Recent advances in cardiopulmonary bypass techniques

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Key points

Cardiac surgery with cardiopulmonary bypass (CPB) frequently produces a systemic inflammatory response syndrome.

The use of biocompatible coatings has been demonstrated to reduce these unwanted effects of bypass.

Minimal extracorporeal circulation can reduce morbidity associated with on-pump cardiac surgery.

Centrifugal pumps reduce damage to red blood cells, platelets, and plasma proteins, in comparison with conventional roller pumps.

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Cardiopulmonary bypass (CPB) allows cardiac surgery to be performed in a motionless, bloodless surgical field. It incorporates an extracorporeal circuit to provide physiological support. Typically, blood is gravity drained from the heart and lungs to a reservoir via venous cannulation and tubing, and returned oxygenated to the arterial system by utilizing a pump and artificial lung (oxygenator or gas exchanger).

In the last 20 yr, improvements in CPB have occurred rapidly due to advances in biomaterials, manufacturing, computer microsystem technology, and electronics.

Complications of CPB

CPB has been implicated in significant morbidity after cardiac surgery. This mainly results because of contact between blood and the vast array of foreign surfaces incorporated into the CPB circuit (including the blood–air interface), and friction damage produced when blood is propelled by the pump. In addition, the suction pumps that recycle shed blood from the mediastinum and thoracic cavities further traumatize blood and allow retransfusion of unwanted byproducts of surgery, such as fat, aggregated platelet, and leucocyte microparticles (Table 1).

Examination of the adverse consequences has led to changes in CPB technology, pharmacological advances, and perfusion techniques.

Centrifugal pump

The roller pump is still the most commonly used blood propulsion device. However, this is known to cause damage to blood elements as a result of the intermittent mechanical shearing caused by the occlusion of the tubing by the pump. This may lead to haemolysis and release of vasoactive substances. Roller compression of PVC or silicone tubing can produce spallation, a breakdown in the tubing wall, and risk of particulate embolism.

The centrifugal pump was developed to eliminate intermittent tubing occlusion. It consists of a vaned impeller or a nest of smooth plastic cones within a plastic casing. These impellers or cones are magnetically coupled (at the base) with an electric motor and, when rotated rapidly, generate a vortex, sucking blood into the pump. As the blood enters the spinning pump, positive pressure is generated by centrifugal force imparting kinetic energy, and blood is expelled from the outlet towards the patient.

There is some evidence that the use of centrifugal pumps reduces damage to red blood cells, platelets, and plasma proteins, when compared with conventional roller pumps.[1] This has led to considerable uptake into clinical practice, particularly during prolonged surgery. Translation of these findings into improved outcome, however, has not yet been proved.

Unlike roller pumps, centrifugal pumps are totally non-occlusive; fluid can flow within the pump itself in either direction. Therefore, the arterial line must be clamped at any time during use when the pump is not running. Centrifugal pumps are also pre- and after-load dependent. Any significant change in resistance/pressure at the outlet or inlet of the pump will alter blood flow rate. The non-occlusive feature of the pump design prevents generation of excessive pressure in the extracorporeal circuit, thus preventing circuit rupture.

Surface-coated circuit

Contact between blood and the foreign surface of the material within the CPB circuit induces

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Table 1 Complications of CPB

Adverse effect	Solutions	Advantages
Haemodilution, blood tranfusion	Minimize circuit and prime volume. Incorporate haemofilter to remove water from blood. Mini bypass. Retrograde autologous prime	Maintenance of safe haematocrit and reduction of homologous blood use
Consumption of coagulation factors	Heparin and phosphorylcholine coating	Reduced inflammatory mediators release. Improved post-CPB platelet count. Reduced blood loss
Roller pump-induced haemolysis	Centrifugal pump	Less haemolysis in longer cases
Fat embolization	Avoid cardiotomy suction. Cell salvage	Improved postoperative neurological outcome
Activation of leucocytes, increase in complement and cytokines	Leucocyte filter. Ultrafiltration	Reduced inflammatory response
Polypropylene microporous membrane wets out after 5 h	True membrane technology developed	Reduced need for exchange of oxygenator during ECMO
Poor control of acid–base balance and oxygenation	Continuous in line blood gas and electrolyte monitoring	Rapid intervention and alteration of oxygen therapy, CO_2 removal and pH balance
Uncontrolled blood loss	Cell salvage	Reduced blood transfusion
Micro and macro air embolism	Use safety devices, automatic clamps, and vented blood filters	Reduction of neurological injury

activation of the complement, kinin, fibrinolytic, and coagulation cascades. It also causes neutrophil activation and aggregation, promoting an inflammatory response. This can cause clinical problems such as bleeding diatheses, systemic inflammatory response syndrome, and multi-organ dysfunction. The use of biocompatible coatings has been demonstrated to reduce these unwanted effects of bypass, thereby reducing platelet activation and ameliorating postoperative bleeding.[2, 3]

Heparin-coated circuit

Coating the internal CPB circuit with surface-bound heparin reduces the inflammatory response. Heparin coating modulates the neutrophil–endothelial interface making it more biocompatible. The heparinized surface also renders the CPB circuits hydrophilic and protein resistant, and augments lipoprotein binding. Heparin-coated circuits have also been shown to decrease the alveolar–arterial ($P_{A_{O_2}}$–$P_{a_{O_2}}$) gradient, decrease pulmonary vascular resistance, and increase static lung compliance, a result of the reduced release of toxic mediators by leucocytes and endothelial cells. These substances exert a well-known damaging effect on the alveolar-capillary membrane, increasing the extravascular lung water content and the intra-alveolar protein and cell contents. This beneficial effect has only been demonstrated at the end of surgery and has not been shown to reduce time to tracheal extubation or length of stay in the intensive care unit.

The major advantage, however, of heparin coating is the enhanced thromboresistance that allows a lower level of systemic anticoagulation to be used (by reducing the total dose of heparin required). This may lead to reduced postoperative bleeding and blood transfusion. This beneficial effect is particularly marked when heparin circuit coating is used for extracorporeal membrane oxygenation (ECMO) in intensive care, which is in effect prolonged CPB.

Phosphorylcholine-coated circuit

The characteristic feature of biological membranes is their functional and compositional lipid asymmetry. Negatively charged phospholipids are found predominantly on the inner cytoplasmic side of the membrane, whereas the neutral zwitter-ionic phosphorylcholine-containing antithrombotic lipids predominate in the outer membrane. This membrane asymmetry plays a part in the maintenance of the delicate balance between haemostasis and thrombosis. Phosphorylcholine coating of the CPB circuit aims to mimic the natural cell membrane, reducing the interaction between plasma proteins and the inner surface. The only benefit that has been shown so far is a reduction in platelet activation and postoperative blood loss.[4]

Oxygenator

The membrane oxygenator is now used most frequently, and has replaced the disc and bubble types. It permits gas exchange with blood through a membrane that decreases the blood trauma of direct-contact oxygenators. Gas transfer is either by transmembrane diffusion or via micropores (0.1 μm diameter) produced by stretching polypropylene. The membrane can take the form of flat sheets (100–150 μm thick) or hollow fibres (100–200 μm ID). Hollow-fibre oxygenators allow high surface area to blood volume ratios and mainly consist of microporous polypropylene or polymethylpentene material.

The blood flows over the fibres while gas passes through them. Eddies induced in the blood continually bring more red cells to the gas exchange surface. The oxygen/air mixture chosen by adjusting the gas blender is used to regulate the partial pressure of oxygen, and fresh gas flow that is set determines the partial pressure of carbon dioxide. As the fresh gas flow is reduced, less carbon dioxide is washed out and the partial pressure in the blood increases.

The membrane oxygenator imposes a significant resistance to blood flow; therefore, it must be placed after the blood pump. During use, the microporous membranes quickly accumulate a proteinaceous coating decreasing the area of direct blood–gas interface.

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Heparin-coated oxygenator

Heparin coating within the oxygenator has been developed to mimic the natural endothelial lining of the vasculature. Studies have shown improved overall biocompatibility, with reduced adhesion of plasma proteins and prevention of denaturation and cellular activation. This leads to a higher postoperative platelet count and reduced lung atelectasis.[5] This does not translate into a reduced time to tracheal extubation or intensive care stay.

Minimal extracorporeal circulation

The concept of mini-bypass aims to combine significantly reduced circuit prime volume with suction blood separation (Fig. 1). Theoretically, this may lead to reduced haemodilution, improved homeostasis, and a reduction in morbidity after on-pump cardiac surgery.[6] The mini-bypass system includes an integrated venous bubble trap, centrifugal pump, heat exchanger, and oxygenator and is designed for use with an autotransfusion/cell saving system for sequestration of aspiration blood.

Major differences from conventional CPB include the lack of a reservoir and cardiotomy suction; this leads to significantly reduced tubing length and decreased priming volume (from ~1800 down to 600 ml). Minimal extracorporeal circulation (MECC) is a closed circuit and involves little or no blood–air contact. In addition, cell salvage of suctioned blood avoids direct reinfusion of air-activated blood that may also be contaminated with tissue debris and lipids. Although studies have failed to show a difference in outcome, there is some evidence of reduced postoperative bleeding and blood transfusion, probably as a result of the reduced haemodilution and coagulation cascade activation. There is also some evidence of decreased cerebral microembolization and improved postoperative renal function.[7]

The use of mini-bypass requires considerable changes in surgical practice. Coronary anastomotic suturing may be more difficult due to persistent coronary artery back bleeding. This is because the heart cannot be completely emptied without the use of a vent. In addition, there is increased risk of gas embolism resulting from venous air intake (which would normally be safely managed by the reservoir, absent in MECC). Particular care is required with placement of the venous drainage cannula. MECC has only been studied in coronary surgery, because of these limitations.

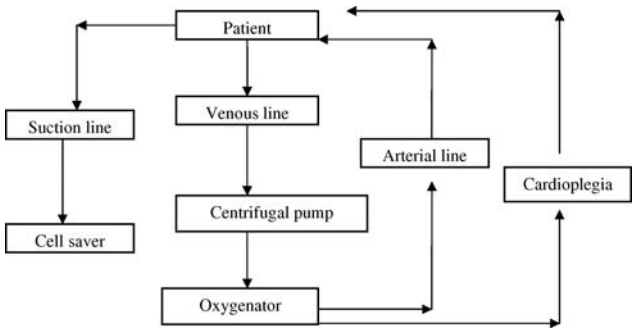

Fig 1 Schematic representation of minimal extracorporeal circulation—mini bypass.

Cell salvage

Intraoperative autologous red cell salvage during CPB is an attractive alternative to cardiotomy suction. The cell saver separates red cells from plasma and debris by washing and differential centrifugation, providing a high concentration of red blood cells and little or no contaminant. When the blood is aspirated from the pericardium, heparin is delivered at an appropriate rate to the tip of the suction cannula to minimize activation of coagulation. The salvaged blood is then stored in a reservoir containing additional heparinized saline before processing. During processing, the red cells are retained in the bowl whereas the plasma, platelets, heparin, free haemoglobin, and inflammatory mediators are discarded with the wash solution. This process may be discontinuous or continuous, and the resulting red cells are finally resuspended at a haematocrit of 50–70% in normal saline, and reinfused. It allows the conservation of red blood cells while reducing the retransfusion of fat microemboli, activated coagulation, and inflammatory markers. Fat microembolic load is decreased by the cell saver by as much as 85%.[8] The process of cell salvage results in the activation of white blood cells leading to the release of inflammatory mediators (IL-6, C5a, C3a, terminal complement complexes). However, unlike cardiotomy suction blood, the centrifugation and washing processes reduce the concentration of white blood cells by 30–80% and inflammatory mediators by 90–95%. Cell salvage is not, however, entirely without problems; the issue of air–fluid interfaces remains, although the avoidance of 'skimming' and the presence of heparin at the tip of the suction apparatus reduce the activation of the clotting and inflammatory cascades. If very large volumes of blood are processed through a cell saver, there is depletion in platelets and clotting factors; careful monitoring and replacement of these may be necessary.

Haemofiltration during CPB

Haemoconcentration with the use of a haemofilter has been utilized as a modality of therapy to reverse the effects of haemodilution during CPB and reduce volume overload. The anti-oedemic quality of haemofiltration via a haemofilter also has been suggested as a possible benefit by decreasing extravascular lung water, raising the haematocrit, and improving haemostasis, after operation. Ultrafiltration devices used during CPB are similar to those used for dialysis patients. The ultrafilter is composed of a bundle of microporous fibres that permit removal of plasma water and solutes from the blood without the loss of proteins and clotting factors. The ultrafiltrate that crosses the fibres is similar to the glomerular filtrate and is collected in a waste bag and discarded. Ultrafiltration occurs when blood cells and proteins pass along the inside of the hollow fibre and back to the patient while water

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permeable solutes pass through and to the outside of the fibre into a waste bag. In recently published reports, it was shown that the haemofilter was able to remove inflammatory mediators such as C3a, C4a, C5a, and IL-8. However, no data are available as to patient outcome as a result of the role the haemofilter may have in minimizing the post-bypass inflammatory response. Adverse effects associated with the use of ultrafiltration include leucopoenia, complement activation, increased red blood cell trauma, and increased plasma haemoglobin. Additionally, heparin retention in the ultrafilter is a potential problem.

Continuous in-line monitoring

Continuous in-line monitoring systems use spectrophotometric optical fluorescence and reflectance-based systems to continuously monitor up to 11 critical blood gas parameters with lab-quality accuracy. One such device, the Terumo CDI 500 (Terumo Cardiovascular Systems, Ann Arbor, MI, USA), incorporates a multi-analytic cell placed within the circuit. Near real-time results are displayed and can be temperature corrected. Such systems have become a gold standard of continuous in-line monitoring.[9]

A sensor is placed around the blood-filled tubing of the CPB circuit. They allow measurement of pH, P_{CO_2}, P_{O_2}, potassium, oxygen saturation, haematocrit, haemoglobin, and temperature. Although the initial cost of the monitor is high, they do not require the use of disposables and can be reused indefinitely. Frequent recalibration during use is essential.

Leucocyte depleting filter

Activation of leucocytes, in particular neutrophils, is an important step in the inflammatory reaction caused by CPB. Leucocyte removal with specialized filters within the CPB circuit has recently been studied. Although it is indisputable that leucocytes are removed from the stream of blood, the concentration within the circulation as a whole does not appear to be reduced; this may be as a result of the transient effect of such filters, or because of the speed of leucocyte production and replacement by the patient. The only demonstrated benefit to date is a slight improvement in post-operative renal function.[10]

Low prime volume CPB circuit

Haemodilution resulting from crystalloid priming of the CPB circuit represents a major risk factor for blood transfusion in cardiac surgery. Retrograde autologous priming (RAP) is a technique that has been shown to reduce transfusion requirements, and appears to be safe and cost-effective.[11] After surgical cannulation of the aorta and the vena cava but before institution of CPB, blood is allowed to flow (down the pressure gradient) from the aorta into the circuit through the arterial line and filter, displacing crystalloid prime into a blood transfer bag. Next, the crystalloid in the venous reservoir and oxygenator is similarly displaced by the patients' blood. Finally, the entire prime from the venous line is displaced at the onset of CPB. Approximately 300 ml of volume in the circuit is replaced with the patient's own blood during each of these steps. Care must be exercised during RAP, as blood is rapidly removed from the circulating volume of the patient. This may lead to haemodynamic instability and an increased risk of myocardial ischaemia or infarction. If arterial pressure decreases precipitously, vasoconstrictor administration may be required or the RAP should be abandoned and CPB commenced.

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Please see multiple choice questions 15–18

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