CHAPTER 208

Modified Ultrafiltration in Pediatric Heart Surgery

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OBJECTIVES

This chapter will:

1. Present a rationale for use of modified ultrafiltration in pediatric cardiac surgery.
2. Review the pathophysiologic changes leading to the systemic inflammatory response syndrome with use of cardiopulmonary bypass.
3. Summarize the benefits of modified ultrafiltration for pediatric cardiac surgery.
4. Provide guidelines for the modified ultrafiltration procedure based on clinical experience.

Pediatric heart surgery is an area with consolidated excellent results, and survival for children with congenital heart disease is more often the rule than an exception. Many infants and children born with congenital heart defects now have a future, and they grow up to be adults with congenital heart disease, a new subgroup of patients who require appropriate treatment and follow-up. The routine application of cardiopulmonary bypass (CPB), along with new strides in technology and surgical procedures, has provided new hope for the possibility of repairing complex defects in pediatric patients. Although open heart surgery for congenital heart disease is currently routine in most western countries, such procedures requiring CPB are not

free yet from serious risks or adverse events. If it is true that technical improvements have significantly reduced postoperative morbidity, however, use of CPB exposes neonates and infants to extremes of hemodilution and hypothermia, often associated with tissue ischemia, as well as initiating a systemic inflammatory response, with significant accumulation of excess body water.

One of the most challenging problems related to use of CPB is hemodilution. In fact, the bypass pump must be primed with solutions to provide an air-free circuit. Despite use of blood-derived products during bypass, these solutions are introduced into the patient's vascular space, causing hemodilution and a consequent decrease in the patient's hematocrit level, platelets, and clotting factors. These changes in turn cause increased bleeding, need for transfusions, prolonged intubation time, and increased length of stay in the intensive care unit (ICU). Hemodilution also decreases the patient's colloid osmotic pressure, which causes fluid to move into the extravascular tissues, producing edema of interstitial space.

In addition, a cardiac surgical procedure, much like a traumatic injury, triggers an acute inflammatory response, but the continuous exposure of heparinized blood to nonendothelial cell surfaces, followed by reinfusion and circulation within the body, greatly magnifies this response in procedures in which CPB is used. This inflammatory response is extremely pronounced in neonates and infants, in whom it is expressed as the *systemic inflammatory response syndrome* (SIRS) and *capillary leak syndrome*. The resulting edema affects many organs, including the heart, brain, kidneys, liver, and lungs.

Therefore the final effect of these abnormalities is fluid overload, defined as a positive value of the

$$\text{Total input} - \text{Total output}/\text{Initial body weight}$$ [1]

Fluid overload is associated with deleterious consequences proportional to its severity.[1–3] A 3% increase in mortality for every 1% increase in fluid overload has been reported, and children with more than 20% of fluid overload had an odds ratio for mortality of 8.5 compared with less than 20% fluid overload.[4] In particular, a significant interaction between fluid overload and acute kidney injury is demonstrated in determining risk of onset of adverse outcomes.

For these reasons, all available technology should be used whenever possible to minimize fluid overload so as to decrease hemodilution. Continuous hemofiltration is useful not only to limit azotemia but also to control electrolytes and fluid balance in critically ill adults as well as pediatric patients with acute renal dysfunction and fluid accumulation.[5–9] Conventional and modified ultrafiltration are techniques derived from hemofiltration that currently are used during and after CPB to combat the aforementioned inevitable adverse effects, which are more pronounced in neonates and infants.

HISTORICAL BACKGROUND

In 1974 Silverstein et al.[10] modified the extracorporeal dialytic circuit by introducing an additional filter that could eliminate water and proteins with a molecular weight lower than 50,000 daltons (Da). With this modification, ultrafiltration could be used to treat conditions of chronic water retention or pulmonary edema; the filtration circuit was designed to be separate from and independent of the dialysis circuit. In 1979, Darup et al.[11] applied hemofiltration to CPB in 10 patients with reduced or borderline kidney function undergoing cardiac surgery. During the 1980s, ultrafiltration was used as an adjunct to CBP only in patients with preoperative renal failure or edema. The concept of ultrafiltration arose as a response to the observation of an accumulation of total body water associated with open heart surgery. In the later 1980s and early 1990s, the hypothesis that tissue edema was causing organ dysfunction postoperatively stimulated the idea that removal of water from the body at the end of CPB would result in improved organ function and perhaps better outcomes. Introduction of ultrafiltration during and after CPB came right after this recognition. Naik et al. in 1991[12] were the first to report results with the use of *modified ultrafiltration* (MUF) in pediatric patients. Their randomized study, which included 50 children, showed that this technique decreased the need for blood products and colloids, reduced the amount of body fluid, and improved postoperative cardiac function. Several later studies have confirmed these results.

INFLAMMATORY RESPONSE TO CARDIOPULMONARY BYPASS

It is widely known that CPB in cardiac surgery unleashes a broad and intense acute inflammatory response of variable degree, which, together with microembolization, is responsible for most of the morbidity of CPB. The inflammatory response to CPB is initiated by contact between heparinized blood and nonendothelial cell surfaces, with continuous recirculation of blood that is sequentially in contact with the wound, the perfusion circuit, and the intravascular compartment, to which is added the washout from reperfused ischemic organs and tissues.[13] Blood contact with nonendothelial cell surfaces in the wound and in the perfusion circuit activates plasma zymogens and cellular blood elements that constitute part of the body's defense reaction to all noxious substances (including infectious agents, toxins, foreign antigens, allergens) and injuries. All surgery, like traumatic injury, triggers an acute inflammatory response, but the continuous exposure of heparinized blood to nonendothelial cell surfaces followed by reinfusion and circulation within the body greatly magnifies this response in procedures in which CPB is used.

Although far from fully elucidated, this predominantly "blood" injury is known to produce a unique response that differs from that caused by other threats to homeostasis. The principal blood elements involved in this acute defense reaction are contact and complement plasma protein systems, neutrophils, monocytes, endothelial cells, and, to a lesser extent, platelets. When activated during CPB, the principal blood elements release vasoactive and cytotoxic substances; produce cell signaling inflammatory and inhibitory cytokines; express complementary cellular receptors that interact with specific cell signaling substances and other cells; and generate a host of vasoactive and cytotoxic substances for release into the circulation.[14] Blood circulating during clinical cardiac surgery with cardiopulmonary bypass is a stew of vasoactive and cytotoxic substances, activated blood cells, and microemboli. Shear stress, turbulence, cavitation, and other rheologic forces and complement components cause hemolysis of some red cells. Complement anaphylatoxins, bradykinin formed by activation of the contact proteins, and proinflammatory cytokines stimulate endothelial cells to contract, allowing extravasation of intravascular fluid into the extravascular space.[15] As neutrophils and monocytes

migrate across the endothelial cell barrier, stromal and parenchymal cells are exposed to a cytotoxic environment mediated by neutral proteases, collagenases, and gelatinases, reactive oxidants, lipid peroxides, complement components, and other cytotoxins.[16]

The clinical manifestations of the inflammatory response include systemic signs and symptoms such as malaise, fever, increased heart rate, mild hypotension, interstitial fluid accumulation,[17] and temporary organ dysfunction, particularly of the brain, heart, lungs, and kidneys. The magnitude of this defense reaction during and after CPB is influenced by many exogenous factors, including the surface area of the perfusion circuit, the duration of blood contact with extravascular surfaces, general health and preoperative organ function of the patient, extent of blood loss and replacement, organ ischemia and reperfusion injury, sepsis, different degrees of hypothermia, periods of circulatory arrest, the patient's genetic profile, and use of corticosteroids or other pharmacologic agents. Several methods have been proposed to control the acute inflammatory response to CBP such as off-pump cardiac surgery,[18] maintenance of a perfusion temperature between 32°C and 34°C,[19] utilization of perfusion circuit coatings with ionic- or covalent-bonded heparin, complement inhibitors,[20] administration of glucocorticoids,[21,22] and protease inhibitors such as aprotinin.[22–24] The efficacy of these techniques as effective antiinflammatory approaches remains essentially unresolved and strictly linked to institutional protocols.

MODIFIED ULTRAFILTRATION

For more than 10 years, MUF is being used in pediatric cardiac surgery as an additional way to limit the deleterious effects of CPB. According to the International Pediatric Perfusion Practice 2011 survey including 146 pediatric cardiac centers worldwide, 71% of centers in the survey were using some form of MUF.[25] To be effective as a technical innovation, MUF is to be conducted according to specific guidelines (Box 208.1).

The recognized benefits of MUF are reduction in total body water accumulation seen after CPB, improved left ventricular function, increase in hematocrit with concomitant

BOX 208.1

Guidelines for Performance of Modified Ultrafiltration

- MUF after CPB must be performed by a certified clinical perfusionist.
- To use MUF, the perfusionist who operates the heart-lung machine modifies the pediatric bypass circuit to incorporate the MUF system before starting CPB when setting up the circuit.
- MUF for patients who weigh less than 15 kg is implemented immediately after CPB ceases.
- MUF typically is performed for 20 minutes to remove an approximate volume of filtrate determined using the following equation: F = (P + Ca + Cr) – (Cuf + D), where F is filtrate volume, P is priming crystalloid volume, Ca is cardioplegia volume, Cr is crystalloid volume added during CPB, Cuf is ultrafiltrate volume removed during CUF, and D is diuresis volume.
- Approximately 10 to 20 mL/kg per minute of fluid is removed from the patient, which averages between 400 and 600 mL, depending on the patient's weight, amount of time the MUF system is deployed, and the surgeon's preference.

Procedure

Set-Up

- Before priming the CPB circuit, the perfusionist adds a roller head, a hemoconcentrator, extra tubing, and connectors to the circuit to incorporate the MUF line. The pump and these extra supplies then are primed to ensure a bubble-free circuit.
- The MUF line is a PVC tube with dimensions of 2.8 mm × 4.2 mm × 150 cm; both ends are connected to a "male" Luer-Lok connector.
- Insert a three-way stopcock on the primed arterial filter.
- Connect the MUF line to the CPB circuit.
- Pass the MUF line to the sterile field.
- At the sterile field, the nurse clamps and cuts the venous line to add a Luer-Lok connector.
- Discuss with the nursing staff the types of connectors required (usually ¼-inch connector–Luer-Lok–¼-inch connector–venous cannula) before starting CPB.
- It is essential to account for all pieces of ¼-inch tubing required to complete the connections.
- Flush the MUF line with blood prime from the CPB circuit while on pump to "debubble" it.
- The MUF line coming from the pump will be attached to the Luer-Lok connector by the surgeon. Take care in avoiding air bubbles in lines.

Initiation of MUF

- When CPB is off, on full heparinization, clamp out the venous line, and drain it.
- When the venous line is in place (usually the superior vena cava or the right atrium), bubble-free and secure, start MUF for 15–20 minutes, approximately.
- Estimated volume of removed filtrate (F) = (P + Ca + Cr) – (Cuf + D), where P is priming crystalloid volume, Ca is cardioplegia volume, Cr is crystalloid volume added during CPB, Cuf is ultrafiltrate volume removed during CUF, and D is diuresis volume.
- Adapt MUF extraction to patient hemodynamics (i.e., CVP, MAP) and check stable positive pressure in the arterial line.
- As systemic pressure falls, turn on the arterial pump head slowly to stabilize.
- **Remember:** *Never* increase the arterial pump head more than the MUF roller pump head.
- The optimal flow through the hemoconcentrator is 8 to 10 mL/kg per minute, according to patient's hemodynamics
- Ensure a positive pressure in the arterial line at all times. **Remember:** If the arterial line pressure becomes negative or a quick drop in positive pressure occurs, air may be drawn across the membrane and into the circuit.

Supplies Required

- Hemoconcentrator
- Hemoconcentration tubing pack
- Two perfusion adapters: ¼-inch Luer-Lok, ¼-inch connectors (2 inches of ¼-inch tubing)
- Sterile blade and alcohol
- Effluent container with measuring capability (i.e., urometer)
- **Note:** When arterial pump flow is used to supplement MUF, *never* increase arterial pump flow to a rate greater than that of MUF pump flow.

CPB, Cardiopulmonary bypass; *CUF,* continuous ultrafiltration; *CVP,* central venous pressure; *MAP,* mean arterial pressure; *MUF,* modified ultrafiltration; *PVC,* polyvinylchloride.

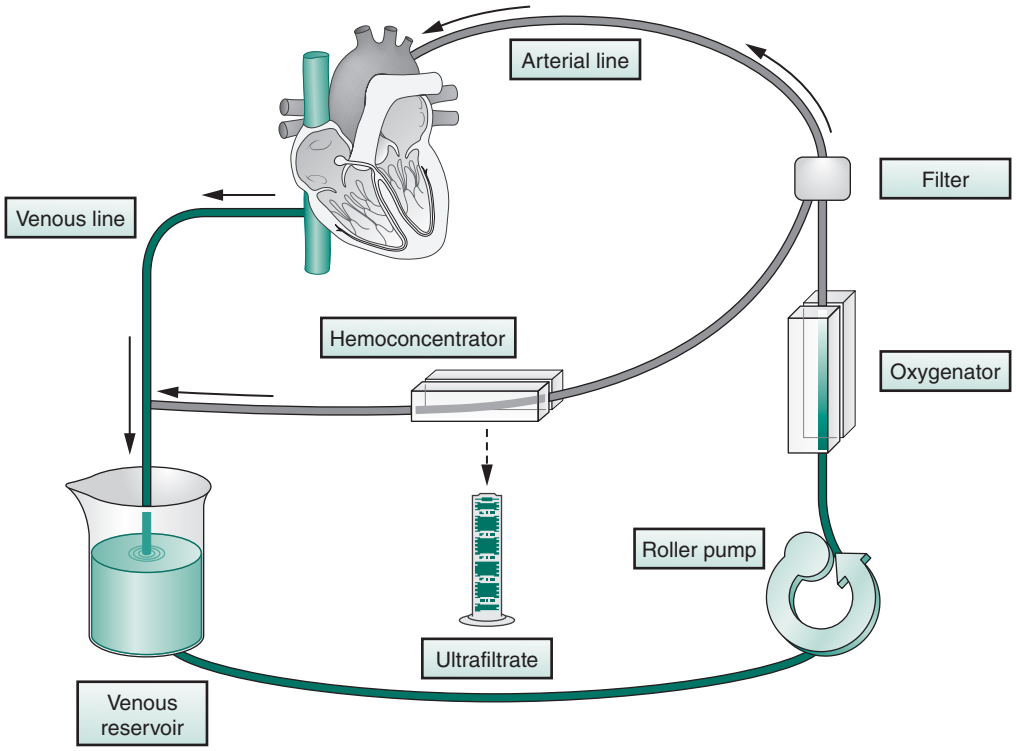

FIGURE 208.1 Diagram showing continuous ultrafiltration (CUF) circuit (arteriovenous). The hemoconcentrator is connected by means of a Luer-Lok connector to the arterial filter. During cardiopulmonary bypass, part of the oxygenated blood is bypassed to the ultrafilter, from which filtered blood reaches the venous line and is stored in the venous reservoir. Filtrate fluid is stored in a separate waste container, to be discarded later.

reduction of transfused blood products, improved hemostasis, dynamic pulmonary compliance, and modification of complement activation.[26] Ultrafiltration is a technique that removes plasma water and low-molecular-weight solutes by a convective process involving hydrostatic forces acting across a semipermeable membrane; substances with a molecular mass less than the membrane pore size are filtered because of the transmembrane gradient. The composition of filtrate is dependent on the pore size of the hemofilter. Continuous ultrafiltration (CUF) usually is performed during the rewarming phase of CPB to decrease the excess of total body water and limit postoperative edema (Fig. 208.1). The increase in total body water is caused by the relatively large volume of pump prime compared with the circulating blood volume, especially in small children. Because SIRS is triggered by CPB, it increases capillary permeability and further aggravates the increase in total body water. It is demonstrated that CUF fails to produce a consistent reduction in postoperative total body water or in transfusion requirements because of frequent addition of crystalloid or blood to the circuit to maintain an adequate reservoir level and CPB while on support. These unsatisfactory results with CUF in consistently preventing an increase in total body water and reversing hemodilution after CPB in children were the stimulus for the development of MUF by Naik et al.,[12] as mentioned earlier. In a preliminary study, these investigators compared the efficacy of no ultrafiltration, CUF, and MUF in preventing accumulation of excess total body water.[27] MUF is performed after CPB weaning: the blood is pumped retrograde from the aortic cannula, through the hemoconcentrator, and returned to the right atrium. This design results in return of warmed, hemoconcentrated, oxygenated blood to the heart and pulmonary vasculature (Fig. 208.2). The absolute volume of ultrafiltrate that should be removed to obtain maximal hemodynamic and end-organ functional improvement is not well defined. End points differ among institutions: some remove a specific volume (mL/kg) of ultrafiltrate; others perform MUF for a predetermined period of time (usually 15 to 20 minutes) or to achieve a specific hematocrit (usually greater than 40%).

Effectiveness of MUF has been quantified by Maehara et al.,[28] who validated the use of bioelectrical impedance as a noninvasive means of determining changes in total body water associated with CPB. The same group of investigators have demonstrated an increase in total body water of 11% to 18% higher than pre-CPB levels. Thus the optimal filtrate volume could be assessed by impedance evaluation before and after CPB. In fact, the benefits of MUF versus standard ultrafiltration (CUF) were first shown by the GOS group[12,28] as measured by bioelectrical impedance. The volume of ultrafiltrate that could be removed during MUF was significantly greater than that during CUF; MUF significantly reduced the postoperative increase in total body water, whereas the response to CUF was neither uniform nor reproducible.

The beneficial effects of MUF are multiple and have been demonstrated by several groups of investigators. Naik et al.[12] demonstrated a decrease in postoperative blood loss and consequently a reduction in blood products usage after MUF when compared with no ultrafiltration during CPB. A significant decrease in blood loss and blood transfusion requirements has been demonstrated by others.[29] In addition, MUF resulted in an unexpected increase in arterial blood pressure, increase in cardiac index, and decrease in pulmonary vascular resistance, without changes in systemic

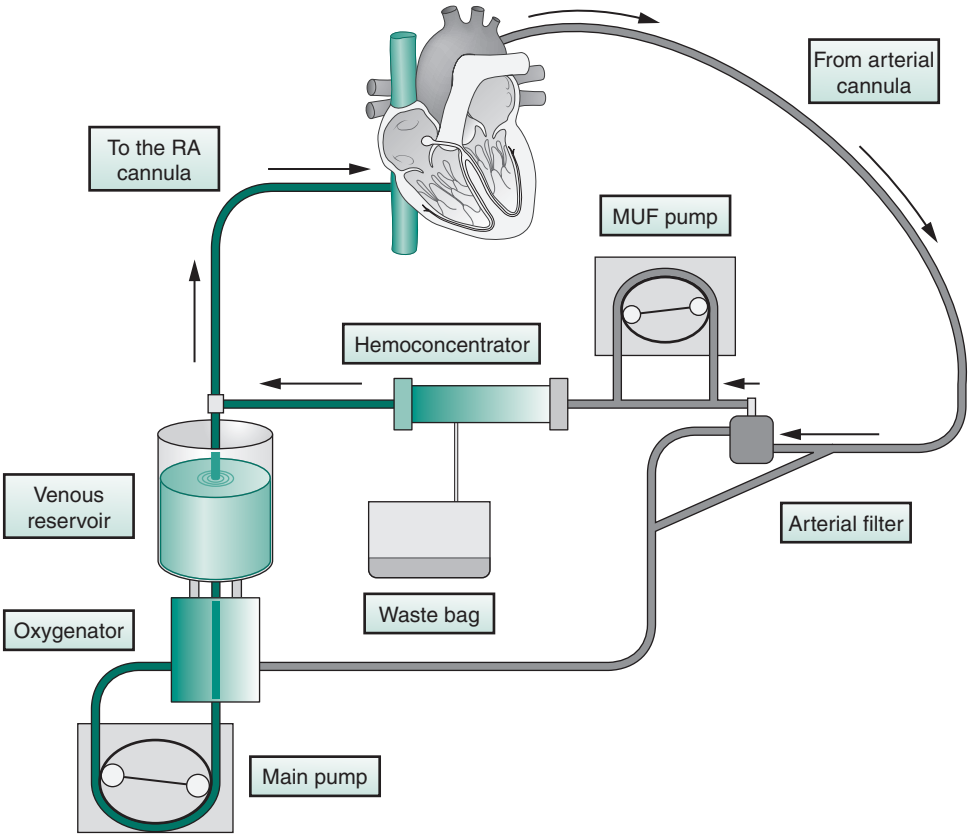

FIGURE 208.2 Diagram showing modified ultrafiltration (MUF) circuit. Ultrafilter/hemoconcentrator is connected by means of a Luer-Lok connector to the arterial filter. When cardiopulmonary bypass is off, a roller pump drives blood from the aorta to the ultrafilter-hemoconcentrator, from which filtered blood reaches the venous line and returns to the right atrium (RA). In this case, the venous reservoir line is clamped. Filtrate fluid is stored in a separate waste container, to be discarded later.

vascular resistance. These hemodynamic benefits correlated directly with the increasing hematocrit and thus the degree of hemoconcentration.[30]

Gaynor et al.[31] showed that increase in myocardial cross-sectional area seen after CPB can be reversed after MUF. Davies et al.[32] confirmed that MUF improves intrinsic left ventricular systolic function, improves diastolic compliance, increases blood pressure, and decreases inotropic drug use in the early postoperative period. In a randomized study in 21 infants undergoing CPB, an ultrasound dimension transducer was used to measure the anteroposterior minor axis diameter, and a left ventricular micromanometer was applied as well. Left ventricular systolic function was assessed by means of the slope of the preload-recruitable stroke work index. Myocardial cross-sectional area was measured by echocardiography. In the MUF group, the filtrate volume was 363 ± 262 mL. The hematocrit value increased from 26.0% ± 2.7% to 36.7% ± 9.5% ($p = .018$), myocardial cross-sectional area decreased from 3.72 ± 0.35 cm^2 to 3.63 ± 0.36 cm^2 ($p = .04$), end-diastolic length increased from 25.6 ± 9.0 mm to 28.8 ± 9.9 mm ($P = .01$), and end-diastolic pressure fell from 5.6 ± 0.8 mm Hg to 4.2 ± 0.8 mm Hg ($p = .005$), suggesting an improved diastolic compliance. In the control group, these parameters were unchanged. The demonstration of increased left ventricular end-diastolic length and decreased end-diastolic pressure is consistent with improved left ventricular compliance secondary to decreased myocardial edema.

Daggett et al.[33] confirmed the superiority of MUF to conventional ultrafiltration and no filtration in reducing total body weight gain, lessening myocardial edema, raising mean arterial pressure, and improving left ventricular contractility in neonatal piglets undergoing cardiopulmonary bypass and cardioplegic arrest.

The cause of the increase in blood pressure seen with MUF has raised the concern that substances other than water, such as anesthetic drugs, were being removed. Elliott[34] addressed the issue of fentanyl ultrafiltration by measuring serum fentanyl levels and pointed out that they remained within the high therapeutic range. He concluded that blood pressure changes were not related to a change in depth of anesthesia. By contrast, Taenzer et al.[35] examined the effects of MUF on plasma fentanyl levels using a two-phase in vivo and in vitro study (an in vitro experimental model to simulate MUF that allowed measurement of plasma fentanyl levels while eliminating biologic variables). Increases in plasma fentanyl levels were found in vitro as well as in vivo. These results confirm the beneficial effects of MUF on cardiac function and emphasize that variations in plasma drug levels should be taken into account in delivering anesthetic care and in analyzing the effect of MUF on outcome variables.

Another proven benefit of MUF is reduction in lung water, which will facilitate postoperative respiratory management in the ICU. In fact, reduction in total body water is associated with improved lung compliance and decreased airway pressures after surgery. Dynamic pulmonary compliance, which is decreased in CPB, normalizes after MUF.[36] Sever et al.[37] showed that MUF decreases the duration of mechanical ventilatory support and, subsequently, the length of ICU stay.

Current pediatric cardiac surgery includes use of low-flow CPB or circulatory arrest periods for repair of congenital cardiac disease. Concern has been shared by members of the medical community regarding negative effects of these often necessary techniques. Skaryak et al.[38] investigated the effect of MUF on cerebral metabolic recovery after deep hypothermic circulatory arrest on 1-week-old piglets that were supported by CPB and after 90 minutes of circulatory arrest followed by rewarming to 37°C. After being weaned from CPB, animals were divided into three groups: a control group, an MUF group, and a group in which transfusion with hemoconcentrated blood was given. Global cerebral blood flow was measured by xenon-133 clearance methods. Cerebral metabolic rate of oxygen consumption, cerebral oxygen delivery, and hematocrit were calculated before CPB, after CPB discontinuation, and after completion of MUF. These investigators showed an increase in cerebral oxygen consumption from baseline, suggesting that the decrease in cerebral metabolism seen immediately after CPB is reversible. High levels of cerebral metabolic rate of oxygen consumption may be necessary to repay the oxygen debt incurred during circulatory arrest. After MUF, cerebral oxygen delivery and metabolic rate of oxygen consumption increase, showing that brain recovery from metabolic dysfunction after deep hypothermic circulatory arrest can be improved with MUF. Proposed mechanisms for this improvement include decrease in cerebral edema as a reflection of the decrease in total body water, removal of vasoactive substances, and alteration of leukocyte-mediated injury.

As mentioned, the inflammatory response stimulated by exposure of blood to the nonendothelialized surfaces of the CPB pump, especially if coupled with hypothermia or circulatory arrest, contributes to capillary leakage. Several studies have explored the role of MUF in mediating activation of the inflammatory response seen with CPB. Dagget et al.[33] demonstrated in their neonatal swine model that MUF was effective in preventing accumulation of total body water and myocardial edema and resulted in improved cardiac function. Reinfusion of the filtrate was related to depressed myocardial function, suggesting that the filtrate does contain potentially toxic factors. El Habbal et al.[39] showed a marked decrease in the circulating concentration of IL-8 at the end of MUF. A significant decrease in plasma levels of C3a and C5a after MUF also has been demonstrated.[40] Further support that MUF is responsible for the reduction in circulating plasma levels of inflammatory mediators is the finding of C5a in the ultrafiltrate. Analysis of the ultrafiltrate demonstrated substantial amounts of inflammatory mediators and vasoactive substances, including interleukin (IL)-6, IL-8, and IL-10, tumor necrosis factor-alpha (TNF-α), and endothelin-1.[41–43] This is further evidence that MUF may modulate the inflammatory response. Thus limiting the inflammatory reaction by MUF will have significant effects on postoperative pulmonary and myocardial function. Journois et al.[42] reported a modification of CUF that they called "zero balance ultrafiltration," in which ultrafiltration is performed during rewarming and filtrate is replaced by crystalloid solution to maintain reservoir volume while allowing continuous ultrafiltration. After weaning from CPB is accomplished, MUF is started to reverse hemodilution. The rationale for doing this has been outlined by Gaynor,[44] who states that CUF and MUF are not competing techniques but rather complementary techniques with potentially additive positive effects. In fact, CUF may be used to remove inflammatory mediators and vasoactive substances, whereas MUF can be performed at the end of CPB to reverse hemodilution and decrease tissue edema. The concentration of inflammatory mediators does not differ between CUF and MUF; however, because filtrate volume is significantly greater in MUF, removal of mediators is correspondingly greater. Thus the optimal use of ultrafiltration in children undergoing open heart surgery will likely result from a combination of these two techniques.

Recently, MUF has been proposed as an additional instrument to minimize blood transfusions.[45] In fact, recent evidence showed the negative impact of blood transfusions on morbidity and mortality in the adult literature, including infection risk, increased hospital and intensive care unit stay, and costs.[46] Cardiac surgical repair of congenital heart disease in pediatric patients undergoing CPB can induce up to 300% hemodilutional effect because of circuit prime volumes.[47] The concept of bloodless surgery is not new in pediatric heart surgery. The vast majority of experience has been gained with patients of Jehovah's witness faith.[48–49] Using applicable blood conservation measures, cardiac surgery can be performed with similar outcomes and cost from day of surgery to discharge compared with controls in selected patients without blood transfusion.[50] Use of miniaturized circuit components to reduce overall circuit prime and resulting hemodilution in association to continuous arterial blood gas and venous saturation/hematocrit monitoring with CDI 500 (Terumo Cardiovascular, Ann Arbor, MI) has been reported.[45] Use of MUF at the end of bypass as additional technique for hemoconcentration is an effective method, minimizing necessity of blood transfusions. This has been reported to be effective even in a 3.2-kg patient.[51]

Finally, concerns have been raised about potential risks and complications of MUF resulting from technical errors or mishaps leading to changes in the delicate balance of the CPB circuit: improper assembly of the modified ultrafiltration pump, introduction of air into the patient's vascular system, line rupture, and hypotension resulting from exceedingly quick volume depletion caused by MUF, if appropriate volume replacement (i.e., fresh frozen plasma) is not effected. Neurologic deficits also potentially may be associated with modified ultrafiltration if the blood flow through the system is too high, causing a decrease in blood flow to the brain. An early concern was that MUF would lead to hemodynamic instability secondary to withdrawal of blood from the arterial cannula immediately after CPB.

For these reasons, recently McRobb et al.[52] have reported a total of 160 patients less than 8 kg who underwent congenital cardiac surgery without use of MUF. Although retrospective, this analysis supported an advantage of preventing hemodilution by means of circuit miniaturization instead of using reversing hemodilution by means of MUF.

Actually, the converse has proved to be equally true: implementation of a multidisciplinary bleeding and transfusion protocol associated to adequate utilization of MUF significantly decreased perioperative blood product transfusion and improved some bleeding outcomes.[53] MUF results in an increase in arterial blood pressure, with decreased filling pressure and improved cardiac function. Multiple studies have demonstrated, however, that all concerns over possible complications are primarily theoretical. In a review of 22 centers, Darling et al.[54] found no reports of MUF-related morbidity or mortality.

In conclusion, modified ultrafiltration has proved to be a safe and effective technique to improve the postoperative course in children undergoing open heart surgery. As reported by Groom et al.[55] in a recent survey of data for 76 hospitals in North America, MUF was used in 75% of the centers surveyed. Thus the beneficial effects of MUF currently are recognized, and MUF is used by most pediatric

cardiac surgeons. No study has yet established a definite relationship between removal of inflammatory mediators and improved outcome, however, and the mechanisms by which ultrafiltration results in improved organ function require additional elucidation.

Further studies are needed to identify which patients are most likely to benefit from MUF and to define the best protocols for rational use of this technique.

Key Points

1. Modified ultrafiltration currently is used in pediatric cardiac surgery to minimize the deleterious effects of cardiopulmonary bypass.
2. The recognized benefits of modified ultrafiltration are reduction in total body water accumulation seen after cardiopulmonary bypass, improved left ventricular function, increase in hematocrit with concomitant reduction in need for transfused blood products, improved hemostasis and dynamic pulmonary compliance, and modification of complement activation.
3. Modified ultrafiltration is a safe and effective technique that does not add either additional risk or excessive cost to the procedure of cardiopulmonary bypass.
4. Modified ultrafiltration after cardiopulmonary bypass must be performed by a certified clinical perfusionist.
5. Modified ultrafiltration after cardiopulmonary bypass may be used with hemofiltration during cardiopulmonary bypass to maximize beneficial effects for the patient.

Acknowledgments

We thank our perfusion team at the University of Padua, especially Enrico Ceccherini, CCP, Dario Fichera, CCP and Fabio Zanella, CCP, for their invaluable help in the preparation of the manuscript for this chapter and in our everyday work in the operating room.

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