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**Original Article*****Modified Ultrafiltration After Congenital Heart Surgery:  
A Venovenous Method Using a Dual-Lumen  
Hemodialysis Catheter***

Brian J. LaLone, PhD, CCP;\* Mark W. Turrentine, MD;† Ko Bando, MD;† Chris C. Frederick, BS, CCP;\* Michael T. Horner, BS, CCP;\* Lon H. Richmond, CCP;\* Alex P. Bezruczko, BA, BS, CCP;\* Susan M. Morris, BS, CCP;\* Deborah L. Frankenberg, MS, CCP;\* John W. Brown, MD†

\*Sections of Cardiovascular Perfusion and †Cardiothoracic Surgery, James W. Riley Hospital for Children and Indiana University Medical Center, Indianapolis, Indiana

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**ABSTRACT**

Perfusion practice surveys on modified ultrafiltration show most clinicians reporting the use of arterial to venous cannulation. With an arterial–venous (A–V) approach, the patient's blood is accessed in a retrograde direction from the cardiopulmonary bypass aortic cannula, and the hemoconcentrated blood is returned to a catheter placed at a systemic venous return site. To avoid possible hazards of these arterial–venous techniques, we developed a venovenous (V–V) modified ultrafiltration circuit and method that: (1) uses an 11.5 F dual-lumen hemodialysis catheter placed at a right atrial cannulation site for concomitant pickup and return of the patient's blood; (2) places the ultrafiltration circuit within the cardioplegia delivery system, enabling the use of the heat exchanger/bubble trap features and also allowing hemoconcentration during cardiopulmonary bypass; and (3) uses an elevated, collapsible transfusion bag within the circuit as a holding reservoir for crystalloid-chased blood from the CPB circuit.

The product literature and our lab testing of the hemodialysis catheter indicates adequate hemodynamics for modified ultrafiltration in children, and our clinical experience shows routine completion of the process in about 10–15 min ( $12.67 \pm 1.73$  mins; mean  $\pm$  1 SD,  $N = 9$ ). Advantages of this V–V approach compared to A–V access include: (1) no potential aortic air entrainment at the aortic cannula purse-string suture; (2) modified ultrafiltration in patients regardless of aortic size or anatomy; and (3) avoidance of significant arterial to venous shunts during the performance of modified ultrafiltration. The elevated reservoir within the modified ultrafiltration circuit allows: (1) efficient pre- and/or postultrafiltration fluid chasing of blood from the main cardiopulmonary bypass circuit, thereby keeping it safely primed and allowing for the concentration of all circuit contents before and/or following the ultrafiltration method; (2) maintenance of desired patient filling pressures, temperature, and blood oxygen saturation within the ultrafiltration circuit by intermittent addition of warmed, oxygenated blood to the V–V modified ultrafiltration circuit.

Address correspondence to: Brian J. Lalone, CCP  
Rm 0515, Indiana University Hospital  
550 N. University Boulevard, Indianapolis, IN 46202-5200

## INTRODUCTION

Modified ultrafiltration (MUF) used components of the extracorporeal circuit to perform hemofiltration of the patient for a brief period immediately upon weaning from cardiopulmonary bypass (CPB). First introduced in 1991 by Naik's group (1), clinicians using the method for pediatric cardiac surgery report perioperative hematocrit elevations (1–7), reductions in the rise in total body water (1, 2) and IL-8 levels (2, 8), reduced colloid transfusion needs (2, 9), increased blood colloid osmotic pressure (4), reduced blood loss and lower donor blood requirements (2, 9–12), improved hemodynamics (2, 9, 13–16), improved postoperative oxygenation and reduced duration of ventilator support (11), and reductions in the plasma titer of the terminal complement proteins C3a and C5a (6) as well as endothelin 1 (16). These reports of clinical benefit have been accompanied by a more widespread use of MUF following repair of congenital heart defects. In a series of pediatric perfusion practice surveys (17–20) Groom and associates report an increasing use of perioperative hemofiltration methods, with 43% of the programs responding in 1994 reporting the use of MUF (20).

When first incorporating MUF into clinical practice, perfusion teams have several considerations to weigh in deciding upon the approach that best suits their patients' needs. Chief among these concerns is safety. Because MUF necessitates CPB circuit modifications, a fundamentally safe MUF circuit design (4) and operational protocol (5) are important issues. Safety concerns also drive the decision-making process addressing which MUF cannulation method to use, and what safety devices to incorporate into the MUF circuit (21).

Most clinicians report the use of arterial–venous (A–V) cannulation for MUF (20, 21). With A–V MUF, the patient's blood is accessed in a retrograde direction from the CPB aortic cannula, and the hemofiltered blood is usually returned to a catheter placed in the right atrium. In a 1994 survey (20), 36% of respondents used an A–V method and only 7% of pediatric open-heart centers report using a veno–venous (V–V) approach. Darling and colleagues (21) surveyed 50 North American pediatric perfusion practices in 1996 and reported that of the 22 centers utilizing MUF, 86% were using an A–V approach.

Despite this predominant use of A–V methods, there are several theoretical disadvantages to the use of the CPB aortic cannula as a blood access for MUF. Using this method creates an arterial–venous shunt; which, in hemodynamically compromised patients, may not be well tolerated. In newborns, the aortic cannula is relatively large and can be obstructive to native cardiac output following some surgical corrections; possibly impairing MUF usage. Also, because of occasional malposition during retrograde flow, the tip of the aortic cannula can capture the aortic wall tissue resulting in negative pressures within the MUF circuit and aortic cannula; causing potential aortic air entrainment at the cannula purse-string suture when

capture is released, and/or air entry into the MUF circuit either across the oxygenator membrane or by cavitation.

To potentially address these last concerns regarding air, an A–V MUF circuit can include safety devices such as a pump servo-controlled by circuit pressure and a bubble trap device (4, 5). Alternatively, the use of a V–V cannulation method for MUF would avoid all of the above problems. However, because the ultrafiltration process necessarily removes dissolved oxygen and, thus, desaturates the blood, the V–V method has been suggested to be potentially harmful (3, 22) by presenting to the lungs a blood so desaturated as to cause pulmonary vasoconstriction.

This report presents our experiences in the establishment of a V–V MUF method in our pediatric perfusion practice. The MUF circuit and protocol addresses the concern for an appropriate oxygen saturation of MUF blood returning to the patient and as well, incorporates other safety and cost-minimizing features.

## MATERIALS AND METHODS

This work was conducted in two phases: preclinical and clinical. For the preclinical trials, we conducted both an *in vitro* and an *in vivo* study.

### PRECLINICAL MATERIALS AND METHODS

In the *in vitro* bench testing, we studied three separate and identical circuits with outdated human bank blood to help define optimal operational parameters and protocol before conducting animal tests. These MUF circuits contained 1/8-in ID tubing throughout, except for a 1/4-in ID section of pump raceway tubing that was coupled to an ultrafilter (Minntech<sup>a</sup> HPH400). In these tests, the MUF circuit pick-up and return tubings were connected to a dual-lumen catheter that was inserted into the needle port of a 1000 mL IV bag filled with diluted bank blood.

One *in vitro* circuit was used to test the time required to hemoconcentrate diluted bank blood to a 40-plus hematocrit comparing two dual-lumen subclavian access hemodialysis catheters (Medcomp,<sup>b</sup> #T114C and Cook,<sup>c</sup> #C-PU10. OD-NT-9-NS-DDS). These were identified from the literature (23, 24) as potentially acceptable for MUF use on the basis of the reported flow ranges (200–400 mL/min), outside diameter (10–12 F), and low recirculation rates (~9%). In this test, MUF pump flow was set at 200 mL/min and postultrafilter pressure was set at 400 mmHg by adjustment of a distally placed tubing screw clamp.

Another *in vitro* circuit was used to study pressure-flow relationships of the MUF circuit when using a Medcomp<sup>b</sup>

a Minntech Corp., Minneapolis, MN

b Medcomp, Inc., Harleysville, PA

c Cook, Inc., Bloomington, IN

T114C catheter. For this test, MUF circuit pump flow was set at 113 and 196 mL/min, and pressures were measured at the luer inlet and outlet catheter connection sites during the start (hemodiluted, hematocrit = 14) and completion (hemoconcentrated, hematocrit = 36) of the hemoconcentration period. A third in vitro MUF circuit was connected to our standard pediatric CPB circuit and used to define necessary further circuit modifications and to conduct perfusionist orientation sessions.

In the in vivo preclinical studies, seven dogs weighing 8.4 to 26 kg ( $15.4 \pm 7.8$  kg) were placed on CPB after being anesthetized and paralyzed using guidelines according to "Guide for the Care and Use of Laboratory Animals," (NIH Publication No. 85-23, revised, 1985). These animals were part of ongoing myocardial protection and pulmonary valve replacement studies. MUF was performed post-CPB to evaluate the appropriateness of the earlier bench findings, define necessary modifications in the MUF circuit, and associated procedures, conduct perfusionist troubleshooting and orientation sessions, finalize operational protocols, and familiarize the surgeons, anesthesiologists, and nurses with the MUF procedure.

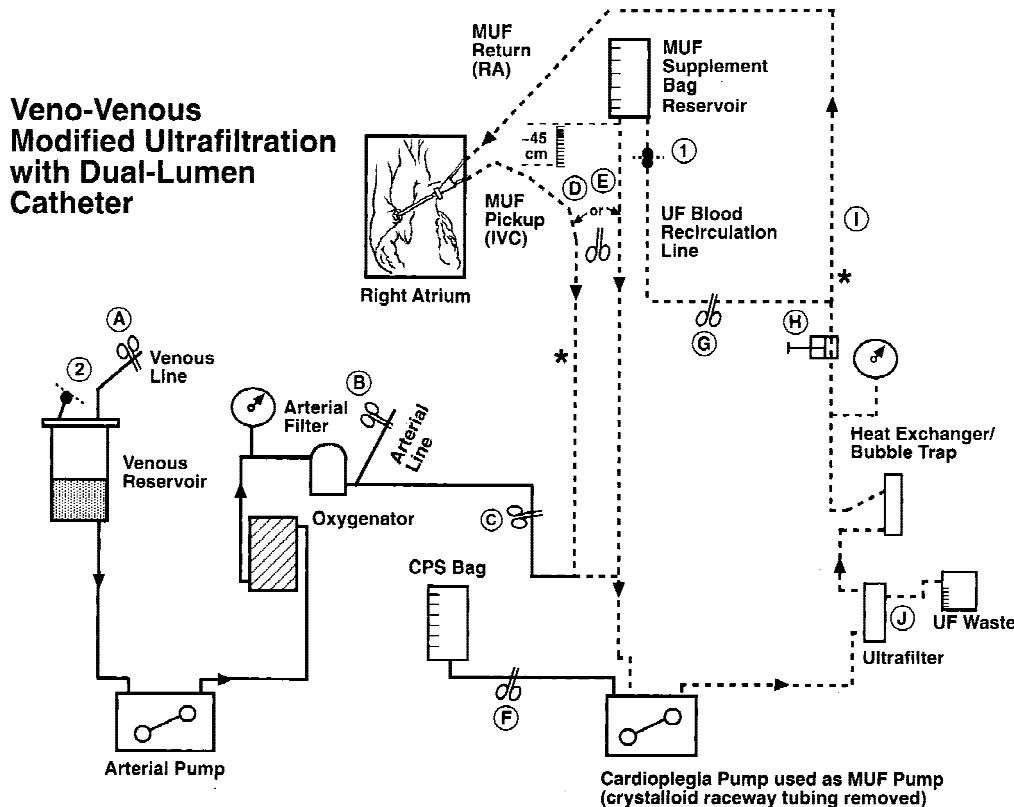
Two different MUF circuit designs were used in the in vivo

studies. In the first animal, a two-pump process for MUF was studied. In this circuit, V-V MUF was performed by one pump, and as ultrafiltrate was formed, the animal's filling pressures were maintained with volume from the oxygenator by transfusion to the MUF circuit loop by the arterial CPB pump. For the remaining six animals studied, a one-pump MUF process was performed using the MUF circuit design employed in the clinical phase.

**CLINICAL MATERIALS AND METHODS**

Figure 1 illustrates the basic MUF circuit that was developed through the preclinical studies and applied to patients following congenital heart surgery. The MUF circuit was introduced into the main CPB circuit just distal to the arterial filter (Terumo<sup>d</sup> Capiox Pediatric #CX\*AF02, or Medtronic<sup>e</sup> Intersept Pediatric #1338). This was the normal position occupied within our CPB circuit for the take-off of blood into a 4:1 blood

d Terumo Medical Corp., Tokyo, Japan  
 e Medtronic, Inc., Anaheim, CA



**Figure 1: Venovenous modified ultrafiltration circuit**

Dashed lines indicate the MUF circuit, with arrows denoting blood flow direction. Tubing clamps are positioned as during conduct of modified ultrafiltration during the postcardiopulmonary bypass period (see Table 1, step #6). Letters within circles (A through J) define potential position(s) of tubing clamps for the various uses of the circuit. Numbers 1 and 2 within circles define alternate stopcock attachment points of the ultrafiltered blood recirculation line. Asterisks denote the location of oxyhemoglobin sensor cuvettes placed within the circuit for five patients. Abbreviations: cm, centimeters; CPS, cardioplegia solution; IVC, inferior vena cava; MUF, modified ultrafiltration; RA, right atrium; UF, ultrafiltered.

cardioplegia set (Sorin<sup>f</sup> Vanguard™ Custom #PTS7028, or Gish<sup>g</sup> Straight Shot™ #SPBC14). This positioning enables cost efficiency, the ability to hemoconcentrate during CPB (when not delivering cardioplegia) and the use of the heat exchanger and bubble trap capabilities of the Vanguard™ during MUF. In our practice, children smaller than 15 kg may receive surgeon-delivered cardioplegia via a syringe. In these instances, we usually include a bubble trap (Terumo<sup>a</sup> Capiox Infant Bubble Trap #CX\*BT05) in the place of the Vanguard™, unless there is concern for excessive heat loss during MUF in a neonate.

The MUF circuit consisted of an ultrafilter (Minntech<sup>b</sup> HPH400, or Baxter<sup>h</sup> Hemocon 0.3), an 11.5 F dual-lumen he-

modialysis catheter (Mecomp<sup>b</sup> Duo-flow™ XTP #T114C) and a 1000 mL transfusion bag (Baxter<sup>h</sup> Clintec® Viaflex® Container #2B8004). The MUF circuit tubing set was custom made (Gish<sup>g</sup>, Cat. #8666 Riley Children's V-V MUF Circuit) with a ¼-in ID pump boot and the remainder made from ⅛-in ID tubing and appropriate connectors. With the transfusion bag (MUF supplement bag reservoir) empty, the total MUF circuit volume was 170 mL with the ⅛-in MUF pickup and return table lines holding 35 mL.

Figure 1 shows tubing clamps positioned for the MUF procedure, with the perioperative events surrounding the MUF procedure schematized in Table 1. Parameters for MUF generally included a pump flow rate set at 10–30 mL/min/kg and a MUF circuit back pressure at the hemoconcentrator (transmembrane pressure, TMP) set to about 450 mmHg with a partial occluding (Hoffman) screw clamp (screw clamp H, see

f Sorin Biomedical, Irvine, CA

g Gish Biomedical Inc., Irvine, CA

h Baxter Healthcare Corp., Irvine, CA

**Table 1: Routine sequence of steps for modified ultrafiltration at Riley Hospital for children**

Step # and approximate running time	Perioperative event	Team goals and procedures	Tubing clamp(s) on position(s)	MUF Pump, arterial pump and circuit characteristics
1. 00:00	Off cardiopulmonary bypass, patient stable, and venous cannulae just removed	Begin pre-MUF circuit preparatory procedures	A–J	CPB and MUF circuits de-aired and blood-filled
2. 00:05	Perfusionist seeks and receives permission to chase venous line blood to oxygenator	Crystalloid chase of venous line blood from saline-filled basin	Clamp A briefly released to allow fluid chase	
3. 00:20	Surgeon initiates MUF cannulation sequence	Perfusionist crystalloid-chases oxygenated, warmed blood in CPB circuit (venous reservoir through arterial filter) to MUF supplement bag reservoir	A, B, D, F, G, I, J	Arterial pump used for fluid chase procedure
4. 00:40	Surgeon asks perfusionist to fill MUF cannula lumens by gravity from MUF supplement bag	De-air MUF cannula lumens and connectors prior to cannulation	A–C; F, J	As surgeon taps cannula, 25–35 ml of blood is drained from MUF supplement reservoir
5. 01:00	Surgeon completes MUF cannulation through existing purse string suture in RA	Placement of cannula tip near inferior caval-atrial junction to pickup IVC blood	A–J	
6. 01:30	Begin MUF procedure	Maintenance of appropriate right heart filling pressures as ultrafiltrate is lost from circulation	A–C; D or E; F and Hoffman clamp H adjusted for a 450 mmHg back pressure	Intermittent placement of tubing clamp at location D or E enabling small aliquot addition of MUF supplement reservoir blood to V–V MUF circuit
7. 9:30 to 14:30	Perfusionist announces completion of MUF procedure	Perfusionist completes MUF procedure when MUF supplement reservoir is empty or desired hemoglobin is achieved	A–J	
8. 15:00	Surgeon removes MUF catheter from RA		A–J	

Figure 1). With the ultrafiltration process ongoing, the perfusionist maintains the patient's right heart filling pressures by frequent (approximately every 3–10 sec) and brief (approximately 2–10 sec duration), intermittent volume additions from the supplement bag to the V–V MUF loop.

The circuit is designed to also enable hemoconcentration during CPB. When the pump is not being used for cardioplegia delivery, on-pump ultrafiltration is accomplished by placement of the UF blood recirculation line (see Figure 1) at stopcock position #2, removal of the crystalloid raceway tubing and tubing clamps placed at the DEFHI (see Figure 1) positions. To prepare for the next potential delivery of cardioplegia, the perfusionist clears the pump side of the cardioplegia circuit of the concentrated blood by pump-filling it with 4:1 cardioplegia (clamps at DEIJ, crystalloid tubing in raceway, and UF blood recirculation line at stopcock position #2: see Figure 1).

While off bypass during pre- and post-MUF periods, the MUF circuit can be used to concentrate blood from the main cardiopulmonary bypass circuit (venous line through arterial filter). This is accomplished by first using the arterial pump to crystalloid-chase that portion of the circuit's contents to the MUF supplement bag (clamps at ABDFGHIJ, see Figure 1). Next, the contents of the MUF bag can be hemoconcentrated (clamps at ABCDFHI, crystalloid tubing out of raceway, UF blood recirculation line at stopcock position #1: see Figure 1).

Following MUF cannula removal, the CPB circuit contents were concentrated as described above when the surgeon requested that the heparin reversal dose of protamine be given. Because use of a hemofilter to concentrate residual pump contents results in a significant concentration of heparin (25–28), the protamine dose was calculated with the assumption that during the hemofiltration process very little heparin crosses into the ultrafiltrate. Supplemental protamine was also given to the patients following transfusion of the concentrated pump blood. The effectiveness of the initial and supplemental protamine doses were assessed by activated coagulation test (ACT) determinations following each protamine dose.

During MUF, patient volume was maintained by the intermittent addition of oxygenated blood to the veno-venous circuit from the supplement bag reservoir. In five patients, we tested the ability of this method to augment the hemoglobin oxygen saturation of the MUF circuit blood returning to the right atrium. For these patients, two ¼-in hemoglobin oxygen saturation cells (Gish<sup>®</sup> STATSAT, #SS2500) were placed in the MUF IVC-pickup and RA-return lines at the locations noted in Figure 1. These cells were connected to the STATSAT monitor (Software version 4.0) and calibrated before the termination of CPB with a 5 min recirculating of CPB circuit blood past the cells through a closed, shunted MUF circuit loop. Meter saturation data were updated at 3.3-sec intervals, and these values were continuously recorded during MUF by a printer coupled to the RS232 dataport of the STATSAT monitor. The STATSAT system digital electronics and software

provide a accuracy and responsiveness that allow it to report an oxygen saturation change as small as 0.2% in 3 sec (29). For each 3.3-sec interval update, a saturation difference was computed between the MUF blood returning to the right atrium (return) and the saturation of blood picked up at the cannula lumen (pickup) in the IVC.

We timed the MUF procedure outlined in Table 1 in nine consecutive patients to assess the time required to perform MUF in our patients. In 12 separate patients, we examined the ability of MUF to augment the patient's hematocrit by performing hematocrit determinations on radial artery blood samples drawn immediately before and following the MUF procedure.

Saturation, time of MUF, and hematocrit data were entered into an Excel<sup>1</sup> database and analyzed for statistical significance using analysis of variance (ANOVA) and paired *t*-tests. All values were expressed as mean  $\pm$  one standard deviation of the mean.

## RESULTS

### PRECLINICAL STUDIES

In our in vitro test of the hemodialysis catheters, both showed an ability to hemoconcentrate 1000 mL of buffered, diluted bank blood from a 15 to a 40-plus hematocrit in less than 10 min. The Medcomp<sup>b</sup> catheter was selected for clinical use on the basis of a thinner wall thickness and the presence of multiple side holes at the pickup and return sites.

The hemodynamics of the Medcomp catheter coupled to our MUF circuit was examined at two blood flow levels and at two different hematocrits in one in vitro circuit. At a flow of 113 mL/min, pressure at the return inlet to the cannula (postpump) ranged from 29 to 33 (mean = 30.7) mmHg at a hematocrit of 14, and from 57 to 74 (mean = 65.5) mmHg at a hematocrit of 36. When pump flow was placed at 196 mL/min, pressure at cannula inlet ranged from 39 to 52 (mean = 45.2) mmHg at a hematocrit of 14, and from 89 to 121 (mean = 105) mmHg at a hematocrit of 36. At a flow of 113 mL/min, pressure at the pickup arm of the cannula outlet (prepump) ranged from –8 to 16 (mean = 7) mmHg at 13 hematocrit, and from –42 to –2 (mean = –22) mmHg at a hematocrit of 36. When pump flow was set to 196 mL/min, pressure at cannula outlet ranged from –32 to 11 (mean = –21) mmHg at 13 hematocrit, and from –48 to –20 (mean = –29) mmHg at a hematocrit of 36.

In the first animal studied, we rejected the use of a two-pump model for MUF as too cumbersome and confirmed the utility of the concept of a MUF supplement bag reservoir in the subsequent six animals studied. Animal studies also confirmed that by frequent intermittent addition from the supplement bag, the apparent blood oxygen saturation (as determined by viewing the "brightness" of the blood) of hemoconcentrated MUF

i Microsoft Corp., Redmond, WA

blood returning to the right atrium could often be maintained at a higher saturation than the IVC pickup blood.

**CLINICAL STUDIES**

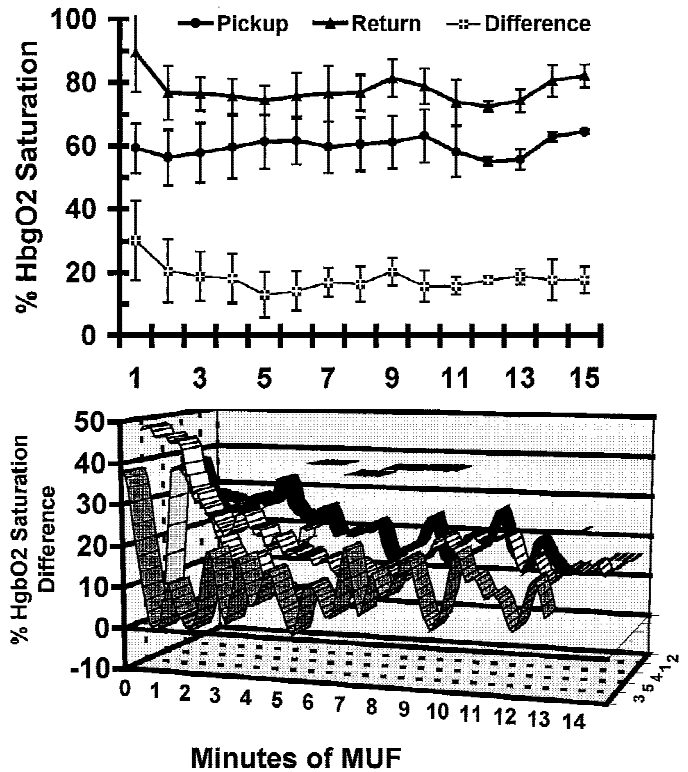
Patient use began in July, 1996 and through October 1998, 487 of 637 patients received MUF following cardiopulmonary bypass. There were no patient complications from the use of the MUF technique. Our total MUF clinical experience can be separated into two sequential periods: early and recent. In our *early* experience (July 1, 1996 through January, 1997) patients were considered for MUF treatment on the basis of patient entry into risk-stratified, randomized prospective trials studying the mechanisms of patient improvement following MUF and the utility of on-pump hemofiltration and MUF treatment. Portions of these studies and their results have been presented elsewhere (11, 16).

In our *recent* clinical experience (February 1, 1997 through October, 1998), 444 of 508 patients received MUF following cardiopulmonary bypass. MUF patients ranged in age from 1 day to 21 years ( $787 \pm 935$  days); weight varied from 2.2 to 152 kg ( $10.7 \pm 9.7$  kg). Of the 64 patients not selected for MUF during this period: 52 were large (weight greater than approximately 35 Kg, with no other indications such as preoperative pulmonary hypertension, pulmonary edema, renal failure); nine were transferred directly from cardiopulmonary bypass to long-term extracorporeal membrane oxygenation (ECMO) support; and three died immediately upon separation from cardiopulmonary bypass following surgical correction. The MUF ultrafiltrate volume ranged from 300 to 3200 mL ( $816 \pm 297$  ml). Indexed to body weight, the MUF fluid loss ranged from 19 to 431 mL/kg ( $106 \pm 59$  mL/kg).

In a consecutive group of MUF patients treated in February, 1997 ( $N = 9$ ); the time required to accomplish the V-V MUF technique as outlined in Table 1 was  $12.7 \pm 1.73$  min. In 12 other MUF patients treated before February, 1997, the patient hematocrit was elevated  $56.4 \pm 27.7\%$  by MUF from  $20.1 \pm 4.4$  to  $30.9 \pm 5.5$  ( $p = .00008$ ).

The oxygen hemoglobin saturation data from five patients are displayed in Figure 2. As illustrated by the oxygen hemoglobin saturation difference (Figure 2, lower panel), the MUF blood returning to the patient was augmented with oxygen in 760 of the 762 STATSAT meter updates throughout the duration of MUF. The saturation difference ranged from  $-0.1\% + 48.3\%$ ; whereas, time of MUF varied between 5.3 to 14.5 min. The mean saturation data (Figure 2, upper panel) demonstrates that this veno-venous MUF method consistently elevates the oxygen hemoglobin saturation of the MUF blood returning to the patient's right atrium. For the entire duration of MUF in these five patients, the IVC pickup blood averaged  $59.5 \pm 8.6\%$  and was augmented to  $78 \pm 8.6\%$  upon return to the patient's RA,  $18.6 \pm 9.1\%$  difference ( $p < .00001$ ).

In an attempt to reduce cost and increase utility, we incorporated the MUF circuit into the cardioplegia circuit and included a bag reservoir to enable postpump processing of circuit



Upper panel: Pickup values were those obtained from the sensor cuvette placed in the MUF pump inlet tubing to assess blood entering the MUF circuit from the patient's IVC (see Figure 1). Return values were obtained from the cuvette placed in the MUF circuit tubing postpump to assess MUF blood returning to the patient's RA (see Figure 1). Difference values were those computed by subtracting the pickup from the return. Values are expressed as mean  $\pm$  1 standard deviation of the mean. Lower Panel: Oxygen hemoglobin saturation difference during MUF in each of the five patients. Values plotted to form a continuous ribbon are the individual saturation differences calculated from each consecutive pair of pickup and return 3.3-sec STATSAT meter updates. The discontinuous data illustrated in minutes 4-7 of patient #2, and minutes 11-15 of patient #1, displays the data obtained from audiotape dictation of intermittent STATSAT meter updates during these intervals when the printer coupled to the STATSAT meter failed to capture the data. Abbreviations: HgbO2, oxygen hemoglobin; MUF, modified ultrafiltration.

**Figure 2: Oxygen hemoglobin saturation during modified ultrafiltration**

**Table 2: Disposables cost difference for use of MUF compared to post-CPB centrifugal cell salvage and 4:1 blood cardioplegia delivery**

MUF replaces post-CPB cell salvage of CPB circuit contents*		MUF replaces post-CPB cell salvage of CPB circuit contents and 4:1 blood cardioplegia*
Heat exchanger in MUF circuit	Bubble trap in MUF circuit	
\$89.40	\$34.80	\$6.72

\*Assumes hemoconcentrator use during CPB on all cases.

contents. Thus, our MUF method was employed without the concurrent use of a centrifugal cell salvage device for post-MUF processing of the extracorporeal circuit blood. As illustrated by the cost data of Table 2, our experience shows an approximate additional cost of \$7 to perform MUF on pump cardioplegia cases; with higher costs incurred on cases in which cardioplegia is delivered by the surgeon.

## DISCUSSION

Our experiences with the dual-lumen hemodialysis catheter indicate that although MUF hemodynamics were satisfactory, improvements are needed in the catheter design to optimize it for MUF. This catheter was designed for a Seldinger guidewire insertion via a subclavian or femoral stick (24). Accordingly, it has a sharper tip than is desired for placement at the inferior cavoatrial junction. In addition, being designed for longer-term use than a 10–15 min MUF treatment, the materials of construction are necessarily more expensive than may be required for MUF.

It is noteworthy that although we experimented with a dual cannulation technique for V–V MUF in the animal lab setting, we have no clinical experience using this modality. With practiced technique, it is reasonable to expect that the cost of the dual-lumen cannula could be eliminated by instead using two cannulae (i.e., a vent catheter and a small venous cannula) already opened on the operative field. An important feature of the particular dual-lumen cannula chosen for our work, is that its inherent design limits the recirculation rate to a nominal amount (24). As discussed by Darling and colleagues (21), one potential disadvantage of a veno–venous method that both accesses and returns blood to the right atrium is the possibility of considerable recirculation. Because we found that MUF can be accomplished in a reasonably short period of time with the use of the chosen dual lumen catheter, our studies suggest that recirculation effects are minimal.

The veno–venous approach avoids the risks of aortic-cannula related arterial air embolism that may accompany a negative pressure event with arterial-venous methods. Although servo-control of the arterial–venous pump may reduce the likelihood of such embolisms, this technology is not available from all pump manufacturers. It is important to note that negative pressure is present within the IVC pickup arm of our MUF circuit during routine operation. Accordingly, within our protocol we have a mandatory check of a tubing clamp placed on the MUF access line to the main CPB circuit (position C, Figure 1), preventing air entry across the membrane oxygenator.

The method reported here illustrates the utility of including an in-line reservoir within the MUF circuit. Circuit blood contents can be translocated to the reservoir enabling a hemoconcentrated blood product for later transfusion, thus avoiding the use of centrifugal cell processing with its attendant loss of

platelets, clotting factors, and other plasma proteins. In addition, by semicontinuous addition of the warm supplement reservoir blood to the V–V MUF circuit, the patient's filling pressures and blood temperature can be easily maintained.

This study indicates that while supplement bag blood is added to the circuit, the hemoconcentrated MUF blood returning to the right atrium has an approximate 18% higher blood oxygen saturation than that blood entering the MUF circuit from the IVC. Elliott has suggested that the benefits of MUF may partially derive from the delivery of an oxygenated blood to the lungs (8). In this regard, one group reports abandonment of V–V MUF (nonoxygen supplemented) in a patient when pulmonary hypertension was observed (3). In our own experience, this has not been found. Rather, in a prospective study using the particular veno–venous method reported herein, patients with preoperative pulmonary hypertension receiving V–V MUF have a reduced incidence of perioperative pulmonary hypertension compared to the control group not receiving MUF (16). Other benefits accompanying MUF usage in our patients included a decreased need for blood transfusion and a reduced duration of ventilatory support with an improved post-operative oxygenation (11).

Our experience, like that of others working with arterial–venous methods, shows a marked rise in hematocrit through the use of modified ultrafiltration. In addition, this method is generally performed in less than 15 min and is accompanied with improved hemodynamics. Results to date indicate that the technique has great promise.

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## REFERENCES

1. Naik SK, Knight A, Elliott MJ. A successful modification of ultrafiltration for cardiopulmonary bypass in children. *Perfusion*. 1991;6:41–50.
2. Naik SK, Knight A, Elliott M. A prospective randomized study of a modified technique of ultrafiltration during pediatric open-heart surgery. *Circulation*. 1991;84(Suppl III):III422–III431.
3. Mongero L, Sistino JJ. Techniques for modified ultrafiltration following cardiopulmonary bypass. *Proc Am Acad Cardiovasc Perf*. 1994;15:34–5.
4. Groom RC, Akl BF, Albus RA, et al. Alternative method

- of ultrafiltration after cardiopulmonary bypass. *Ann Thorac Surg.* 1994;58:573-4.
5. Darling EM, Shearer IR, Nanry K, et al. Modified ultrafiltration in pediatric cardiopulmonary bypass. *J Extra-Corp Technol.* 1994;26:205-09.
  6. Andreasson S, Gothberg S, Berggren H, et al. Hemofiltration modifies complement activation after extracorporeal circulation in infants. *Ann Thorac Surg.* 1993;56:1515-17.
  7. Freisen RH, Campbell DN, Clark DR, et al. Modified ultrafiltration attenuates dilutional coagulopathy in pediatric open heart operations. *Ann Thorac Surg.* 1997;64:1787-9.
  8. El Habbal MH, Smith L, Strobel S, et al. Modified ultrafiltration after cardiopulmonary bypass for repair of ventricular septal defect reduces serum IL8. *Circulation.* 1993;88(Suppl I):I-96.
  9. Ad N, Snir E, Katz J, et al. Use of the modified technique of ultrafiltration in pediatric open-heart surgery: A prospective study. *Isr J Med Sci* 1996;32:1326-31.
  10. Koutlas TC, Gaynor JW, Nicolson SC, et al. Modified ultrafiltration reduces postoperative morbidity after cavopulmonary connection. *Ann Thorac Surg.* 1997;64:37-42.
  11. Bando K, Turrentine MW, Vijayaraghaven P, et al. Effect of modified ultrafiltration in high-risk patients undergoing operations for congenital heart disease. *Ann Thorac Surg.* 1998;66:821-8.
  12. Draaisma AM, Hazekamp MG, Frank M, et al. Modified ultrafiltration after cardiopulmonary bypass in pediatric cardiac surgery. *Ann Thorac Surg.* 1997;64:521-5.
  13. Elliott MJ. Ultrafiltration and modified ultrafiltration in pediatric open heart operations. *Ann Thorac Surg.* 1993;56:1518-22.
  14. Naik S, Balaji S, Elliott MJ. Modified ultrafiltration improves hemodynamics after cardiopulmonary bypass in children. (Abstract) *J Am Coll Cardiol.* 1992;19:37A.
  15. Davies MJ, Nguyen K, Gaynor JW, et al. Modified ultrafiltration improves left ventricular systolic function in infants after cardiopulmonary bypass. *J Thorac Cardiovasc Surg.* 1998;115:361-70.
  16. Bando K, Vijay P, Turrentine MW, et al. Dilutional and modified ultrafiltration reduces pulmonary hypertension after operations for congenital heart disease: A prospective randomized study. *J Thorac Cardiovasc Surg.* 1998;115:517-27.
  17. Groom RC, Hill AG, Akl BF, et al. Pediatric perfusion survey. *Proc Am Acad Cardiovasc Perfus.* 1990;11:78-84.
  18. Hill AG, Groom RC, Akl BF, et al. Current paediatric practice in North America. *Perfusion.* 1993;8:27-38.
  19. Groom RC, Hill AG, Akl B, et al. Neonatal cardiopulmonary bypass—A review of current practice in North America. *Cardiol Young.* 1993;3:353-69.
  20. Groom RC, Hill AG, Kurusz M, et al. Paediatric perfusion practice in North America: An update. *Perfusion.* 1995;10:393-401.
  21. Darling E, Nanry K, Shearer I, et al. Techniques of paediatric modified ultrafiltration: 1996 Survey results. *Perfusion.* 1998;13:93-103.
  22. Elliot MJ, Gorney RM, Mongero LB, et al. Ultrafiltration: Panel discussion. *Proc Am Acad Cardiovasc Perfus.* 1994;15:37-40.
  23. Bunchman TE, Donckerwolcke RA. Continuous arterial-venous diahemofiltration and continuous veno-venous diahemofiltration in infants and children. *Pediatr Nephrol.* 1994;8:96-102.
  24. Milligan C, Morgan AG. A trial of two sizes of dual-lumen subclavian catheters for acute hemodialysis. *Dial Transplant.* 1989;18:601-11.
  25. Groom RC, Munoz R, McGowen K, et al. Ultrafiltration concentrates heparin. *Proc Am Acad Cardiovasc Perfus.* 1996;17:83-5.
  26. Clar A, Larson DF. Hemofiltration: Determinants of drug loss and concentration. *J Extra-Corpor Technol.* 1995;27:158-63.
  27. Traynor L, Sutton R, Riley J, et al. Comparing ultrafiltration and centrifugation during and after pediatric cardiopulmonary bypass. *J Extra-Corpor Technol.* 1992;23:140-51.
  28. Williams GD, Oakes RL, Totzec FR, et al. Comparison of the effects of red cell separation and ultrafiltration on heparin concentration during pediatric cardiac surgery. *J Cardiothorac Vasc Anesth.* 1997;11:840-4.
  29. Gish STATSAT product brochure. Gish Biomedical, Inc., Irvine, CA, 1992.