

THEORY AND PRACTICE IN THE USE OF A PUMP-OXYGENATOR FOR OPEN INTRACARDIAC SURGERY*

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It is now accepted that certain intracardiac operations are best accomplished with the aid of a mechanical pump-oxygenator for the extracorporeal circulation and oxygenation of blood. There is not general agreement on either the theory or practice of establishing the extracorporeal circulation. Perhaps at this stage there is merit in recording some of the conclusions arrived at by one group after five years of experimental study in animals and two years of clinical experience embracing operations using this technique in 200 patients.

This presentation omits experimental details, protocol of cases, and statistical analysis of results. Concepts and techniques presented are, of course, subject to modification by further data and experience. Although the authors bear full responsibility for the views presented, which might in some instances be challenged even by members of their own group, these views have been the result not only of their own observations and investigations, but also that of their colleagues in the Mayo Clinic. These include Dr. D. E. Donald of the Section of Experimental Surgery; Drs. E. H. Wood and H. J. C. Swan of the Section of Physiology; Mr. Richard E. Jones of the Section of Engineering; Dr. J. W. DuShane of the Section of Pediatrics; Drs. H. B. Burchell and R. W. Brandenburg of the Section of Medicine; and Dr. H. G. Harshbarger, fellow in surgery.

BASIC REQUIREMENTS FOR OPEN INTRACARDIAC OPERATIONS

For open intracardiac operations in man, the perfusion from the pump-oxygenator must supply

* Many surgeons in Great Britain and throughout the world are trying to perfect apparatus and techniques which allow open cardiac surgery. We thought it desirable to ask Dr. Kirklin and his associates at the Mayo Clinic, who have done so much in this field, to help us all by putting down on paper the points which they consider fundamental in this work. Dr. Kirklin's own experience of these matters exceeds that of most other surgeons: his opinions carry weight.—Ed.

properly prepared arterial blood to the arterial system of the subject in proper amounts. The technique must allow maintenance of the functional integrity of the organism for as long as is required for the intracardiac procedure. No deleterious effects should be produced by the perfusion, and the risk of the perfusion itself must be low. The technique must be practicable within the general framework of accepted surgical techniques.

“For as long as is required” needs comment. To be generally applicable to all types of intracardiac surgery, perfusion must be so managed that it can be safely maintained for approximately one hour. In cases of ventricular septal defect, repairs in some instances can be made in five to 10 minutes, but in others the experienced surgeon will require 30 to 40 minutes to correct the defect precisely. These times refer to the period of induced cardiac asystole, and total perfusion times will ordinarily exceed asystole time by 10 to 20 minutes. Complete repair of the tetralogy of Fallot or of common atrioventricular canal of the complete type may require 25 to 40 minutes of asystole, and a correspondingly longer time of perfusion. As attention is gradually turned to the more complex procedures of repair of transposition of the great vessels or replacement of diseased valves with new, synthetic ones, somewhat longer operating times may on occasion result. Techniques that allow safe perfusion for only a short period must become of only historic interest in the presence of those allowing safe perfusion in man for periods of at least one hour.

FUNCTION OF THE OXYGENATOR

Oxygenation of blood and elimination of carbon dioxide are the two functions of an artificial oxygenator. Since whole-body perfusion was first studied, there has been concern over the fact that other functions of the human lung are missing in artificial oxygenators. There is no good evidence that absence of such possible additional functions

of the human lung has been a serious shortcoming of artificial oxygenators.

OXYGENATION OF BLOOD.—The performance requirements of an oxygenator are best defined in terms of the amount of oxygen it will add, under specified conditions, to blood passing through it at a specified rate of flow. In order to prevent the gradual lowering of oxygen content of venous and arterial blood during perfusion, the oxygenator must add to the venous blood entering it the amount of oxygen consumed by the subject while undergoing perfusion.

Knowledge concerning oxygen consumption during extracorporeal circulation in man then becomes of extreme importance in defining the performance requirements of oxygenators. Data are not available in sufficient quantity to allow final conclusions on this matter. Those which are available would suggest strongly that oxygen consumption in lightly anaesthetized man during whole-body perfusion is between 110 and 120 ml. per square metre of body surface per minute.

This amount of oxygen should then be added to the blood per minute of perfusion. The oxygenator must not only accomplish this, but it must do so under certain specified conditions of flow and venous oxygen saturation. The oxygen content of venous blood entering the oxygenator has an important bearing on the amount of oxygen that will be added to the blood. Other factors remaining equal, the lower the oxygen content of this venous blood the more the oxygen that will be added to the blood in its passage through the oxygenator. This phenomenon is related of course to the oxygen-dissociation characteristics of human blood, and they are reflected in the classic oxygen-dissociation curves of this substance.

The relation between the oxygen saturation of venous blood entering the oxygenator and the amount of oxygen that is added to the blood at a given flow rate is a basic phenomenon which pertains in all types of oxygenators. An example of its importance can be illustrated by a hypothetical situation involving a given oxygenator, so designed as to add 110 ml. of oxygen per minute during the perfusion of a subject with a body surface of 1 square metre, being perfused at a flow rate of 1½ litres under circumstances such that venous blood entering the oxygenator has an oxygen saturation of 45%. Should this oxygenator now be made to perform under identical circumstances, except that the saturation of venous blood returning to it is 75%, it would add only 72 ml. of oxygen per minute.

It is of obvious importance, then, to specify that the oxygenator add 110 to 120 ml. of oxygen per minute per square metre of body surface at a given venous oxygen saturation and at a given flow rate. Oxygen tension in the tissues is of basic importance in the metabolism of cells, and it would appear of importance in the prevention of metabolic acidosis and other undesirable effects, including death of highly specialized cells, to maintain the oxygen tension in tissue within normal limits during whole-body perfusion. Oxygen tension in the tissues is related not only to arterial oxygen tension but to venous oxygen tension as well. The latter should then likewise be maintained at near normal levels. Venous oxygen saturations of approximately 70 to 75% during perfusion would thus appear desirable, and the oxygenator should be able to add the desired amounts of oxygen to blood entering it with these saturations. For reasons to be given below, it is our practice to maintain flow rates of 2.2 to 2.5 litres per minute per square metre of body surface.

Final answers are not available to allow the above specified conditions to be proved correct or incorrect, nor to allow a comparison of perfusions established on these bases with those established on other ones. None the less, clinical experience with this type of perfusion indicates to us at least that an oxygenator to be used for clinical intracardiac operations should add 110 to 120 ml. of oxygen per minute per square metre of the subject's body surface to venous blood entering at an oxygen saturation of 70 to 75%, at a flow rate of 2.2 to 2.5 litres per minute per square metre of the subject's body surface. The oxygen tension of arterial blood should probably be maintained in the region of 110 to 150 mm. of mercury, and excessively high oxygen tension in arterialized blood in the pump-oxygenator may be a dangerous situation.

ELIMINATION OF CARBON DIOXIDE.—Elimination of carbon dioxide is a second function of the oxygenator. In general, an oxygenator of reasonable adequacy as regards introduction of oxygen into blood will easily be sufficient for elimination of carbon dioxide, a readily diffusible substance.

It is not possible at present to state with assurance how much carbon dioxide should be eliminated from the blood during its passage through an oxygenator. Put another way, it is not possible to state with assurance the tension of carbon dioxide that is most desirable in the arterial blood leaving the oxygenator. Under light ether anaesthesia with respiration completely controlled by the anaes-

thetist and ventilation well maintained, the tension of arterial carbon dioxide may be as low as 15 to 20 mm. of mercury. Whether it is desirable that this tension of carbon dioxide be present in arterial blood during perfusion is not yet established, but a tension of 30 to 40 mm. of mercury during perfusion has appeared reasonable.

In oxygenators with an atmosphere that is controllable, such as the stationary vertical-screen oxygenator, it is possible to regulate the partial pressure of carbon dioxide in the oxygenator, and thus the tension of carbon dioxide of the arterial blood. In bubble oxygenators, the carbon dioxide content of air within the bubbles is not easily regulated. This may or may not be an important consideration.

FUNCTION OF THE ARTERIAL PUMP

This is easily defined as the pumping of adequate amounts of blood into the arterial system of the patient. It is advantageous that the pump should have a capacity of 5 litres per minute and that it should function satisfactorily at a flow rate as low as 0.3 litre per minute. It must be possible to determine with reasonable accuracy the output of the arterial pump during perfusion.

Virtually all pumps being used produce a slightly pulsatile flow, including the non-occlusive DeBakey-type roller pump. Some pumps produce a very pulsatile flow and some, such as that in the Melrose pump-oxygenator, allow rather precise regulation of stroke volume and rate as well as total output per minute. Although certain theoretical arguments can be brought to bear as to the possible advantages or disadvantages of a pulsatile or a non-pulsatile flow from the arterial pump, data are not available to settle this point.

A large clinical experience with the Gibbon-type pump-oxygenator, delivering a virtually non-pulsatile flow, has indicated that very adequate whole-body perfusion is accomplished in this way. It is not denied that better perfusion of remote parts of the arterial tree might possibly result from the use of a pulsatile flow, but there is as yet no evidence that this is true. The higher velocity reached by the blood during its flow across the arterial cannula during the peak of systole might result in sufficient additional trauma of the blood to be an argument against this type of flow unless it were found to be of unquestioned superiority in other respects.

COLLECTION OF VENOUS BLOOD

The size and method of placing venous cannulas, and the method of collecting venous blood from

the patient, determine in large part the adequacy of venous return under a given set of circumstances during extracorporeal circulation.

Either a pump or a method for achieving steady, gentle, negative pressure can be applied to the venous cannulas for the collection of blood from them. There is reason to believe that steady, gentle, negative pressure, achieved by a controlled degree of vacuum in the venous reservoir, or by gravity, is superior to the use of a pump. Gravity is appealing in its ready availability, but under operating-room conditions is not quite so easily controlled as is an induced gentle negative pressure within the venous reservoir.

Venous cannulas should be as large as the vena cava will comfortably accommodate.

PROPER FLOW RATE DURING WHOLE-BODY PERFUSION

No detail of the theory and practice of the extracorporeal circulation of blood for open intracardiac operations has excited more partisan discussion than flow rates. As in many other aspects of this subject, data are not available, or at least are not presented in a sufficiently complete form, to allow a final conclusive statement on this matter. The experience of our group at the Mayo Clinic, the material published in the literature, and the observations of others which have been communicated to us have resulted in our having clear beliefs as regards flow. These beliefs have been translated into clinical practice in patients subjected to whole-body perfusion for open intracardiac operations.

The reasons were stated previously in this presentation for our considering it desirable to maintain the oxygen saturation of haemoglobin in systemic venous blood at 70 to 75%. There is clear evidence that, in using a system in which the oxygenator has a proper ability to add oxygen to the blood, there is a direct relation between the oxygen saturation of the haemoglobin in the systemic venous blood and flow rate. In order to maintain desired venous saturation during whole-body perfusions in which arterial oxygen tensions are in the ideal range of 115 to 150 mm. of mercury, perfusion flows of approximately 2.2 to 2.5 litres per minute per square metre of body surface are necessary.

If the oxygen tension in the arterial blood is considerably higher, for instance in the range of 400 to 500 mm. of mercury, the transport of a similar amount of oxygen to the patient can be made with perfusion flow of 1.7 litres per minute per square metre of body surface. There is suggestive evi-

dence that the completeness of perfusion of the most distant reaches of the vascular system may be related, during extracorporeal circulation, to the flow rate. There are theoretical considerations suggesting that very high arterial oxygen tension could be disadvantageous during whole-body perfusion. These two lines of thought have made us believe that flow rates of 2.2 to 2.5 litres per minute per square metre, with arterial oxygen tension of approximately 115 mm. of mercury, offer a better way of transporting the oxygen required by the subject than does a somewhat lower rate of flow of arterial blood of higher oxygen tension. The attainment of very high oxygen tension in arterial blood is possible with the Gibbon oxygenator and with other types, but probably should be avoided.

It is possible that in infants and very small children oxygen consumption and cardiac output related to surface area are somewhat higher than in older individuals. It is our practice then to conduct the perfusion in such small patients in accord with this possibility.

Normal basic cardiac output is generally considered to be about 3.0 litres per minute per square metre and basal oxygen consumption to be approximately 160 ml. per minute per square metre. Although the evidence is not complete, it is probable that under conditions of quietly induced light anaesthesia, there is an approximately 25% reduction in both these variables. It would then appear that in patients operated upon by us under the conditions described above, the perfusion flow rate closely approximates the cardiac output pertaining before and after the perfusion.

It can be categorically stated that with proper technique and equipment such flow rates are regularly possible in patients of all sizes without difficulty in venous return and without deleterious side-effects such as excessive trauma of the blood.

AVOIDANCE OF DELETERIOUS EFFECTS

BLOOD TRAUMA.—A pump-oxygenator for clinical use should be so designed that blood trauma is minimal, at whatever flow rates need be employed. The commonest method of estimating such trauma is by measurement of the increase in plasma haemoglobin produced by passage of blood through the apparatus. Measurement of plasma haemoglobin during whole-body perfusion is misleading, for the subject continually removes some free plasma haemoglobin from the blood. For the purpose of measuring the increase in plasma haemoglobin during the extracorporeal circulation of blood, there should be no subject in the circuit, but the arterial line should be connected to the

venous line of the apparatus. A known amount of blood should then be circulated through the pump oxygenator at a known flow rate with a resistance of physiological ranges in the arterial line. Samples taken at hourly intervals are analysed for plasma haemoglobin, and a measure of the blood trauma produced by the apparatus is obtained.

Apparatus can be, and has been, so designed and maintained that high flow rates are accommodated with minimal trauma to the blood. A large number of factors, including the velocity of blood flow in various portions of the system, must be carefully controlled to achieve this.

BACTERIAL CONTAMINATION.—It is of obvious importance that any equipment used during a surgical procedure must be sterilized. Experience has indicated that assembly of the pump-oxygenator, and its sterilization by filling it with a sterilizing agent, are not completely satisfactory. The packaging and sterilization of the individual pieces of the disassembled apparatus by standard surgical techniques and their assembly under sterile precautions just before the operation have been found by us to be an ideal method of achieving asepsis. The pump-oxygenator should be constructed so that this is possible.

HEAT LOSS.—During the extracorporeal circulation of blood, there is opportunity for continued loss of heat from the blood to the cooler room atmosphere. Although the body temperature of the subject can be fairly well maintained by external heating of the body, the temperature of the arterial blood may be from 3° to 6° C. cooler than the subject when it leaves the pump-oxygenator unless special precautions are taken against this loss. Thermal gradients have profound effects, among other things, on gaseous tensions in blood.

Some method for preventing heat loss from blood during its extracorporeal circulation must then be a part of a pump-oxygenator.

EMBOLISM.—Neither particulate matter nor air must be present in the arterial blood as it enters the patient.

ESTABLISHMENT OF PROPER INTRACARDIAC EXPOSURE

Experience has satisfied us that precise surgical procedures within the ventricles are not regularly possible in the beating heart. In just 80% of cases of ventricular septal defect in which repair was made in the beating heart the repair was adjudged to be complete at post-operative evalua-

tion. Subsequent experience with similar operations in the heart, quieted by the Melrose technique, has indicated that complete repairs are now always possible with this technique. Design of apparatus and conduct of the operation must therefore be such that induced cardiac arrest can be safely employed.

It is our experience that with a proper technique the heart can be arrested by potassium for periods up to 40 minutes without a demonstrable increase in risk to the patient. We believe that it is essential in this technique that there should be an excellent perfusion when the aortic clamp is released or else difficulty may be encountered in the prompt re-establishment of an effective cardiac action.

Even with the aorta cross-clamped and the heart arrested, there may be a considerable flow of blood into the cardiac chambers during cardiotomy. This presumably is blood entering pulmonary vessels from bronchial arteries and then flowing back into the heart. If this blood is aspirated and discarded, it may result in excessive loss of blood during some operations. It appears wise to incorporate within the pump-oxygenator a method for collecting and handling this intracardiac blood so that it may be admitted again to the general circulation.

GIBBON-TYPE PUMP-OXYGENATOR

On the basis of the previously enumerated theoretical considerations, each individual group must reach a decision as to the type of pump-oxygenator that is to be employed. Although we have worked at times with other types of apparatus in the laboratory, most of our laboratory experience and our entire clinical experience have been with a slightly modified Gibbon-type pump-oxygenator. We have been unable to find equipment superior to it, and believe that it possesses certain distinctive features rendering it a superb clinical tool.

The apparatus has previously been described by us in detail. Certain modifications have subsequently been incorporated, but basic design remains unaltered. It is of interest to point out certain features of this apparatus.

1. The size of the oxygenator is adjusted in each case so as to be proper for the patient's size. For perfusion of a child with 0.4 square metre of surface area, for example, six screens are loaded into the oxygenator, and for one of 0.9 square metre, 11 screens. For an adult of 1.6 square metres, 14 screens are employed. Oxygenators that are not so flexible must be either too large,

and potentially dangerous, for small subjects; or too small to allow proper oxygenation in large subjects.

2. The partial pressure of gases within the oxygenator can be regulated precisely.

3. The volume of blood within the pump-oxygenator is maintained constant by the interaction of two level-sensing devices, and the occluder mechanism between the recirculation and venous lines. This feature of the flow circuit of the original Gibbon-type pump-oxygenator serves admirably the purpose for which it is designed. Whatever mechanism for achieving it is employed, it would seem that a truly satisfactory pump-oxygenator should be a constant-volume one. In this way, the maintenance of a constant volume of blood in the patient during the operation is greatly facilitated.

4. The output of arterial blood is determined by, and at all times is equal to, the return of venous blood from subject to machine. At first glance it might seem that regulation of total flow by the venous return is fundamentally different than pre-setting the artery pump to a certain flow rate. This is probably not so. There is, however, an immense safety factor to the regulation of total flow by venous return which renders it in our opinion the desirable way of accomplishing this.

5. Design and construction are such that blood trauma is minimal. This is essential if one anticipates whole-body perfusion at flow rates that approximate cardiac output. Abnormal bleeding following operations in which this apparatus is used does not occur.

6. The automatic devices within the machine allow it to be operated by two technicians, working during the perfusion under the supervision of the anaesthetist. Two individuals, the surgeon and the anaesthetist, are the only full-time professional staff employed during these operations. Two surgical assistants (who are men in training), two surgical nurses, and a nurse anaesthetist comprise the remainder of the surgical team. It is believed that maximal economy can be practised by using this type of equipment which minimizes the number of professional staff required during operation.

THE CONDUCT OF WHOLE-BODY PERFUSION FOR INTRACARDIAC OPERATIONS

In previous publications by our group, the surgical technique for establishing whole-body perfusion and the management of the patient before, during, and after the perfusion have been described. Certain principles can be repeated.

1. For reasons enumerated earlier, it is our practice to perfuse patients at flow rates of 2.2 to 2.5 litres per minute per square metre of body surface. It is to our mind clear that this is desirable if maximal safety is to be achieved.

2. Large and properly placed venous cannulas are essential, lest high venous pressures be present in the subject during perfusion at these flow rates. A large arterial cannula is likewise essential.

3. Careful attention is given to the maintenance of an approximately normal volume of blood in the subject. Particular care is given to prevent hypervolaemia.

4. Maintenance of the temperature of the subject and the blood at normal values is sought.

SUMMARY

The maintenance of life by whole-body perfusion for one hour, during which time open intracardiac operation is performed, can be accomplished at a very low risk, provided all details are properly managed. While sporadically satisfactory results can be obtained otherwise, uniformly excellent results demand a thorough knowledge of the myriad of factors affecting the adequacy of the procedure, a carefully trained team, and proper equipment.