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Review articles

Extracorporeal membrane oxygenation (ECMO): prolonged bedside cardiopulmonary bypass

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Introduction

Extracorporeal membrane oxygenation (ECMO) is a unique form of cardiopulmonary bypass which has been in clinical use for 20 years. It has become standard therapy in the management of neonatal respiratory failure in the past decade, and is also being used selectively in the support of respiratory and cardiac failure in the paediatric and adult populations. New applications are constantly being evaluated, considerably expanding the range of patient care that can be provided in an intensive care unit. Depending upon the vascular access and intent, extracorporeal life support may be called ECMO, $ECCO_2R$ (extracorporeal CO_2 removal), ECLA (extracorporeal lung assist) and CPS (cardiopulmonary support) – all are essentially synonymous. ECMO has brought the technology of cardiopulmonary bypass to the bedside under the management of intensive care physicians and ECMO specialists. A brief description of the technique of ECMO support follows, in which similarities and differences between it and operative cardiopulmonary bypass are noted.

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Background

The beginning of extracorporeal circulation dates back to 1936 when John Gibbon first developed a means by which haemodynamic and pulmonary support could be delivered using external (extracorporeal) circulating devices.[1] His first heart-lung machine consisted of a roller pump, which provided a mechanism for delivering flow, and a vertically-oriented revolving cylinder, over which blood would drip.[2] Oxygenation occurred through the direct exposure of red blood cells to ambient oxygen. Heparin, discovered by McLean in 1917 and introduced into clinical practice in 1938,[3] permitted blood to be delivered through artificial conduits without clotting. With the advent of these basic components, the technique of extracorporeal circulation began to evolve.

The design of the original oxygenators was not

suitable for the prolonged support provided by ECMO, since the direct exposure of blood cells to air or oxygen required by these oxygenators caused extensive protein denaturation after several hours.[4,5] Changes in oxygenator design, however, eventually occurred. In 1956, Clowes introduced a plastic membrane into his oxygenator in order to separate the blood and gas phases,[6] and Kammermeyer, in 1957, discovered that gas exchange could occur more effectively if a thin membrane of dimethlysiloxane, commonly known as silicone rubber, was used instead of plastic.[7] In the early 1960s, Kolobow incorporated both these features into his 'membrane lung', which permitted blood and oxygen to flow separately between thin layers of silastic-coated Dacron and fibre-glass screens.[8] The layers of silicone membranes were spirally wrapped to form a compact unit resembling the appearance of modern membrane lungs. Eliminating the direct interface between blood and oxygen significantly decreased protein denaturation and permitted prolonged support with an external oxygenator. Kolobow tested his lung in lambs and was able to support them on partial bypass for up to seven days.[9]

The first successful case of prolonged extracorporeal support in humans was reported by Hill in 1972.[10] Several other investigators began applying this new method of pulmonary support to moribund adults with respiratory failure.[11,12] In order to assess the efficacy of ECMO, a prospective randomized trial, funded by the National Institutes of Health, was instituted to compare survival in adults with respiratory insufficiency treated by conventional therapy to those treated with ECMO.[13] Although the survival rate with ECMO was 9.5% compared to 8.3% using traditional management,[14] the lack of a statistically significant difference between the two survival rates dampened enthusiasm to pursue further clinical trials in adults. A retrospective assessment of these results suggested that the entrance criteria into the study were too stringent, as most patients who were enrolled already had permanent and irreversible lung injury, caused either by the disease process itself or by prolonged aggressive ventilatory support[15] – the benefits of ECMO could not be realized in such circumstances. Continued research into the clinical application of ECMO did persist, however, with a new focus on cardiac and respiratory support in neonates.

Most forms of neonatal pulmonary pathology and subsequent respiratory insufficiency follow a clinical course that lends itself readily to support with ECMO. A common denominator seen in neonatal pulmonary failure is a condition known as persistent fetal circulation (PFC). PFC denotes an abnormal shunting of deoxygenated blood from the right to the left heart across a patent ductus arteriosus or foramen ovale. PFC may result from deficiencies in alveolar surfactant, hyper-reactivity of the pulmonary vasculature, infection or from a toxic insult such as meconium or blood aspiration. Unlike several adult pulmonary diseases, PFC is a reversible phenomenon. The goal, therefore, in using ECMO in the neonatal population is to provide temporary respiratory support during the acute disease process until the PFC is resolved. Conventional mechanical ventilation is often inadequate in providing sufficient oxygenation during the acute phase. The high ventilatory associated pressures cause significant barotrauma with immediate and long-term pulmonary morbidity. ECMO obviates the need for such high ventilatory pressures during the acute disease process and enables adequate oxygenation to occur without the attendant barotrauma. When the acute process resolves, ECMO can be discontinued and ventilation resumed at reasonable pressure levels.

In 1975, Bartlett *et al.* reported the first neonatal survivor of acute respiratory insufficiency from meconium aspiration in which ECMO was used.[16] With this encouraging report, two prospective randomized trials were launched which ultimately demonstrated the safety, efficacy and benefit of ECMO support in neonatal respiratory failure.[17,18]

Presently, over 3300 patients have been treated with ECMO with a neonatal survival rate of 83%.[19] Using previously established criteria, survival without ECMO would be only about 15%.[20–22] The present applications of ECMO continue to expand and include postoperative cardiac support in the paediatric population, perioperative support in cardiac transplantation and paediatric and adult respiratory support from viral, bacterial, toxic or traumatic lung injury.

ECMO circuitry

The circuitry of ECMO represents a simplified modification of that used during cardiopulmonary bypass. Certain obvious differences are readily apparent to the perfusionist who is unfamiliar with an ECMO circuit: perfusion and siphon cannulae do not exit the chest through a sternotomy; there is no reservoir to transfuse or haemodeplete a patient; no coronary suction device exists; blood filters are eliminated; stagnant areas are avoided; and servoregulation of pump flow is present. Management issues in caring for the patient on bypass are likewise different: the level of anticoagulation appears unusually low; variations in pump flow rates do not universally improve tissue perfusion; ventilatory support is titrated with and not completely replaced by bypass; patients are awake and moving about; and care is provided for several days rather than several hours. To present the significance of the differences between ECMO and operative cardiopulmonary bypass more clearly, each component of the ECMO circuit will be addressed individually. The circuitry discussed will apply specifically to neonates, in whom the majority of the ECMO cases have been performed. Similar comparisons also apply to the circuitry for paediatric and adult patients except that larger cannulae, tubing and circuit components are used.

Cannulation and the two methods of ECMO bypass

The most striking initial difference between ECMO and bypass for cardiac surgery is that cannulation for ECMO is performed extrathoracically and at the bedside in an intensive care unit. Perfusion can be accomplished by two forms of bypass: veno–arterial (VA) or veno–venous (VV). For either form of bypass, an incision is made over the target vessels to be cannulated. In VA bypass, blood is typically siphoned from a cannula placed through the right internal jugular vein into the right atrium and is returned to the patient by a catheter placed through the right common carotid artery into the aortic arch after being oxygenated. Venous drainage may also occur from cannulae placed in the common femoral or external iliac veins; likewise, reinfusion can be accomplished through access in the common femoral or axillary arteries. The largest-sized catheter that can be introduced into the target vessel is selected. For neonates, adequate flow rates (200–500cc/min) and pressures (100–250mmHg preoxygenator) are best achieved with a 14 French (F) venous catheter placed in the right internal jugular vein and a 10–12F arterial catheter in the right common carotid artery. The venous catheter has several side-holes which improve the siphoned flow within it. Using smaller catheters may cause insufficient venous drainage or prohibitively high circuit pressures when flow rates greater than 300cc/min are required. VA bypass in ECMO is similar physiologically to operative cardiopulmonary bypass in that it provides both cardiac and pulmonary support for the patient. Increasing the flow rate through the ECMO circuit will improve whole-body perfusion, elevate the mean arterial blood pressure and ensure haemodynamic stability while providing adequate gas exchange for the blood.

In VV bypass, blood is both withdrawn from and reinfused into the central venous system. Blood is siphoned from the right atrium in a manner similar to that in VA bypass but is returned, after being oxygenated, into either the femoral vein (or other suitably sized peripheral vein) or back into the right atrium by a newly designed catheter which has two channels.[23] This double lumen venous catheter, recently developed and tested at our facility, has a 14F outer diameter. Its cross-sectional area is divided disproportionately to enable the larger lumen to siphon blood from the catheter tip and the smaller lumen to perfuse through side-holes directed into the right ventricle. With VV bypass 15–50% of the central venous blood siphoned into the ECMO circuit represents recirculated blood from the venous perfusion cannula. The amount of recirculation increases as the flow rate increases. Despite recirculation, sufficient oxygenation of blood occurs to compensate for the failing lungs. The primary advantage of VV bypass is that it avoids ligation of a major artery; sacrificing such an artery can cause distal ischaemic symptoms if insufficient collaterals are present. VV bypass is ideally suited for the patient who has isolated respiratory failure. Unlike VA bypass, VV bypass has no role in cardiac surgery. It does not divert blood away from either the heart or the lung,

making most modern cardiac surgical procedures impossible. Furthermore, it provides no haemodynamic support; adequate tissue perfusion is entirely dependent upon the patient's own cardiac function.

Priming the circuit

While a surgical team cannulates the patient, ECMO specialists construct and prime the circuit. The individual steps involved in priming an ECMO circuit closely parallel those in the priming of a circuit for operative bypass. The circuit is first constructed using standard tubing, connectors and components with the drainage and infusion tubing leading to a priming reservoir. Carbon dioxide is flushed through the circuit to displace atmospheric oxygen and nitrogen. Any CO_2 remaining in the circuit after the prime is completed will dissolve in blood more readily than will either oxygen or nitrogen, thereby reducing the chance of inadvertent gas embolism. Once the circuit is filled with CO_2, suction is applied to the gas phase of the membrane lung, removing much of the gas within the circuit. The ECMO specialist then adds, sequentially to the circuit, a balanced crystalloid prime, albumin to coat the prosthetic surfaces and decrease platelet and fibrinogen adherence and, finally, blood to displace the crystalloid. A neonatal circuit contains approximately 500cc of volume, which is considerably more than the blood volume of a neonate. Initiating bypass without a blood prime would cause significant haemodilution and haemodynamic instability. Adjustments of the primed blood's pH and temperature frequently need to be made before connecting the patient to the circuit.

Blood saturation monitoring

After the vessels are cannulated, the catheters are connected to the polyvinylchloride (PVC) tubing of the primed ECMO circuit. Figure 1 depicts the individual components of the system diagrammatically. As blood is siphoned from the right atrium, it drains past a fibre-optic probe into a bladder reservoir. The fibre-optic probe is attached to the circuit through a Tuohy-Borst connector and is in constant contact with the flowing blood. This probe provides a continuous on-line measurement of the saturation of blood being siphoned from the right atrium. In VA bypass this value actually represents the patient's mixed venous saturation. Variance in the mixed venous saturation reflects changes in the haematocrit, haemoglobin saturation, bypass flow rate, the patient's own cardiac output or the rate of tissue metabolism. In VV bypass the saturation value is of less importance as an absolute number but is helpful when considered as a trending value. Changes in the saturation during VV bypass are likely to reflect similar changes observed in VA bypass, but the magnitude of these changes may be masked because of recirculation effects.

Servoregulation

The bladder reservoir is the component of the circuit that lies in the most dependent portion, since siphoned flow to it is determined by its distance from the right atrium. The reservoir is made of silicone rubber which permits small changes in its volume to occur. The reservoir servoregulates a double occlusion roller pump which drives flow within the system. A pressure sensor which is in continuous contact with the elastic wall monitors the bladder volume. When the volume falls and the bladder walls begin to collapse, a pressure change is detected and power to the roller pump is temporarily interrupted, stopping flow. Continuous suctioning by the roller pump against inadequate venous return would cause haemolysis, cavitation of dissolved oxygen and damage to the endothelium at the side-holes of the venous catheter. A momentary interruption of flow permits additional blood to enter the bladder reservoir, replenish its volume and displace the pressure sensor of the reservoir back to its normal position. Power returns to the roller pump which restores flow in the circuit. Adjustments in flow rate or catheter position can then be made to ensure continuous, uninterrupted flow. The servoregulation between the bladder and the roller pump replaces the open or bag blood reservoir used during bypass for cardiac surgery. Removing this component eliminates any direct interface between blood and ambient gases and reduces protein denaturation during prolonged bypass. Maintaining a closed system further decreases the possibility of inadvertent air embolism.

Other centres employ different means of controlling ECMO bypass flow. Shiley (Irvine,

California) has introduced a system in which changes in luminal pressure control pump flow: a sensitive transducer on the venous end detects pressure drops below a preset level; as the pressure falls, the transducer effects a decrease in the pump's flow rate and therefore causes a rise in venous pressure towards a baseline value. To prevent excessive pressurization within the circuit, transducers placed on the high-pressure side of the pump can slow down the flow rate in a similar fashion. In Europe, a unique flow device called the Rhone-Poulenc pump (Paris, France) does not require an external device to servoregulate its drive mechanism. This pump contains three vertical posts around which a distensible silastic tube connected in series with the ECMO circuit is stretched. Flow is delivered when the rotating posts pinch off segments of the tubing and deliver the contained blood. If the rate of blood siphoning cannot keep pace

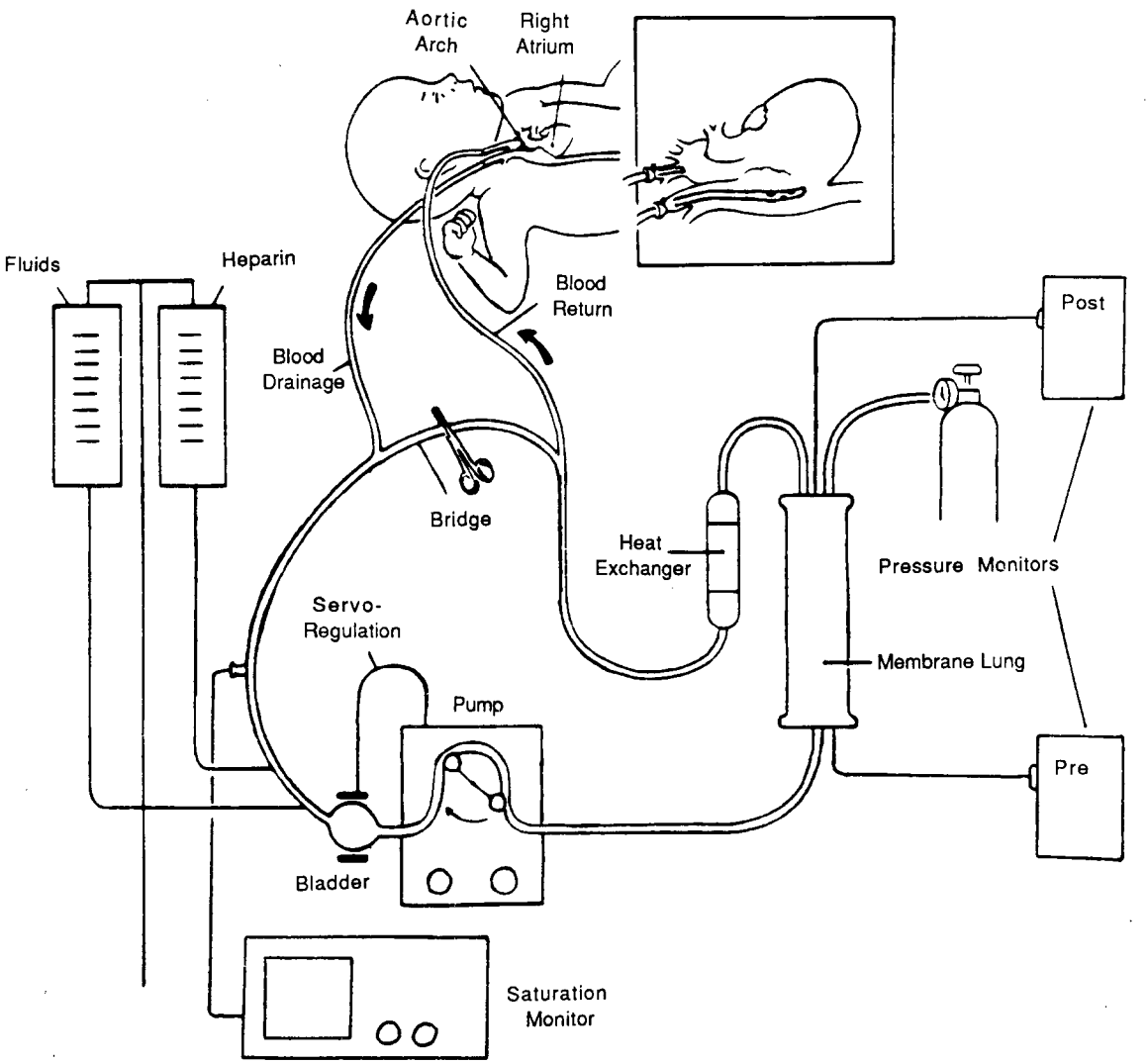

Figure 1 ECMO circuit.

with the rate of attempted delivery, the amount of blood contained between each pinched off segment of raceway tubing will fall, decreasing the effective blood flow. When venous pressure rises and the siphon rate increases, blood flow within the circuit will increase.[24]

Pumps

In most ECMO centres, roller pumps rather than centrifugal pumps are used to deliver flow. Roller pumps offer several advantages, making them more suitable for long-term bypass. Studies performed in our laboratory with different centrifugal pumps and our standard double occlusion roller pump demonstrate significantly less haemolysis with the latter pump.[25] In addition, the mechanics of a centrifugal pump are not as tightly responsive to servoregulation as those of a roller pump. When power to a roller pump is interrupted, as occurs with insufficient venous return, the heads of the pump stop turning and flow in the circuit ceases immediately. The rotating head of a centrifugal pump, on the other hand, will continue to spin for a brief time after servoregulation interrupts its power. The negative pressure generated (relative to atmospheric pressure) can lead to gas cavitation, vessel endothelial damage and additional haemolysis from erythrocyte deformation. Other features of a roller pump's simple design make it a preferred flow-delivering device: it contains no valves, chambers or complex moving parts to malfunction; flow rate can be directly calculated from the RPM of the pump head, obviating the need for an in-line flow probe; the chamber in contact with the roller pump is a component of the bypass circuit, i.e. the PVC tubing; and it does not require cleaning, replacement or adjustments.[1] Disadvantages of roller pumps include tubing rupture in the raceway, gas embolization and over-pressurizing the circuit. Flow is calculated from RPM of a roller pump; if the raceway tubing deforms during prolonged bypass, the calculated flow will be inaccurate.

Tubing, raceway and compliance

The tubing used in the raceway of the roller pump is different from that in the remainder of the circuit. A neonatal circuit is made of PVC tubing with a wall thickness of 1/16 inch. In the past, when this tubing was used throughout the circuit, raceway rupture was a not uncommon event and the raceway tubing would be regularly 'walked' or advanced to avoid the continuous stress placed by the roller head on the raceway. This problem is now averted with the use of more durable PVC tubing ('Supertygon'®, Norton Plastics, Akron, Ohio). The bypass circuitry used during cardiac surgery does not need to incorporate 'Supertygon'® tubing because the duration of bypass is relatively short.

An ECMO circuit contains a relatively fixed volume of blood, the silicone bladder being the only element of volume variability. Volume cannot be transferred from a patient to a component in an ECMO circuit as can be done with a reservoir in an operative bypass circuit. The patient is the only compliant component of an ECMO circuit, and excess volume in this closed system is seen as third-spaced oedema and intravascular volume expansion in the patient. Reduction in the total fluid requires diuresis, haemofiltration or actually removing blood from the circuit.

Oxygenators

After leaving the roller pump, blood flows under positive pressure to the membrane lung. At the University of Michigan Medical Center (UMMC) we use Sci-Med (Minneapolis, Minnesota) lungs routinely. Neonates require lung sizes ranging from 0.4 to 0.8m^2, children from 1.5 to 2.5m^2 and adults from 3.5 to 4.5m^2. Selection of a properly sized membrane lung requires knowledge of its blood and gas flow properties. As the surface area of a membrane lung increases, the pressure drop across the lung becomes less for any given flow rate. The internal resistance of each lung is a function of both its surface area and the volume in which it is wrapped. If high flow rates are anticipated a larger lung should be incorporated into the circuit. Excessively high circuit pressures (>400mmHg preoxygenator) may cause circuit rupture or premature lung failure. In addition to internal resistance, each lung is characterized by its ability to transfer gases at specific blood flow rates. The 'rated flow' of a lung describes the maximal flow at which blood, entering a lung with a saturation of 75%, can exit the lung at 95% saturation; selection of an appropriately

sized lung, therefore, requires an estimate of the anticipated flow through it. Cardiac outputs in resting patients range from 70–90cc/kg/min in adults, 80–100cc/kg/min in children and 120–170cc/kg/min in neonates. Lungs incorporated into bypass circuits need to transfer both O_2 and CO_2 adequately at the anticipated flow rates required by the patient.

Oxygen, carbogen or a mixture of the two is ventilated through the membrane lung in a counter-current fashion at a rate sufficient to maintain the postoxygenator pCO_2 below 40mmHg. Carbogen is commonly used in the neonatal population. At lower blood flow rates the removal of CO_2 from the blood is more effective than is the transfer of oxygen to the blood. A marked respiratory alkalosis can occur if pure oxygen is ventilated through the membrane lung. When carbogen is added the resulting pCO_2 will rise, but not by more than 40mmHg. When pure carbogen cannot reduce the pCO_2 of exiting blood sufficiently and pure oxygen causes excessive CO_2 removal, oxygen and carbogen can be blended together in the ventilating gas to create a mixture that produces a normal arterial pCO_2.

Several monitoring features are attached to components of the membrane lung. Pressure transducers connected immediately before and after the oxygenator provide a continuous assessment of oxygenator function in terms of its blood flow characteristics. A high pressure drop across the membrane lung indicates impending lung failure and a need for replacement. High postoxygenator pressures warn of prohibitively high blood flow rates through a narrow reinfusion catheter or of a kink within the system. When the rate of gas flow through a membrane lung is high, over-pressurization of the gas phase and subsequent gas embolization could occur. Pressure pop-off valves are therefore included in the sweep gas line to guard against inadvertent and excessive pressure build up.

Heat exchangers

After leaving the oxygenator, blood flows through a separate heat exchanger, where it is warmed to 37°C. The heat exchanger used at UMMC is made by Sci-Med and is connected to a heating unit made by Seabrook (Cincinnati, Ohio). Unlike the circuits for bypass surgery, the heat exchanger in an ECMO circuit lies in series *after* the membrane lung. Exposure of the blood tubing and circuit components to ambient temperature causes rapid cooling of the patient, especially the neonate who lacks mature thermogenesis capabilities. A membrane lung with its large surface area will cause the greatest temperature drop in the circuit. High gas flow rates through the membrane lung will further accentuate this temperature drop. Placing the heat exchanger immediately after the membrane lung will warm the blood just before it returns to the patient. This design ensures that minimal heat loss will occur between the heat exchanger and the patient. The theoretical problem of generating oxygen bubbles by heating saturated blood has not proved to be a significant consideration.

The PVC tubing connecting the membrane lung to the heat exchanger lies at the highest part of the bypass circuit, arching between these two components. This area serves as the last bubble trap within the circuit and helps to minimize the risks of gas embolism.

Bridge

From the heat exchanger, blood travels directly to the reinfusion cannula. A bridge of PVC tubing connects the arterial and venous lines. Flow through the bridge is prevented by a tubing clamp which occludes its lumen. Periodic flushing of the bridge by releasing the clamp avoids prolonged periods of blood stagnation and reduces the incidence of clot formation. This bridge permits recirculation of blood within the ECMO circuit when the patient-connecting lines are clamped during cannulation and trials off bypass.

Managing a patient on ECMO

Typically, the care of a patient on bypass requires two persons, a nurse and an ECMO specialist. Nurses generally perform bedside patient care, dressing changes and medicine acquisition. ECMO specialists are trained nurses, respiratory technicians, perfusionists or physicians who have completed an extensive course dealing with the physiology and technology of prolonged extracorporeal support.[26] Their course work is

supplemented with hours of bedside instruction. ECMO specialists maintain circuit integrity, administer medication and blood products into the circuit and regulate the blood flow rate. All interventions are made within the boundaries of prewritten orders provided by a physician.

Numerous details are addressed by the ECMO specialist, the most time-consuming of which is an accurate record of fluid balance. The bedside flow sheet details an hourly and cumulative fluid balance, including the volume of blood sampled, volume of medications given and fluid losses through the dressing, chest tubes and drains. This balance, along with daily weights, provides valuable information in assessing a patient's ability to wean from bypass.

Significant differences exist in the level of anticoagulation needed for ECMO compared to bypass for cardiac surgery. The initial loading dose of heparin is only 100U/kg. Thereafter, heparin is administered (usually 30–60U/kg/hr) to maintain the activated clotting time (ACT) between 180–200 seconds under normal circumstances. The ACT is measured hourly. Diligent attention to the urine output, volume of plasma transfused and rate of heparin infusion permits very precise control of the ACT. The infinite ACTs maintained during operative cardiopulmonary bypass are not needed while on ECMO and would greatly increase the incidence of bleeding complications. ACTs for ECMO were formerly maintained near 250 seconds, but as our experience has evolved we have progressively reduced ACTs to present levels without developing any new clotting problems. Occasionally, because of extraordinary clinical circumstances, ECMO bypass has been run with little or no heparinization for periods longer than 48 hours. If flow rates are great enough, clotting problems do not usually occur.

Platelets are administered as necessary to maintain a level greater than 100 000/mm^3. Because of their adherence to the membranes, platelets are infused into the circuit after the oxygenator. Elimination of filters on the infusion side of the circuit helps to prevent the consumptive thrombocytopenia seen during bypass.

The flow rates used during bypass depend upon the type of bypass being employed and the reasons for instituting bypass. VA bypass provides both cardiac and pulmonary support. With neonates, full cardiac output is achieved with flows approaching 120–170cc/kg/min. At these levels the pulse contour of the arterial wave form will be markedly dampened. The adequacy of the flow is measured physiologically by the patient's mean arterial blood pressure, urine output and mixed venous saturation. Mean arterial blood pressure (MAP) can be affected by administering volume to ensure adequate vascular capacitance and by regulating pump blood flow to act against a patient's vascular resistance. Correct selection of the proper intervention depends upon the information available to the physician or ECMO specialist at the patient's bedside. Urine output is traditionally regarded as the best physiological parameter of adequate perfusion. Unfortunately, it is not always reliable early in the patient's course on bypass. Not infrequently, patients are placed on ECMO after a prolonged period of hypotension, anoxia or both during which attempts at more conventional management have failed. Renal tubular damage occurs and can cause a low urine output despite apparently adequate flow rates and mean arterial pressures.

Mixed venous saturation (SVO_2) at the UMMC is the parameter in VA bypass most commonly used to assess the adequacy of flow and total oxygen delivery. In healthy adults the SVO_2 is approximately 75% at a resting state. Given an arterial saturation near 100%, oxygen delivery is four times greater than oxygen consumption. If bypass is able to achieve near 100% arterial oxygen saturation in the patient, flow rates will be adjusted to maintain an SVO_2 of approximately 75%. A fall in SVO_2 will reflect either a decrease in haematocrit, arterial haemoglobin saturation or total cardiac output or an increase in tissue metabolism. In practice, several variables are assessed and treated when a low SVO_2 occurs: first, blood should be transfused if the haematocrit is less than 45%; secondly, the function and adequacy of the size of the oxygenator must be addressed, especially if the postoxygenator haemoglobin saturation is less than 100%; thirdly, the bypass flow rate may need to be increased if the first two variables are optimized; and fourthly, sedation, paralysis, or modest cooling of the patient should be instituted

if the patient is hypermetabolic.

In VV bypass, management issues are slightly different. The primary goal of VV bypass is to permit a reduction of the high pressures delivered by mechanical ventilators by oxygenating the central venous blood. Bypass flow rates are increased to effect an arterial haemoglobin saturation greater than 90% if possible. Unlike VA bypass, VV bypass provides no direct improvement in cardiac output. The saturation of siphoned venous blood will not represent the true SVO_2 because of recirculation effects, and the adequacy of tissue perfusion is therefore assessed based on clinical and laboratory observations. Usual clinical measures of tissue perfusion include urine output, time for capillary refill, quality of peripheral pulses and blood pressure, while comparable biochemical measures include pH, lactate levels, creatinine, etc. Patients will retain the typical wave contour of arterial blood pressure which will not be dampened as in VA bypass. Enhancing cardiac output in patients on VV bypass requires the administration of inotropic and chronotropic agents. The function of the patient's own heart is the sole determinant of cardiac output, and changes in bypass flow will not directly alter cardiac function or tissue perfusion.

Airway management during bypass requires individualized attention based upon a patient's specific disease process and the level of ECMO support provided. When full bypass flows are reached, the amount of ventilator support can be reduced to 'rest settings'. In the neonate these generally include a peak inspiratory pressure of 20cm H_2O, a positive end-expiratory pressure (PEEP) of 4cm H_2O, respiratory rate of 10–20 breaths per minute and an inspired FiO_2 of 30%. Reducing airway pressures avoids barotrauma and reduces the incidence of late development of bronchopulmonary dysplasia. Other means of airway management are possible and may include extubation, low continuous positive airway pressure (CPAP) in patients with a bronchopulmonary fistua, high PEEP or frequent pulmonary lavages.

Complications

Bleeding is the most common complication seen in patients on ECMO.[27] Bleeding has been reported from operative sites, mucous membranes, stomach and distal gastrointestinal tract, and miscellaneous locations within the cranium, pleura, pericardium or retroperitoneum. Conservative techniques used to manage bleeding complications include maintaining the platelet count at above 150 000/mm^3 and lowering the ACT levels. ACTs have been lowered into the 120–140 second range without apparent clotting problems. On rare occasions, if flow rates are high, heparinization can be discontinued with caution. All surgical sites should be re-explored, and other more aggressive operative interventions may be required. If bleeding is severe, ECMO bypass may need to be temporarily or permanently discontinued. Of all potential bleeding sites, intracranial haemorrhage is most serious. Fortunately it occurs in only 14% of neonates with gestational ages greater than 35 weeks.[28]

Circuit-related problems are occurring less frequently as modifications in design and better-tested equipment are incorporated. Technical problems include oxygenator failure, roller pump or heat exchanger malfunction, raceway or other tubing rupture and air leakage into the circuit. Most of these complications cause temporary physiological instability while the circuit components are changed and rarely cause any permanent morbidity.

Other complications seen include tension pneumothorax, pericardial tamponade, seizures and organ failure; surprisingly, catheter-related sepsis is vanishingly rare.

Weaning the patient off ECMO

The duration of ECMO support in the neonatal population ranges from four to seven days (average 126 hours). The longest length of time spent on ECMO at UMMC as of January 1990 is 27 days for a child with severe viral respiratory illness; he subsequently recovered and suffers no apparent long-term sequelae.

After cannulation, the majority of ECMO patients are allowed to stabilize for 24–48 hours

at a flow rate sufficient to provide adequate oxygenation. If patients receive large volumes of fluid during their resuscitation prior to initiating ECMO, aggressive diuresis with frusemide or mannitol is begun. Haemofiltration is used to remove excess volume when the kidneys are unresponsive to diuretics.

Signs of improvement are assessed daily while on ECMO bypass. These include parenchymal clearing on serial chest X-rays, rising pulmonary compliance, increasing end-expiratory CO_2 production measured in the airway, rising pO_2 in the patient's arterial blood gases (ABG) in addition to mobilization of third-spaced fluid, rising SVO_2 or MAP. With VA bypass the flow rate is progressively reduced to maintain MAP, SVO_2 and ABGs at acceptable levels. When it appears that a patient can support himself haemodynamically and maintain adequate oxygenation with minimal ventilator support, a trial off bypass is attempted. This necessitates clamping the patient-connecting lines and removing the clamp on the bridge to allow recirculation. Ventilatory support needs to be increased from 'rest settings' to those sufficient to provide adequate pulmonary gas exchange. Decannulation can proceed if the patient remains stable for 45–60 minutes.

In theory, weaning off VV bypass is simpler since VV bypass provides no cardiac support. During a course on VV bypass the ECMO flow rate is progressively reduced as pulmonary function improves. This improvement is evidenced by a rising arterial haemoglobin saturation seen on a transcutaneous sensor. The bypass flow rate can then be decreased to maintain the arterial haemoglobin saturation greater than a suitable minimum value, usually 90%. When the flow rate reaches a low level (30cc/kg/min), a trial off bypass can be attempted. This trial involves removing the ventilating gas line from the membrane lung and capping off the gas inlet and outlet ports. Blood is still siphoned from and returned to the patient, but no gas exchange occurs. The bridge remains clamped. The settings on the ventilator are increased to levels commensurate with physiological support. A successful trial off bypass for 30–45 minutes demonstrates sufficient lung recovery to permit decannulation.

Summary

The technology of ECMO support continues to evolve. New advances presently in development include the manufacturing of paediatric- and adult-sized double lumen catheters, the use of heparin-coated tubing and the automation of bedside ECMO control. As the applications of ECMO branch deeper into the area of cardiac transplantation and support, the interface between the ECMO specialist and perfusionist will become less distinct. Both the ECMO specialist and perfusionist will provide a continuum of patient care, spanning preoperative cannulation in the intensive care unit, intraoperative management during corrective cardiac surgery and postoperative cardiac recovery back in the ICU. As bypass technology advances and its applications broaden, the challenges faced by perfusionists will continue to grow.

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