Technique

Modified Ultrafiltration in Pediatric Cardiopulmonary Bypass

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ABSTRACT

Cardiopulmonary bypass in children is frequently associated with increased capillary permeability resulting in increased total body water, tissue edema, and organ dysfunction. Hemodilution also occurs and may require transfusion. Modified ultrafiltration utilizes the extracorporeal circuit to perform hemofiltration of the patient immediately following cardiopulmonary bypass and has been shown to significantly reduce total body water and to improve hemodynamics. The circuit contents can be concentrated to reverse hemodilution without transfusion. This report describes circuit modifications, management, and preliminary results of modified ultrafiltration in 23 infants and children following cardiopulmonary bypass.

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INTRODUCTION

Pediatric cardiopulmonary bypass (CPB) often results in increased capillary permeability and increased total body water (TBW) (1-5). The increase in TBW may lead to tissue edema and multiple organ dysfunction including the brain, heart, and lungs. The small blood volume of children compared to the priming volume of the CPB circuit results in significant hemodilution. Exposure of the patient's blood to the foreign surface of the oxygenator results in a significant inflammatory response which may exacerbate the increase in TBW (1-11). A variety of techniques have been developed to reverse tissue edema and hemodilution following CPB including ultrafiltration during CPB, postoperative peritoneal dialysis, postoperative continuous arteriovenous hemofiltration, aggressive use of diuretics postoperatively, and infusion of salvaged circuit volume (1-11). In the pediatric population, ultrafiltration and cell centrifugation during CPB are restricted by the volume in the venous reservoir and provide only a limited ability to remove excess water and reverse hemodilution (1-5).

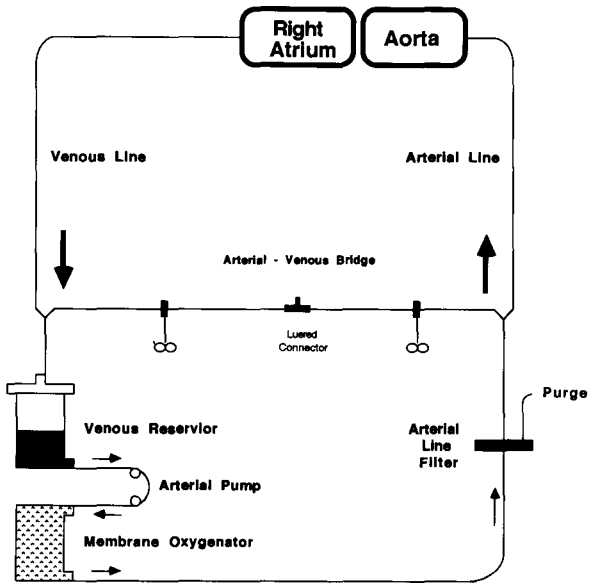
A modification of standard ultrafiltration, termed modified ultrafiltration (MUF), has been developed at the Hospital for Sick Children in London (1-5). Unlike standard ultrafiltration, MUF is performed in the immediate post-CPB period and removes excess water from the patient directly as well as providing a method of salvaging volume from the circuit. The aortic cannula is left in situ so that blood from the aorta is pumped through the hemoconcentrator and warm, concentrated oxygenated blood is returned to the right atrium. A prospective randomized trial showed that MUF improved hemodynamics with a reduction of TBW and decreased the need for blood transfusion when compared to nonfiltered controls (1). A separate trial documented increased systolic blood pressure and cardiac index with decreased pulmonary vascular resistance when MUF was performed after CPB (2). MUF is also a rapid and effective method of salvaging circuit blood volume and raising the patient's hematocrit without transfusion. This report discusses the CPB circuit modifications necessary for MUF, management of the circuit during MUF, and safety considerations.

MATERIALS AND METHODS

MODIFICATIONS OF THE STANDARD NEONATAL CIRCUIT

For neonates weighing less than 7 kilograms, a standard circuit consisting of 1/4 inch internal diameter (ID) polyvinylchloride (PVC) tubing, 1/4 inch ID PVC arterial pump raceway tubing, pediatric oxygenator[a], arterial line filter[b] is used, with a priming volume of approximately 550 ml (Figure 1). A bridge consisting of 18 inches of 1/4 inch PVC tubing is placed between the arterial and venous lines to allow rapid recirculation of circuit volume if necessary for rapid de-bubbling. The bridge remains clamped during standard CPB unless standard ultrafiltration is performed during CPB.

Figure 1
Standard neonatal CPB circuit configuration. Note the arterial to venous bridge with a luered connector.



To modify the standard circuit for MUF, a luered connector is placed midway in the bridge and provides access for the inlet of a 1/4 inch ID PVC raceway tubing (approximately 36 inches in length). The MUF raceway tubing is placed into an available pump housing. The outlet of the raceway tubing is attached to the inlet of a rinsed pediatric hemoconcentrator[c]. The outlet of the hemoconcentrator drains to the venous reservoir (Figure 2). After crystalloid priming of the bypass circuit, the MUF circuit can be primed and de-aired by arranging clamps to divert flow through the MUF circuit. After priming and prior to the initiation of CPB, the MUF circuit is excluded from the CPB circuit with clamps. CPB is initiated and managed in the standard fashion. The MUF circuit may be utilized for conventional ultrafiltration during CPB (Figure 2) or may remain excluded. If standard ultrafiltration is performed during CPB, it is important to compensate for the shunt of arterial blood through the MUF circuit by increasing arterial pump flow by an equivalent amount. Approximately 10 minutes prior to separation from CPB, blood is slowly circulated through the MUF circuit by removing the bridge clamps between the CPB circuit and the MUF circuit (Figure 2) to allow final de-airing and pre-warming of the MUF circuit.

Upon termination of CPB, the venous cannulae are removed and the venous line volume drained into the reservoir.

a Cobe Cardiovascular Incorporated, Arvada, CO 80004-3599
b Pall Biomedical Products Corporation, Glen Cove, NY 11542
c Amicon, Beverly, MA 01915

Figure 2
Placement of hemoconcentrator in neonatal CPB circuit for MUF. Note that conventional ultrafiltration during CPB is possible.

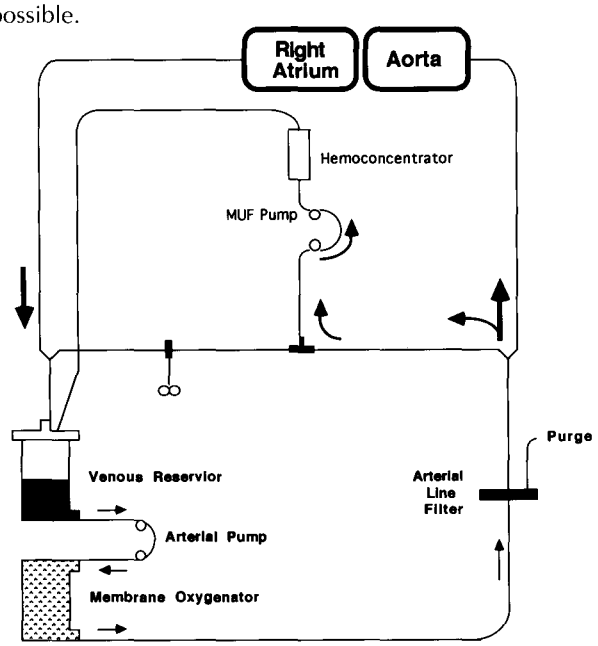
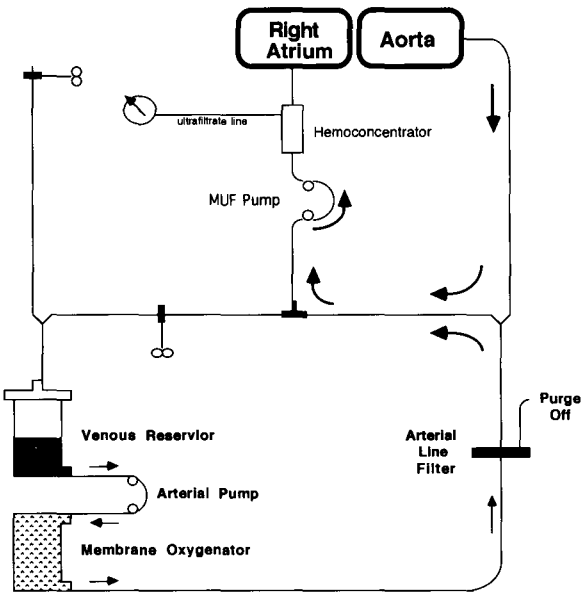


Figure 3
Circuit and hemoconcentrator during MUF.



Protamine administration must be delayed until MUF is completed. On the surgical field, a 10 Fr vent catheter[d] (or larger if desired) is attached to one end of a sterile 24 inch piece of 1/4 inch ID PVC tubing and used as the MUF infusion cannula. The other end of the PVC tubing is handed down to the perfusionist and connected to the hemoconcentrator outlet tubing. The MUF line is primed up to the MUF infusion cannula to remove all air, the cannula inserted through the venous purse string, and MUF initiated. Careful de-airing of the MUF infusion cannula is especially important in children with residual intracardiac shunts.

INITIATION OF MUF

Before initiation of MUF, confirm that the arterial filter purge is turned off. All arterial line clamps are removed and the MUF pump flow is gradually increased to a target rate of 10-15 ml/kg/min. During MUF blood is pumped retrograde from the aortic cannula, through the hemoconcentrator, and returned to the right atrium (Figure 3). This results in an infusion of concentrated, oxygenated blood into the right atrium and pulmonary vasculature. The ultrafiltration line is connected to a regulated vacuum source and opened. Suction is gradually increased to a level of -150 mmHg. As ultrafiltrate is removed, the patient's intravascular volume will decrease. The central venous pressure (CVP) or left atrial pressure (LAP) must be carefully monitored as well as the systemic blood pressure. By starting the arterial pump at a flow rate slower than the MUF pump, circuit blood can be pumped through the hemoconcentrator and into the right atrium allowing concentration of the circuit contents and maintenance of intravascular volume.

When both pumps are on, the MUF circuit receives volume from both the patient and the CPB circuit. The relative contributions from the patient and from the CPB circuit can be titrated by varying the flow rates of the MUF and arterial pumps. Unless emergency volume infusion is required, the flow rate of the arterial pump must not exceed the flow rate of the MUF pump as this will result in antegrade flow through the aortic cannula. Changes in intravascular volume are more gradual and less volume infusion from the reservoir is required when the MUF pump is maintained at a slower flow rate. Ultrafiltration of the patient is more effective and a greater reduction of TBW is achieved at slower flow rates (1, 3-5). A faster flow rate will result in more rapid changes in intravascular volume and require greater infusions from the reservoir to maintain filling pressures and hemodynamic stability. Usually the MUF pump is maintained at a constant flow rate while the arterial pump flow rate can be increased or decreased depending on the patient's hemodynamic status. As the venous reservoir empties, the reservoir level is maintained with crystalloid infusion to completely displace blood from the circuit and allow emergency reinstitution of CPB if necessary.

MUF is continued until the hematocrit is greater than 40% or when all blood from the circuit has been salvaged and crystalloid infusion is required to maintain intravascular volume. Typically, MUF requires 15-20 minutes following separation from bypass. When MUF is completed, protamine is administered, the cannulae are removed, and the operation completed in standard

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fashion. Usually, 60 to 120 ml of blood can be removed from the MUF circuit via syringe from a port between the hemoconcentrator and the patient for later infusion if necessary.

The use of MUF does not preclude the rapid reinstitution of CPB if necessary, as the circuit remains primed by crystalloid infusion during MUF. To resume CPB, the MUF pump is stopped and the MUF circuit clamped. The MUF cannula is removed from the right atrium, the venous cannula reinserted through the right atrial purse-string and CPB resumed. Emergent volume infusion via the aortic cannula can be performed during MUF simply by increasing the arterial pump flow rate while stopping the MUF pump (suction on the ultrafiltration line should be discontinued), blood is then infused from the reservoir through the aortic cannula.

MONITORING DURING MUF

CIRCUIT MONITORING

The arterial line pressure must be carefully monitored during MUF. Using the Shiley CAPS system[e], high line pressure servo-regulation of the arterial pump head can be accomplished. In addition, the MUF pump is servo-regulated to stop if a negative arterial line pressure is encountered. Since the MUF pump flow rate exceeds that of the arterial pump, a negative arterial line pressure will occur if the arterial cannula becomes kinked or is inadvertently clamped. Negative pressure in the circuit arterial line can introduce air into the circuit by pulling air across the membrane oxygenator or by cavitation. Because of this possibility, a bubble detector is positioned between the oxygenator and arterial line filter.

PATIENT MONITORING

Careful attention to the patient's volume status is essential to maintain hemodynamic stability during MUF. The central venous pressure (CVP) or left atrial pressure (LAP) can be maintained at appropriate levels by adjusting the flow rates of the arterial and MUF pumps. Generally, the MUF pump is maintained at a set flow rate of 15-20 ml/kg/min. When the CVP or LAP drops, the arterial pump flow rate is slightly increased from the baseline flow rate. If the CVP or LAP is higher than desired, then the arterial pump flow rate is decreased or stopped. The arterial pump flow rate should not exceed the MUF pump flow rate unless emergency rapid volume replacement is necessary, and before resuming antegrade flow through the aortic cannula, the arterial line should be carefully inspected for the presence of air. The patient's hematocrit is measured from arterial blood samples every 5 minutes during MUF and after completion of MUF.

RESULTS

Duke University Medical Center has utilized MUF in 23 patients undergoing CPB for the repair of congenital heart disease. In two patients MUF was utilized again at a second operation.

The mean patient age was 17.5 ± 28 months and varied from 1 day to 8.5 years. Fifteen patients were under 6 months of age. The mean weight was 7.3 ± 5.6 kg and ranged from 2.5 to 24 kg. The mean duration of CPB and MUF were 119 ± 46 min and 16 ± 3 min, respectively. The hematocrit at the end of CPB was 18 ± 3% and (after MUF) increased to 41 ± 8%, a mean increase of 133 ± 49%. Technical difficulties were encountered in two cases early in our experience involving a kinked aortic cannula during MUF which resulted in air entrainment across the oxygenator membrane due to negative pressure in the arterial line which was detected by the bubble detector. In both patients, MUF was immediately discontinued, the air evacuated from the arterial line and no air embolism occurred. Routine negative pressure monitoring was instituted after these events. There were no intraoperative deaths and no additional complications attributable to MUF.

DISCUSSION

Despite significant reductions in CPB circuit priming volume and other improvements in technique and circuit design over the last decade, excessive tissue edema and hemodilution requiring transfusion remain common occurrences in pediatric open-heart surgery cases (1, 3-5). A variety of techniques have been utilized to decrease excess TBW following CPB including ultrafiltration, postoperative peritoneal dialysis or arteriovenous hemofiltration, and aggressive use of diuretics (1-11). Blood conservation in pediatric CPB has generally utilized two strategies to salvage the remaining circuit volume for reinfusion: 1) ultrafiltration both during and after CPB (8-10), and 2) post-CPB centrifugation of the circuit volume (7).

In smaller patients (<10 kg), both the centrifugation and ultrafiltration techniques have limitations. When conventional ultrafiltration is performed during CPB, additional volume infusion is usually required to maintain a safe reservoir level (1, 3-7). Although centrifugation of the circuit contents after CPB effectively eliminates heparin, it also removes platelets, clotting factors, and other plasma proteins from the blood. Ultrafiltration of the circuit volume after CPB yields a concentrated blood product which preserves plasma proteins, but is also heparinized (6). Because of the limited volume capacity of the neonate, the infusion of this heparinized circuit blood requires a prolonged period of time. Delayed infusion of hemoconcentrated circuit blood is undesirable as it may lead to an elevation of the activated clotting times (ACT) and increased bleeding. A combined approach of ultrafiltration during CPB, followed by centrifugation of the circuit contents after CPB to maximize the benefits of both these techniques has been suggested (9). MUF provides another option which may overcome the limitations of conventional techniques by both preserving plasma proteins and by allowing hemofiltration of the patient as well as the circuit. MUF was

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shown in a randomized trial to result in a greater reduction in TBW and edema when compared to standard practice without MUF (1). MUF has also been shown to result in improved hemodynamics and cardiac output as well as a decreased need for blood transfusions (1, 2).

As with any new procedure or CPB circuit modification, MUF should be experimented with in a laboratory setting prior to clinical utilization to determine individual circuit adaptations and other safety considerations. Retrograde flow from the aortic cannula is contrary to standard perfusion practice. If reinstitution of CPB becomes necessary during MUF, the arterial line must be carefully inspected before antegrade flow through the arterial cannula is resumed to ensure that no air is present. There is a theoretic risk of air entrainment around the aortic purse string sutures; however, this has not occurred in our experience. Accidental kinking or clamping of the aortic line during MUF will produce a negative pressure in the arterial line with risk of cavitation or air entrainment across the membrane oxygenator and has occurred twice in our experience. To minimize the risk of air entrainment, the arterial line pressure must be carefully monitored and, if possible, servo-regulation utilized so a negative arterial line pressure drop will stop the MUF pump. If servo-regulation of the MUF pump is not used, the perfusionist must be aware of arterial line pressure at all times, and manually stop the MUF pump if the line pressure abruptly drops. MUF also requires other changes in standard post-CPB management. Protamine administration must be delayed until MUF is completed as the patient must remain fully anticoagulated. The ACT is measured immediately prior to separation from CPB and additional heparin given to maintain a level of 380 seconds. Fluid administration by anesthesia is unnecessary during MUF, as the perfusionist can adjust the filling pressures using the MUF circuit.

Patient cooling during the MUF process has been observed and the following steps can be taken to minimize this problem: 1) Patients should be fully warmed (37°C rectal) prior to termination of CPB; 2) the MUF circuit should be prewarmed by recirculating warm blood through the hemoconcentrator; 3) the MUF infusion cannula should be made as short as possible; and 4) the operating room temperature increased.

In conclusion, MUF is effective in reducing total body water following CPB in infants and children and may reduce postoperative edema and organ dysfunction (1, 5). MUF has been shown to significantly improve post-CPB hemodynamics and cardiac output (1, 2). In addition, MUF allows salvage of circuit red blood cells and normalization of the patient's hematocrit without transfusion. Clinical use of this technique can be safely accomplished with appropriate circuit modifications and training.

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