# RECENT ADVANCES IN CARDIAC SURGERY *

## I. DIRECT VISION INTRA-CARDIAC SURGERY

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The dramatic advances made in cardiac surgery during the last decade represent one of the outstanding breakthroughs in the history of medicine. This almost phenomenal rate of progress has been accompanied by a wealth of literature in which all aspects of both the experimental and clinical experience have been profusely documented. It is the purpose of this review to attempt a summary of these recent advances, with particular emphasis on intra-cardiac surgery.

### HISTORICAL

The first successful mitral valvotomy was performed by Henry Souttar in 1925 using the same finger fracture method used today. Despite the success of the operation, no further cases were referred to him for surgery. It was not till 1939 that a major step forward in the treatment of congenital heart disease was made when Gross (Gross and Hubbard, 1939) successfully performed the first ligation of a patent ductus. In 1945, Gross in Boston (Gross and Hufnagel, 1945) and Craaford in Sweden (Craaford and Nylin, 1945) almost simultaneously reported the treatment of coarctation of the aorta by resection and end-to-end anastomosis. In the same year, Blalock, and Taussig (1945), described the effective palliation of Fallot's tetralogy by subclavian artery-pulmonary artery anastomosis, an operation which was to bring relief to countless numbers of 'blue' children. It was not till 1948 that mitral valvotomy for mitral stenosis was reintroduced by Bailey, (1949), Harken (Harken et al, 1948) and Brock (Baker et al, 1950), and in the same year, Brock (1948) introduced the operation of pulmonary valvotomy for isolated pulmonary stenosis and also for Fallot's tetralogy.

Since 1934, however, John Gibbon in Philadelphia (Gibbon, 1937), who may well be called the 'Father of Open-Heart Surgery' had been working on an artificial heart-lung machine which would take over the functions of the heart and lungs, and so permit the performance of intracardiac surgery. It was not till almost 20 years later, in 1953, that total cardiopulmonary bypass was successfully applied clinically in the open repair of a secundum type of atrial septal defect. Fittingly, the honour fell to John Gibbon himself.

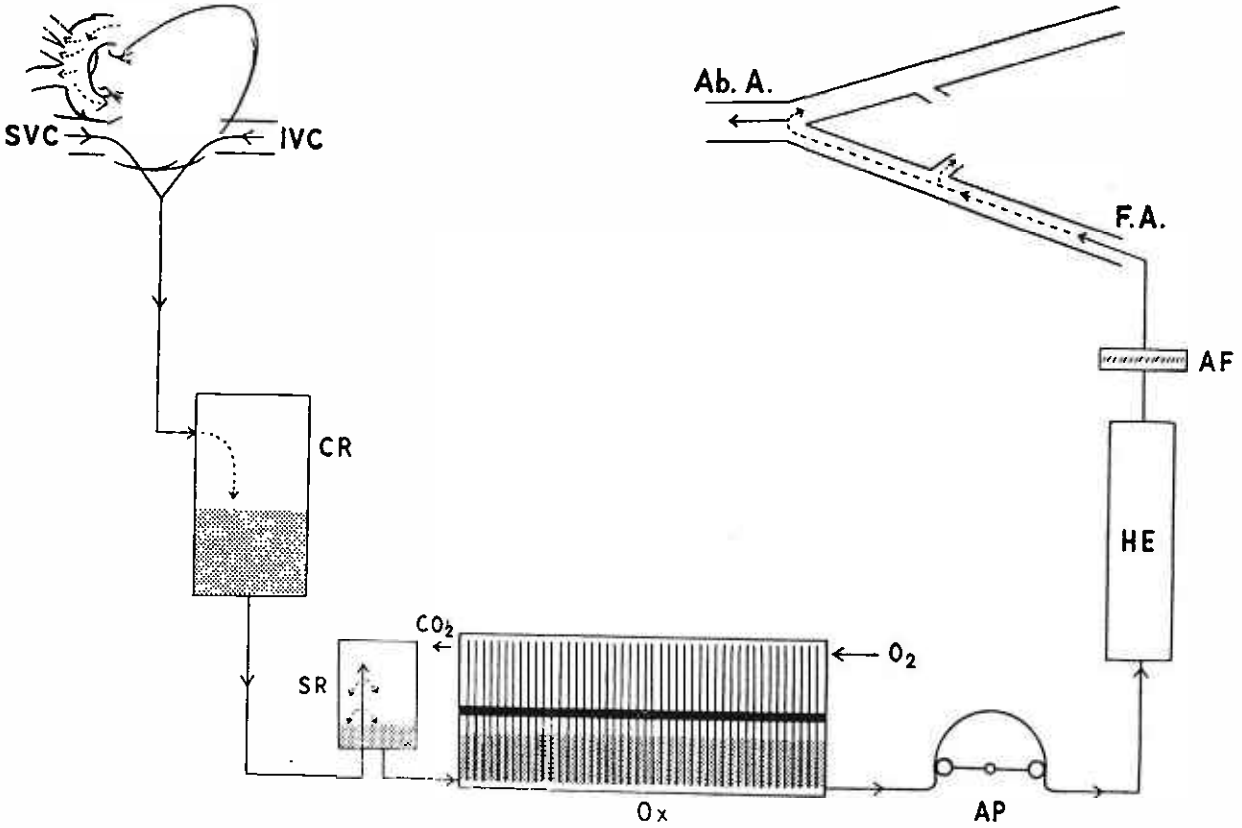
An alternative technique, hypothermic open-heart surgery, was being developed concurrently. Bigelow's fundamental work on hypothermia (Bigelow et al, 1950) paved the way for the first successful clinical application of this technique by F.J. Lewis (Lewis and Taufic, 1953) and H. Swan (Swan et al, 1953). For a short period during the developmental phase of cardiopulmonary bypass techniques, hypothermic cardiac surgery enjoyed widespread popularity, justified by the favourable results reported. Its inherent disadvantages resulted though in its gradual obsolescence as safe techniques of cardiopulmonary bypass became rapidly established.

### EXTRACORPOREAL CIRCULATION

The term "extracorporeal circulation" is a general term for a system employing a circulation outside the body (Allen, 1957). "Cardiopulmonary bypass" refers to the condition existing when the patient's heart and lungs are bypassed and the circulation is maintained by artificial heart and lungs. "Pump-oxygenator" is a synonym for 'heart-lung machine', a general term referring to a system of mechanical devices consisting of pumps and gas exchangers which substitute for the patient's heart and lungs in the extracorporeal circuit. "Perfusion" is a general term referring to the flow of blood through the patient's circulation. (Galletti & Brecher, 1962).

The basis of cardiopulmonary bypass lies in the complete diversion of the vena caval blood from its normal return into the right atrium into the pump-oxygenator system where the appropriate gas exchange takes place. It is then returned to the patient's cir-

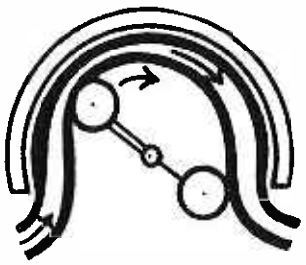
* Based on an address to the Singapore Cardiac Society, November, 1963.




PUMP-OXYGENATOR SYSTEM

CR = Collecting Reservoir
SR = Settling Reservoir
Ox = Oxygenator (Rotating disc)
AP = Arterial pump
HE = Heat-exchanger
AF = Arterial Filter
FA = Femoral Artery
Ab. A = Abdominal Aorta

Fig. 1.



**Roller Pump**

Fig. 2.

**Finger Pump (Sigmamotor)**

Fig. 3.

culation through a cannula inserted into a systemic artery. (Fig. 1). The heart is thus empty, (except for the coronary venous return into the right atrium), and the appropriate cardiotomy may then be made for direct vision repair.

## PUMP-OXYGENATOR DESIGN

The pump-oxygenator basically consists of one or two pumps (the artificial heart) and a mechanical oxygenator. A heat-exchanger, an arterial filter, one or two venous reservoirs, and the various connecting plastic tubing complete the extra-corporeal circuit. Caval blood is initially received into a collecting reservoir, caval drainage being effected usually by the simple method of gravity-siphonage. A settling reservoir is interposed between the collecting reservoir and the oxygenator to allow foam and bubbles to settle out. At the arterial end of the oxygenator, oxygenated blood is led through plastic tubing to the pump which provides the propulsive force for the onward passage of the blood, through the heat exchanger and arterial filter back into the patient's arterial circulation via a cannula in the femoral or subclavian artery. (Fig.1).

The two basic requirements of a pump are (1) it should be capable of a continuously variable output up to 5 litres/min against pressures up to 300 mm Hg.; and (2) minimal blood trauma. The latter is achieved by preventing blood from coming into contact with the movable parts of the pump mechanism. Two types of pumps in popular use today are (1) the roller pump (DeBakey), a rotary pump, consisting of a pair of steel rollers, diametrically mounted on a revolving arm (Fig. 2); the rollers compress the plastic tube against a semi-cicular rigid housing; (2) the finger pump (Sigmamotor pump) which depends for its propulsive action on the serial compression of a plastic or rubber tube against a metal plate by a row of steel fingers. (Fig. 3). The roller pump causes less blood damage and is much more widely used.

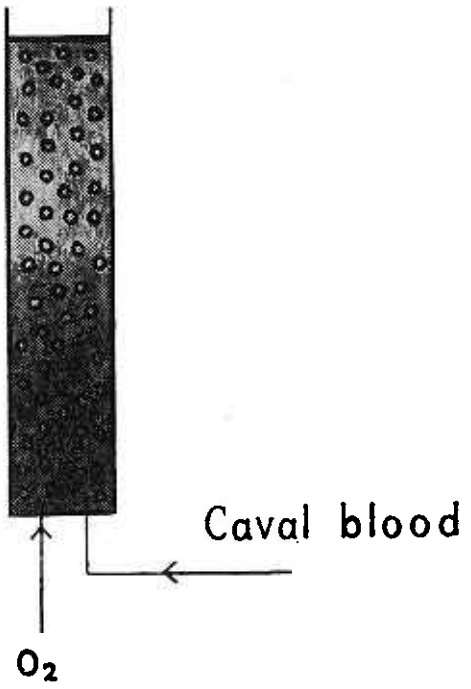
## OXYGENATORS

There are three basic types:

1. *Bubbler Oxygenators: (Fig. 4)*

   The oxygenation of blood by the passage of a stream of fine bubbles of oxygen through a column of blood is a simple method, and was popularised by the work of DeWall and associates (1956). In its simplest form, the bubbler oxygenator consists of a vertically-mounted four-inch diameter plastic tube, into the bottom of which both venous blood and oxygen bubbles, are introduced. The foam produced is carried upwards with the oxygen bubbles and at the upper-end spills over into an inclined tube of similar diameter (the debubbling chamber) in which debubbling takes place. Blood then passes into the top end of a spirally-arranged plastic tube in which further debubbling takes place, and which also serves as a reservoir. The major disadvantages of this simple oxygenator lie in its inability to achieve high flow rates due to the limitation of its ability to remove excess gas bubbles, and in the tendency to cause greater trauma to the blood.

   One of the most successful variants on this simple design was originally devised by Gott and associates (1957), and now very extensively used (Cooley et al, 1962). The oxygenating, debubbling and spiral reservoir channels are heat-



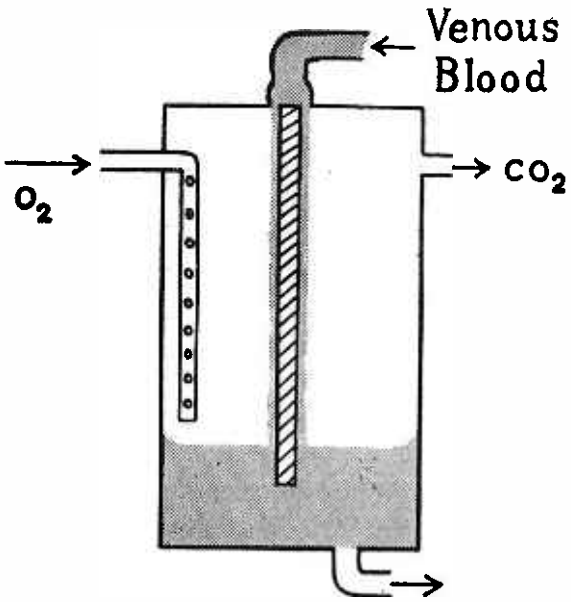

**Bubbler oxygenator**

Fig. 4.

sealed between two layers of heavy plastic sheets, and the entire system is available commercially,* sterilised ready for use as a disposable oxygenator.

2. *Film Oxygenators:*

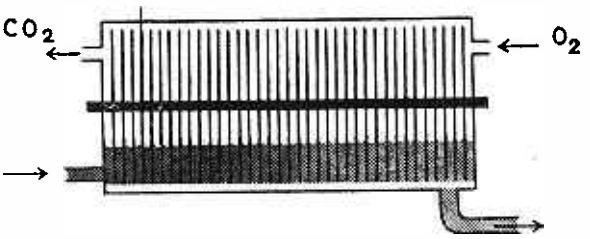
*a)* Vertical Stationary Screen. (Fig. 5). Initially developed by John Gibbon, this oxygenator consists of a battery of vertical screens, made of stainless steel mesh or plastic sheets, mounted within a plastic oxygenating case. The thin films of blood on the screens are progressively oxygenated as they flow downwards. This is a particularly efficient oxygenator, with excellent blood-handling properties, and of a design which facilitates the incorporation of a high degree of automatic control. Difficulties in cleaning and sterilisation, its high priming volume and extremely high cost have prevented it from being widely adopted.




Vertical Screen Oxygenator (Gibbon)

Fig. 5.

*b)* Rotating Disc (Fig. 6). An alternative method of filming blood is achieved by revolving circular stainless steel discs which are partially immersed in a pool of blood. In practice, this is effected by mounting th discs on a central shaft which rotates in a glass cylinder along the floor of which blood flows in a steady stream from the venous to the arterial end. Originated by Bjork in Sweden (1948), it was subsequently improved by Melrose and Aird (1953), Kay and Cross (1957), and Gross (1960). The efforts of the American workers in particular have resulted in widespread recognition of the value of this design and several commercial models are now available. It has proved to be a safe and efficient oxygenator, capable of near-optimum flow rates, and is the most widely used type of oxygenator.




Rotating Disc Oxygenator

Fig. 6.

3. *Membrane Oxygenators:*

In this, the theoretically ideal type of oxygenator, blood and gas are separated by a semi-permeable membrane. No direct contact between the two occurs, therefore eliminating one major source of gas embolism and blood trauma. Gas exchange is effected by a process of molecular diffusion. It is undoubtedly the artificial lung of the future, but difficulties in assembly, high cost of the disposable membranes, and difficulties in developing a membrane with more suitable properties are amongst the chief drawbacks.

## BASIC PROBLEMS

### I. Trauma

Trauma to blood elements represented for a long time the greatest difficulty in pump-oxygenator design. Complete

* Travenol Laboratories.

elimination of blood trauma is impossible, but it has been successfully minimised by the use of stainless steel with mirror-finish surfaces for all metal parts, highly-polished glassware, high-grade plastic tubing and silicone coating of all metal and glass surfaces, and by scrupulous attention to the prevention of eddy currents and swirling. Overt trauma as indicated by destruction of cellular elements has by this means been reduced to acceptable levels.

Occult trauma, however, may be more significant than hitherto realised, and may be manifest by such phenomena as protein denaturation (Lee et al 1961), and hidden coagulation defects. Certainly, the sequelae of "sludging" in the microcirculation (Lee et al, 1961), prolonged continued oozing from bleeding points despite normal clotting times, the unexplained morta ity associated with prolonged perfusion, and the development of increased pulmonary vascular resistance (Spencer et al, 1963) in the immediate post-operative period cannot be accounted for in terms of overt trauma.

## II. Control of Clotting

Despite the use of highly-polished surfaces and adequate siliconisation anticoagulation is required. Donor blood used for filling the extra-corporeal circuit is usually collected on the morning of the day of operation and anti-coagulated with heparin in a dose of 25 mgm (2,500 I.U.) heparin per 500 ml. Heparinisation of the patient is instituted immediately before cardiopulmonary bypass in a dose of 2—3 mgm./Kg. body weight. Adequate heparinisation is essential as inadequate dosage leads to intravascular clotting and excessive consumption of fibrinogen, resulting in severe post-operative coagulation defects.

Neutralisation of heparin at the termination of bypass is achieved by the administration of protamine sulphate, in a dose $1\frac{1}{2}$-4 times the heparinising dose. A more refined method of calculating the dose of protamine sulphate is based on heparin-titration studies (Rothnie and Kinmonth, 1960).

## III. Gas Exchange

Gas exchange in all three types of oxygenators is adequate. In all oxygenators, the blood film is much thicker than in the pulmonary capillaries, resulting in a slower rate of diffusion of oxygen through the blood film. This is offset by prolongation of contact time, by making the blood film as thin as possible and by increasing the partial pressure of oxygen. All oxygenators are ventilated with a mixture of 3-4% $CO_2$ in oxygen.

Carbon dioxide elimination presents less of a problem as the permeation of $CO_2$ through blood is much faster than oxygen. In practice, the use of 100% oxygen results in excessive removal of carbon dioxide. The use of 3-4% $CO_2$ in oxygen, however, avoids undue disturbances of the acid-base balance from respiratory causes.

High partial pressures of oxygen in the arterialised blood appear to be undesirable. Partial pressures up to 300 mm Hg. are especially liable to occur in rotating disc oxygenators. A much greater degree of control of oxygen partial pressures is possible in the vertical screen oxygenators. The high partial pressure of oxygen may result in the release of gas bubbles at the point where the artificially oxygenated blood is infused into the arterial circulation. There is a further danger in the possibility of oxygen intoxication, a vague clinical syndrome, the definition of which, in terms of neurological sequelae, and pulmonary parenchymal and vascular changes is still the subject of continuing investigation (Spencer et al, 1963).

## PUMP PRIME

The term 'pump prime' refers to the fluid used for filling the entire pump-oxygenator system. Various types of pump prime are in use today. Heparinised whole blood, freshly collected was the obvious first choice. As 2.5-3.5 litres are required to fill each pump oxy-

genator, regardless of the type, this represents a severe strain on blood bank facilities. When the blood volumes required during and after operation are also taken into account, each "pump" case requires a total of 15 to 17 pints of blood.

Sufficient experimental and clinical evidence are now available (Zuhdi et al, 1961; Paton, 1963; Roe et al, 1964) which convincingly show that whole blood is not as satisfactory a perfusate as mixtures of blood and other fluids such as 5% dextrose in water, Ringer's solution, low molecular weight dextran, etc. The proportion of non-blood fluid to blood varies from 1:2 to 1:1.

Apart from the conservation in blood, this results in moderate haemodilution, thus reducing viscosity and resulting in better perfusion flow rates. Clotting problems appear to have been reduced by the use of haemodilution techniques. In bubbler oxygenators, where low flow rates are utilised, either dextrose in water or low molecular weight dextran may be used alone (Zuhdi et al, 1961; Cooley et al, 1962). Rotating disc and vertical screen oxygenator require much higher priming volumes, and are usually primed with the mixture of blood and dextrose referred to. The type of non-blood fluid used appears to be less important than the perfusion technique, judging by the equally favourable results obtained by various workers. A recent report (Neville et al, 1964), however, indicates that total non-blood prime for disc oxygenators can be successfully used for human cardiopulmonary bypass.

Although freshly collected heparinised blood is preferred for priming purposes, it is possible to use ordinary citrated bank blood. This is converted to heparinised blood by adding calcium and heparin.

## CARDIOPULMONARY BYPASS

A brief description of techniques of cardiopulmonary bypass may be of interest.

General anaesthesia is employed, the patient being kept quite lightly anaesthetised and well curarised. Incisions used vary, the most popular and most useful being the vertical midline sternum-splitting incision. For procedures involving the right heart or left heart alone, an antero-lateral thoracotomy on the same side may be preferred.

For total cardiopulmonary bypass, the vena cavae are individually cannulated through the right atrium. Arterial input is usually made through a cannula in the femoral artery or external iliac artery. Alternatively, the left subclavian, or even the ascending aorta may be used in children.

When total cardiopulmonary bypass is required, snares are placed around the cavae and tightened over the cannulae, thus diverting all caval blood into the oxygenator. All operations on the right heart require cannulation of both cavae. For left heart operations, *e.g.*, mitral or aortic valve procedures, a single catheter in the right atrium or ventricle permits adequate venous drainage, which may be made complete by clamping the pulmonary artery.

Although ideally flow rates should approximate the normal cardiac output of 3-4 litres/min/sq. m. body surface area, lower flows of 2.0-2.4 litres/min/sq. meter body surface area have been found satisfactory. Flow rates of 20-50 ml./kg. body weight are used with bubble oxygenators (Cooley et al, 1962; Zuhdi et al, 1961). The very low flow rates are used in association with moderate hypothermia, which by reducing the metabolic rate, diminishes the tendency to metabolic acidosis, an inherent disadvantage of low flow perfusions.

## HYPOTHERMIA

Hypothermic open-heart surgery, employing complete inflow occlusion by clamping off the vena cavae, was developed at the same time as pump-oxygenator techniques. A body temperature of 30°C reduces oxygen requirements to 50% and permits safe prolongation of the period of complete circulatory arrest. A safe maximal period of 6-7 minutes allows the surgical closure of secundum atrial septal defects, and pulmonary valvotomy. Hypothermia is effected by surface cooling with ice-packs, or more effectively by the immersion of the anaesthetised patient in a bath of ice water.

The method itself is simple and inexpensive, and the surgical techniques involved are correspondingly simpler. Complete circulatory arrest under hypothermia, however, carries with it grave disadvantages and risks. While anoxia is reduced it is not completely abolished, resulting in a definite metabolic acidosis. The

risk of ventricular fibrillation, the extremely limited period of circulatory arrest, and disturbances of the coagulation mechanism are distinct and serious disadvantages. With the development of safe cardiopulmonary bypass techniques, hypothermia as the sole supportive measure in open-heart surgery has rapidly fallen into disuse.

The combination of hypothermia and cardiopulmonary bypass however utilises the advantages of both techniques. It allows the use of lower flow rates, thus further minimising the extent of blood damage, and providing additional protection for the myocardium and brain against anoxia. Hypothermic cardiac arrest at 20°C is utilised for operative proceddures on the mitral or aortic valve. The quiet heart facilitates visualisation of the intracardiac lesion and minimises the danger of air embolism, a complication always to be feared when the left heart is opened.

Mention should be made of the technique of complete circulatory arrest at deep hypothermic levels of 15°-17°C, as practised by Drew and Anderson (1959). Hypothermia is produced during total cardiac bypass by passing the blood through a heat exchanger. This method has proved very effective in the hands of the originators. However, the report by Bjork (1961) and other workers of residual neurologieal sequelae after profound hypothermia has prevented its wide acceptance.

## CARDIAC ARREST

Intracardiac surgical procedures are hampered when the empty heart continues to beat. In the early stages, deliberate cardiac arrest was induced by injecting acetyl-choline (Lam et al, 1957) or potassium citrate (Melrose et al, 1955) into the coronary circulation. Reports of refractory cases of cardiac arrest cardiac failure and microscopic myocardial damage, following chemically-induced cardiac arrest led to the discontinuance of these techniques. Two other techniques of inducing cardiac arrest are available, and are in use at the moment. Anoxic cardiac arrest for a limited period has proved quite safe in some hands (Cooley 1963) although others feel uneasy about its use, especially in severely hypertrophied hearts. Hypothermic cardiac arrest, however, at temperatures down to 20 C, especially when used in conjunction with individual coronary arterial perfusion, has been found to be the safest method. More recently, great interest is being shown in deliberately induced ventricular fibrillation, using a small electrical fibrillator, and employing voltages under 100 v. (Roe, 1962; Glenn et al, 1960; Levy & Lillehei, 1963).

## CORONARY PERFUSION

Surgery of the aortic valve under direct vision necessitates incision of the ascending aorta after it has been clamped off just proximal to the innominate branch. This perforce excludes the coronary circulation from perfusion. Hypertrophied myocardium tolerates anoxia poorly, even when the metabolic demands have been reduced by hypothermia. This was one of the major factors responsible for the high mortality in the early days of aortic valvular surgery. More adequate protection of the myocardium, in addition to hypothermia, was clearly necessary and led to the development of individual coronary perfusion. For this purpose, each coronary is individually cannulated with suitably designed metal or plastic cannula and the coronary circulation is perfused, either with a separate, low-flow pump, or from the main arterial line of the pump-oxygenator via a T-junction. Coronary perfusion is usually combined with moderate hypothermia, thereby increasing the protective effect on the myocardium. The ensuing results have proved very gratifying.

## MONITORING

In the early stages of open-heart surgery, the monitoring of numerous parameters both during and after operation was a standard practice. The electro-cardiogram, electro-encephalogram, systemic arterial and central venous pressures, arterial and venous oxygenation saturations, blood pH, plasma haemoglobin, serum electrolytes, and perfusion flow rates were all determined either intermittently or continuously throughout perfusion. With increasing clinical experience and better understanding of the haemodynamics and physiology of perfusion, operative monitoring has been greatly simplified. Direct observation of the cardiac activity has to a great extent supplanted the ECG; recognition that adequate flow rate is of more importance than the arterial pressure has reduced the significance of monitoring arterial pressure and the electroencephalogram;

repeated observations of pump-oxygenator performance both in the laboratory and in the operating room have led to confidence in its efficiency under a well-defined range or conditions, abolishing the need for monitoring of arterial and venous oxygen saturations, and plasma haemoglobin levels.

In centres with considerable experience in perfusion techniques, central venous pressure and perfusion flow rate are the only two parameters constantly monitored. Occasional checks on the arterial pressure, blood pH and the ECG complete the monitoring.

Post-operatively, the tendency towards simplification continues. The central venous pressure and the balance between blood loss and replacement and blood pH constitute the most important parameters to be watched. Arterial pressure is checked intermittently. The rate of urine output provides a simple clinical guide to progress. In patients with respiratory insufficiency, however, arterial pH, $pCO_2$, oxygen saturations, bicarbonate reserve are closely followed.

The use of intermittent positive pressure respiration with the aid of mechanical respirators has been an important factor in the improvement of results in patients with respiratory insufficiency, severe pre-and post-operative pulmonary hypertension, and cardiac failure following cardiopulmonary bypass. It has in fact proved life-saving.

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