les résultats sur un papier semilogarithmique.

Nous avons observé que, à la fin de l'opération, un léger excès de transfusion peut être avantageux.

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