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Effect of Modified Ultrafiltration on Pulmonary Function After Cardiopulmonary Bypass*

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Background: **Pulmonary dysfunction is one of the most common manifestations of inflammatory response after cardiopulmonary bypass (CPB).**

Objective: **This prospective randomized study was conducted to evaluate the effect of a modified ultrafiltration (MUF) technique on pulmonary function after CPB in children.**

Methods: **Forty patients weighing from 5 to 10 kg with congenital heart disease who required CPB for primary biventricular operative repair were prospectively randomized into two groups. The control group received conventional ultrafiltration (CUF) during CPB, and the study group received CUF and MUF. Pulmonary compliance (static and dynamic) and gas exchange capacity of the lung expressed as oxygen index, respiratory index, ventilation index, and alveolar-arterial oxygen pressure difference were measured after intubation (baseline), at the termination of CPB, at the end of MUF, on admission to the ICU, and 6 h postoperatively.**

Results: **There was no significant difference in lung compliance and gas exchange between the two groups before CPB. CPB produced a significant decrease in static and dynamic lung compliance in both groups. In the control group, static and dynamic lung compliance decreased from 1.0 ± 0.3 to 0.90 ± 0.3 mL/cm/kg and 0.87 ± 0.2 to 0.71 ± 0.1 mL/cm/kg (± SE) [$p = 0.0002$ and $p = 0.002$, respectively]. In the study group, static and dynamic lung compliance decreased from 1.0 ± 0.2 to 0.89 ± 0.03 mL/cm/kg and 0.94 ± 0.2 to 0.77 ± 0.1 mL/cm/kg ($p = 0.002$ and $p = 0.002$, respectively). There was no significant difference in the decrease in static ($p = 0.9$) or dynamic lung compliance ($p = 0.3$) between the two groups. MUF produced a significant immediate improvement in both static lung compliance (0.89 ± 0.2 to 0.98 ± 0.2 mL/cm/kg, $p = 0.03$) and dynamic lung compliance (0.77 ± 0.1 to 0.93 ± 0.2 mL/cm/kg, $p = 0.007$). The same was observed regarding the gas exchange capacity. CPB produced a significant decrease in lung gas exchange capacity, and MUF produced a significant immediate improvement in lung gas exchange capacity. The effect of MUF on lung compliance and gas exchange capacity was not sustained after admission to the ICU nor 6 h later postoperatively. There was no significant difference in the time of extubation between the two groups (12 ± 3 h and 13 ± 2 h, $p = 0.4$), the length of ICU stay, or the total hospital stay postoperatively.**

Conclusions: **The use of MUF after CPB can produce an immediate improvement in lung compliance and gas exchange capacity, which may effectively minimize pulmonary dysfunction postbiventricular repair of congenital heart disease. However, these improvements are not sustained for the first 6 h postoperatively and do not reduce the duration of postoperative intubation, ICU stay, or total hospital stay.** ***(CHEST 2005; 128:3447–3453)***

Key words: cardiopulmonary bypass; conventional ultrafiltration; gas exchange capacity; lung compliance; modified ultrafiltration; pulmonary function

Abbreviations: CPB = cardiopulmonary bypass; CUF = conventional ultrafiltration; FIO_2 = fraction of inspired oxygen; MUF = modified ultrafiltration; OI = oxygen index; $P(A\text{-}a)O_2$ = alveolar-arterial oxygen pressure difference; PEEP = positive end-expiratory pressure; PF = pulmonary function; PIP = peak inspiratory pressure; RI = respiratory index; VI = ventilation index; VT = tidal volume

Cardiopulmonary bypass (CPB) is a nonphysiologic procedure that is associated with hemodilution and an inflammatory response that leads to the accumulation of body water and organ dysfunction. [1] Clinically, pulmonary dysfunction is one of the most common inflammatory responses, with a high incidence among infants and younger patients. [2] The severity of pulmonary dysfunction is determined by several factors such as CPB time, fluid needed to be added to the CPB circuit, and lung collapse during

CPB. Various methods have been proposed for its prevention. Ultrafiltration has been used almost routinely during CPB to reduce body water retention. [3] However, conventional ultrafiltration (CUF) has its limitations to remove water. In 1991, modified ultrafiltration (MUF) was introduced in an attempt to improve the efficacy of ultrafiltration.[4] Some studies[5–16] have shown that MUF produced immediate improvement in pulmonary function (PF) in children that led to a shorter ventilatory course and possibly a shorter ICU stay; however, these studies included a broad range of patient ages, weights, and immediate outcomes, which made the effect of MUF nonspecific. The purpose of this prospective randomized controlled study was to evaluate the effect of MUF on PF in patients weighing from 5 to 10 kg with congenital heart disease who required CPB for primary biventricular operative repair. Patients were evaluated to determine whether any improvement in PF would result in earlier extubation and/or earlier discharge from the ICU.

Materials and Methods

Patients

Patients weighing from ≥ 5 to ≤ 10 kg and undergoing primary biventricular repair in the period from August 2002 and November 2003 were eligible for inclusion in the study. A power analysis indicated that 18 patients would be needed in each group to show a 20% difference in pulmonary compliance, assuming that type I error is 0.05 and type II error is 0.02 (power 80%). Patients were excluded if they required mechanical ventilation for ≤ 6 h, emergency operations, a redo operation, preexisting pulmonary disease, open chests after surgery, and extracorporeal membrane oxygenation. Patients who had elective residual interatrial or interventricular shunts postoperatively were also excluded. There were 51 patients weighting from ≥ 5 to ≤ 10 kg during the study period. Of this group, 40 patients met the inclusion criteria. Patients were randomized at the time of surgery into a control group (20 patients who received CUF during CPB) and a study group (20 patients who received CUF during CPB and MUF immediately after CPB). Randomization was performed by alternate assignment of consecutive patients to the control or MUF groups.

Operative Management

Operative management was standardized. No changes in surgical, anesthetic, or perfusion techniques were made for the purpose of the study.

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Anesthetic Technique

Patients received oral midazolam, 0.7 mg/kg, for premedication. Anesthesia was induced and maintained with a continuous infusion of 4 μg/kg/min of midazolam, 5 μg/kg/min of fentanyl, and vecuronium boluses, 0.1 mg/kg, as required. All patients were intubated orally with cuffed endotracheal tubes.

CPB

The extracorporeal circuit included a hollow fiber membrane oxygenator (Dideco 705; Dideco; Miranddola, Italy) and a roller pump system (Cobe Cardiovascular Incorporated; Arvada, CO) in both groups. Cannulation was accomplished using the ascending aorta for inflow and the right atrium or separate caval cannulae for the outflow. The pump prime consisted of crystalloid and albumin 25%, $NaHCO_3$, and packed RBCs sufficient to keep hematocrit value from 20 to 25%. Cooling was achieved with the in-line heat exchanger. Mild systemic hypothermia (temperature < 32°C and > 30°C) was maintained during aortic cross-clamping. Cold blood cardioplegic solution was used at 20 to 30 mL initially and 10 to 15 mL/kg every 20 to 30 min for myocardial preservation. Warm blood with normal potassium was administered for 3 min to all patients before removing the aortic cross-clamp. CUF was done during CPB to keep the hematocrit value from 20 to 25%.

MUF Technique

A hemoconcentrator (Hemocor HPH; Minntech Corporation; Heelen, the Netherlands) was used in all cases. The molecular cutoff weight of the filter is 65,000 D. MUF was carried out immediately after the completion of bypass and when the patient was judged to be hemodynamically stable. An arteriovenous technique was performed as described before. [4] Briefly, an aortic cannula was used as the inflow to the ultrafilter, and blood returned to the right atrium via the cardioplegia line, which was attached to the right atrium or superior vena cava cannula. Suction was applied to the filter port at a rate not exceeding 200 mm Hg. The ultrafilterate was removed at a rate not exceeding 50 mL/kg/min. The target volume for ultrafiltration removal was the priming solution plus any additional fluid during CPB minus the CUF fluid minus urine output during bypass.

After discontinuation of CPB in the control group or after MUF in the study group, heparin was reversed with protamine sulfate. All patients were weaned off CPB on small doses of dopamine and dobutamine. In the ICU, inotropic agents (dopamine and dobutamine) and afterload-reducing agents (phentolamine) were used as necessary to maintain appropriate mean arterial BP for age.

PF Measurements

After induction of anesthesia but before surgical incision, measurements of lung compliance and gas exchange capacity were taken (baseline measurement). Repeated measures were obtained immediately after termination of CPB (postbypass measurement), within the first hour after admission to ICU (admission measurement), and 6 h after admission to ICU (6-h measurement). Patients who underwent MUF had an additional measurement immediately after MUF (post-MUF measurement).

Lung Compliance: Static and dynamic lung compliances were measured (Siemens Servo 300; Siemens; Elma, Sweden). Measurements were performed using volume-control mode with a fixed tidal volume (V_T) [10 mL/kg], fixed positive end-expiratory pressure (PEEP), rate, fraction of inspired oxygen (FIO_2) and inspiratory time percentage. Static and dynamic lung compliances were calculated from the following formulae:

$$\text{static compliance} = V_T/(PIP - PEEP)\text{with inspiratory hold}$$

$$\text{dynamic compliance} = V_T/(PIP - PEEP)\text{without inspiratory hold}$$

where PIP = peak inspiratory pressure.

Gas Exchange Capacity: Oxygen index (OI) was calculated according the following formula:

$$OI = MAP \times FIO_2/PaO_2$$

where MAP = mean airway pressure, and FIO_2 = fraction of inspired oxygen. $P(A\text{-}a)O_2$ (alveolar-arterial oxygen pressure difference) was calculated according to the following formula:

$$P(A\text{-}a)O_2 = FIO_2\,(\text{barometric pressure} - 47\text{ mmHg}) - PaCO_2/R - PaO_2$$

also expressed as:

$$P(A\text{-}a)O_2 = FIO_2 \times 713 - PaCO_2/R - PaO_2$$

where 760 = barometric pressure at sea level, and R = respiratory exchange ratio. A value of 0.85 is generally assumed on room air and a value of 1 at FIO_2 of 1. The respiratory index (RI) was calculated according to the following formula:

$$RI = P(A\text{-}a)O_2/PaO_2$$

Ventilation index (VI) was calculated according to the following formula:

$$VI = RR \times (PIP - PEEP) \times PaCO_2/1{,}000$$

where RR = the respiratory rate.

Strategy for Extubation

The protocol for initial respiratory management consisted of mechanical ventilator support to maintain the arterial blood gas levels within normal limits. When the patients were hemodynamically stable, mechanical ventilatory support and sedation were weaned. When the patients were able to sustain adequate spontaneous respiration and required minimal oxygen support as reflected by normal arterial blood gas levels, the patients were extubated. Fluids were restricted to 2 mL/kg/h during the first 24 h postoperatively.

Statistical Analysis

Statistical analysis was performed using software (SPSS version 11; SPSS; Chicago, IL). Comparison between groups was made by using the Student *t* test for paired data. All results were expressed as mean ± SE; $p < 0.05$ was considered significant.

Results

Forty patients were enrolled in this study. Diagnoses were comparable between the two groups (Table 1). Preoperative characteristics for both groups are presented in Tables 2, 3. There were no statistically significant differences between the two groups in age, weight, body surface area, CPB time, aortic cross-clamping time, baseline static lung compliance, or gas exchange capacity. Table 4 showed the effect of CPB on lung compliance and gas exchange capacity. Before bypass, no significant difference existed between the two groups in lung compliance and gas exchange. Compared with the baseline measurements, CPB produced a significant decrease in static and dynamic lung compliances in both groups. In the control group, static and dynamic lung compliances decreased from 1.0 ± 03 to 0.90 ± 0.3 mL/cm/kg and 0.87 ± 0.2 to 0.71 ± 0.1 mL/cm/kg, respectively (p = 0.0002 and p = 0.002). In the MUF group, static and dynamic lung compliances decreased from 1.0 ± 0.2 to 0.89 ± 0.03 mL/cm/kg and 0.94 ± 0.2 to 0.77 ± 0.1 mL/cm/kg, respectively (p = 0.002 and p = 0.002). The effect of

Table 1—*Diagnoses of Children in the Control and MUF Groups**

Diagnoses	Control Group	MUF Group
ASD	1	0
VSD	9	6
ASD plus VSD	2	1
VSD plus subaortic membrane plus mitral valve repair	1	1
VSD plus subaortic membrane	1	0
Double-outlet right ventricle	2	1
Common atrioventricular canal	0	3
Intermediate atrioventricular canal	0	2
Tetralogy of Fallot	4	5
ASD partial anomalies pulmonary venous drainage	0	1
Total	20	20

*Data are presented as No. ASD = atrial septal defect; VSD = ventricular septal defect.

Table 2—*Preoperative Patient Characteristics**

Variables	Control Group	MUF Group	p Value
Male/female gender, No.	9/11	8/12	
Age, mo	11.8 ± 3.3	13.1 ± 4.1	0.830
Weight, kg	8.1 ± 0.37	7.8 ± 2.1	0.29
Body surface area, m^2	0.35 ± 0.1	0.37 ± 0.2	0.756
CBP time, min	81 ± 32	96 ± 45	0.08
Cross-clamp time, min	55 ± 20	68 ± 32	0.07
Static lung compliance, mL/cm H_2O/kg	1.0 ± 0.31	1.0 ± 0.22	0.98
Dynamic lung compliance, mL/cm H_2O/kg	0.87 ± 0.2	0.94 ± 0.2	0.47
$P(A\text{-}a)O_2$, mm Hg	375 ± 112	486 ± 150	0.07
RI	1.4 ± 1.1	2.4 ± 1.4	0.06
VI	6.7 ± 2.8	6.9 ± 2.4	0.83
OI	5.8 ± 3.2	6.7 ± 4.2	0.09

*Data are presented as mean ± SE unless otherwise indicated.

Table 3—*Intraoperative Patient Characteristics**

Variables	Control Group	MUF Group	p Value
CBP time, min	81 ± 32	96 ± 45	0.08
Cross-clamp time, min	55 ± 20	68 ± 32	0.07
CUF volume, mL/kg	123 ± 26	145 ± 591	0.11
MUF volume, mL/kg	0.00	61 ± 14	

*Data are presented as mean ± SE unless otherwise indicated.

CPB on lung compliance and gas exchange capacity was the same in the two groups. After CPB, static and dynamic lung compliance decreased from 0.9 ± 0.3 to 0.71 ± 0.18 mL/cm/kg in the control group and 0.89 ± 0.2 mL/cm/kg to 0.77 ± 0.17 in the MUF group. The decrease in lung compliance after CPB between the two groups did not achieve a statistical significance ($p = 0.9$ and $p = 0.3$). The same was observed in gas exchange capacity. CPB produced significant decrease in gas exchange capacity in both groups. Figure 1 shows static pulmonary compliance at different measurements in both groups.

Table 5 and Figure 2 show the effect of MUF on lung compliance and gas exchange capacity. MUF produced a significant immediate improvement in static lung compliance (from 0.89 ± 0.2 to

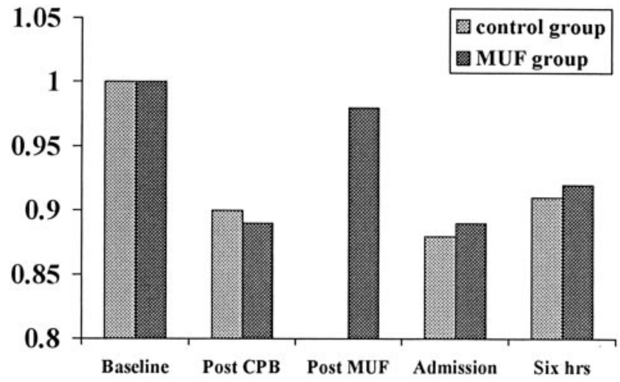

FIGURE 1. PF in both groups. hrs = hours.

0.98 ± 0.2 mL/cm/kg, $p = 0.03$) and dynamic lung compliance (from 0.77 ± 0.1 to 0.93 ± 0.2 mL/cm/kg, $p = 0.007$). The effect of MUF was not sustained after admission to the ICU or 6 h postoperatively. The same was observed in gas exchange capacity. MUF produced a significant immediate improvement in lung exchange capacity, which was not sustained at admission to the ICU or 6 h postoperatively.

There was no significant difference in inotropic support between the two groups. There was no significant difference in the duration of intubation between the two groups (12 ± 3 h and 13 ± 2 h,

Table 4— *Effect of CPB on Lung Compliance and Gas Exchange Capacity**

Variables	Control Group	MUF Group	p Value
Static compliance			
Baseline	1.0 ± 0.31	1.0 ± 0.22	0.98
After CPB	0.90 ± 0.3	0.89 ± 0.2	0.91
p Value	0.02	0.01	
Dynamic compliance			
Baseline	0.87 ± 0.2	0.94 ± 0.2	0.47
After CPB	0.71 ± 0.18	0.77 ± 0.17	0.38
p Value	0.002	0.002	
$P(A\text{-}a)O_2$			
Baseline	375 ± 112	486 ± 150	0.07
After CPB	437 ± 91	418 ± 77	0.24
p Value	0.04	0.05	
RI			
Baseline	1.4 ± 1.1	2.4 ± 1.4	0.06
After CPB	2.1 ± 1.4	1.8 ± 1.0	0.08
p Value	0.02	0.02	
VI			
Baseline	6.7 ± 2.8	6.9 ± 2.4	0.83
After CPB	9.2 ± 3.0	8.6 ± 2.5	0.12
p Value	0.005	0.02	
OI			
Baseline	5.8 ± 3.2	6.7 ± 4.2	0.2
After CPB	4.2 ± 1.8	3.4 ± 1.8	0.1
p Value	0.05	0.02	

*Data are presented as mean ± SE unless otherwise indicated.

Table 5—*Effect of MUF on Lung Compliance and Gas Exchange Capacity**

Variables	Before	After	p Value
Static compliance			
After CPB, before MUF	0.89 ± 0.2	0.98 ± 0.22	0.03
After MUF, admission	0.98 ± 0.22	0.89 ± 0.1	0.02
After MUF, − 6 h	0.98 ± 0.22	0.92 ± 0.2	0.3
Dynamic compliance			
After CPB, after MUF	0.77 ± 0.17	0.93 ± 0.27	0.002
After MUF, admission	0.93 ± 0.27	0.78 ± 0.17	0.004
After MUF, − 6 h	0.93 ± 0.27	0.78 ± 0.18	0.002
$P(A\text{-}a)O_2$			
After CPB, after MUF	418 ± 77	343 ± 131	0.04
After MUF, admission	343 ± 131	401 ± 146	0.05
After MUF, − 6 h	343 ± 131	121 ± 105	0.01
RI			
After CPB, after MUF	1.8 ± 1	1.3 ± 0.8	0.002
After MUF, admission	1.3 ± 0.8	2.7 ± 1.9	0.02
After MUF, −6 h	1.3 ± 0.8	0.9 ± 0.4	0.3
VI			
After CPB, post MUF	8.6 ± 2.5	6.3 ± 2.5	0.002
After MUF, admission	6.3 ± 2.5	8.2 ± 3.6	0.008
After MUF, − 6 h	6.3 ± 2.5	8.3 ± 2.1	0.002
OI			
After CPB, after MUF	3.4 ± 1.8	2.6 ± 1.6	0.01
After MUF, admission	2.6 ± 1.6	2.8 ± 1.1	0.09
After MUF, − 6 h	2.6 ± 1.6	3.5 ± 1.7	0.01

*Data are presented as mean ± SE.

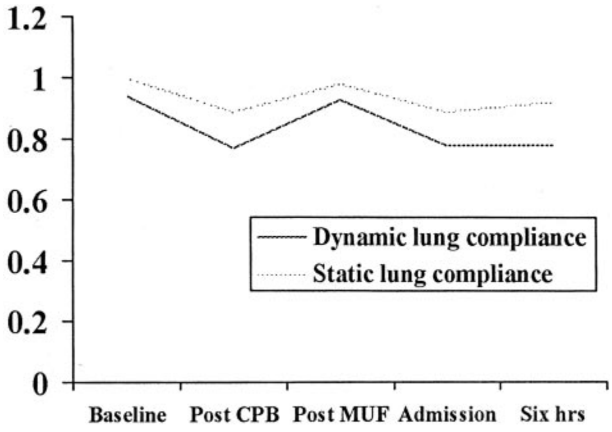

FIGURE 2. Effect of MUF on lung compliance. See Figure 1 legend for expansion of abbreviation.

$p = 0.4$), length of ICU stay (1.7 ± 0.5 days and 1.6 ± 0.29 days, $p = 0.9$), and total hospital stay (5.8 ± 1.2 days and 6.3 ± 1.4 days, $p = 0.9$), respectively, postoperatively.

Discussion

CPB can lead to pulmonary dysfunction manifested by lower pulmonary compliance and poor gas exchange. Sometimes, severe acute dysfunction can lead to death.[17] Hemodilution reduces serum albumin concentration and colloid osmotic pressure and increases the effective capillary filtration pressure. These factors may lead to the accumulation of plasma water in the interstitial space, which will decrease pulmonary compliance and impair gas exchange across the respiratory membrane. During aortic cross-clamping the lung becomes ischemic, and metabolic products accumulate in the interstitial fluid of the lung. Furthermore, hypothermia, the contact of the contact of blood with the bypass circuit, and the hemodynamic changes promote a systemic inflammatory response that can cause further pulmonary damage.[18] A number of methods have been proposed and used to manage the excess tissue water. Ultrafiltration during CPB (CUF) has been proposed and claimed to be effective in reducing the severity of postoperative water retention. Dissatisfied with the results of CUF, Naik and colleagues[4] in 1991 reported a modification of the ultrafiltration technique and claimed it to be superior to CUF particularly in terms of its ability to reduce water accumulation associated with CPB in children. Later on, several studies[5–16] have shown that MUF may produce immediate improvement in PF in children. However, these studies have included a broad range of patient weights and immediate outcomes. This made the effect of MUF on PF nonspecific. In our institute, MUF is used almost routinely in small-body-weight children (< 5 kg). In children > 5 kg, MUF is done according to the surgeon's preference depending on the duration of CPB. We designed this prospective study to evaluate the immediate effect of MUF on PF in children weighing from 5 to 10 kg.

Immediate Effects of MUF on PF

Meliones and colleagues[5] reported the results of 11 patients in whom MUF contributed to an immediate improvement in dynamic lung compliance compared with that found in a control group. Schlunzen and colleagues[10] reported their large study including 138 patients who underwent MUF, observing that Po_2 improved after MUF in a noncontrolled study and their patients had a wide range of body weight (2.2 to 20 kg). In a retrospective study, Onoe and colleagues[13] compared the effect of MUF on $P(A\text{-}a)O_2$. All patients had ventricular septal defect. The control group received no CUF. By the time of postoperative transfer to the ICU, $P(A\text{-}a)O_2$ was lower in the MUF group than in the control group (171 ± 109 mm Hg vs 302 ± 150 mm Hg), whereas Pao_2 was higher in the MUF than in the control group (503 ± 112 mm Hg vs 376 ± 149 mm Hg). Onoe and colleagues[13] did not calculate the RI, but their data indicated that the RI was improved by MUF: $RI = P(A\text{-}a)O_2/Pao_2$. They did not follow up their patients beyond the immediate postoperative period, and they used only MUF.

The principal finding of our study is that MUF after CPB in children weighing ≥ 5 to ≤ 10 kg did result in immediate improvements in both lung compliance and gas exchange capacity. Our results agreed the previous studies.[5,10,13] However, these three studies[5,10,13] reported the immediate effect of MUF on PF, and they did not monitor patients beyond the immediate postoperative period. It is not known whether the improvement was sustained or not postoperatively.

Late Effects of MUF on PF

Our study showed that the immediate improvement in PF observed in the MUF group was not sustained after admission to the ICU or 6 h after the operation and did not permit earlier extubation or discharge from the ICU. Our results agreed with those reported by Keenan and colleagues,[14] who reported on a series of 38 infants for whom MUF after CPB contributed to an immediate improvement in lung compliance, both dynamic and static, compared with that found in the control group, and it had no positive effect on the duration of mechanical ventilation or ICU stay

In contrast to our findings, Bando and colleagues[15] observed that MUF did show marked decrease in postoperative ventilation time and ICU stays postoperatively. They reported their experience with 100 patients, including neonates and children. They compared dilutional ultrafiltration during CPB and MUF after bypass to a control group who underwent only CUF during CPB. The difference was pronounced in patients with preoperative pulmonary hypertension, prolonged bypass times, and in neonates. However, there was a great difference in the amount of fluid removal between the two groups. Their MUF patients underwent CUF with a total of 42.2 ± 10.6 mL/kg of fluid removal during CBP. Their control patients underwent only CUF during CPB with an average of 25.6 ± 28.6 mL/kg removed (40% less). In our group, there was no statistical difference in the amount of fluid removed between the two groups, and the amount of CUF in our group was higher (123 ± 26 mL/kg and 145 ± 59 mL/kg for the control and the MUF groups, respectively). Moreover, the amount of fluid removed by MUF in their group was considerably greater (113.6 ± 65 mL/kg) than our group (61 ± 14 mL/kg). It is possible that more aggressive CUF in their control group would have minimized the reported sustained improvement in their MUF group.

Huang and colleagues[16] observed in a series of 30 patients that MUF did improve lung compliance and the improvement was sustained 6 h postoperatively. The difference can be attributed to the difference in the study design. In their control group, they did not perform ultrafiltration during CPB. In their MUF group, they performed CUF plus MUF. Essentially, they were comparing ultrafiltration vs no ultrafiltration. This may explain the better-sustained results for their MUF group. If they performed CUF in their control group, CUF would have negated some of the benefits ascribed to MUF. Moreover, in the series of Huang and colleagues,[16] their groups had a lower CPB time, 48.7 ± 11.5 min in their MUF group, vs 96 ± 45 min in our groups. They applied MUF for 10 to 15 min after bypass. They did not mention the amount of fluid that was ultrafiltrated. They continued MUF for almost one third of CPB time, and we may expect that they ultrafiltrated more fluid than we did in our study. In our study, we restricted the amount of fluid to be removed by MUF. In our MUF group, our target was to remove the priming solution plus any additional fluid during CPB minus the CUF fluid minus urine output during bypass.

Our results also disagree with the results of Kameyama and colleagues,[12] who observed that MUF improve the RI, which shortened the duration of mechanical ventilation, and MUF did have a significant impact on this improvement. However, their group included a higher body weight up to 20 kg, and it was not a prospective study. They did not perform ultrafiltration in their control group.

The nonsustained effect of MUF in our group may be explained by the fact that PF is affected both by excess fluid from the hemodilution as well as the systemic inflammatory response. MUF decreases total body water as well as inflammatory cytokines.[4] The systemic inflammatory response is most likely initiated during rewarming. Thus, after MUF, the ongoing effect of the capillary leakage possibly led to the decrease in pulmonary compliance and negated the immediate improvements in lung compliance observed by MUF. Another explanation of the nonsustained effect of MUF may be in the observation that there is no difference between CUF and MUF in terms of removing the inflammatory mediators as reported by Wang and colleagues,[19] who observed that plasma concentration of some inflammatory mediators increased after both CUF and MUF.

The significant immediate improvement in lung compliance and gas exchange capacity might be important, especially in those patients with pulmonary hypertension. The improvement in lung function is likely to be mediated by the successful removal of water from the body. Removal of water from the lung may permit better oxygenation. In our study, we did not measure total body water content, but others[4] have reported significant decreases in total body water using MUF. Another point to mention is the beneficial effects of toxin removal on PF by the use of ultrafiltration as demonstrated by Pearl et al.[20].

There are apparent general agreements in the literature that MUF may produce immediate improvements in PF. This effect is under some bias: firstly, as observed in the study design. Schlunzen et al,[10] Kameyama et al,[12] Onoe et al,[13] and Huang et al[16] compared a control group receiving no ultrafiltration during CPB with a MUF group receiving CUF during CPB and MUF after CPB. Secondly, the volume of fluid removed by CUF was not equal for the MUF and the CUF-plus-MUF groups, as in the study by Bando and colleagues,[15] with more fluid removed during CUF in the MUF group. Thirdly, the body weights were different between the two groups (12.8 ± 12 kg in the control group vs 8.5 ± 5.2 kg in the CUF group) in the same study by Bando and colleagues.[15] Fourthly, it is not clear that MUF really directly affects PF capacity. In the study of Journois,[21] aggressive CUF during CPB improved $P(A\text{-}a)O_2$ and decreased ventilator time; MUF was not used. Journois[21] attributed the improved PF to the decrease in total body water.

It is worthwhile to mention that the values obtained immediately after MUF were taken 15 to 20 min after separation of CPB. Similar lung function values were not taken at similar time points in the control group. We do not know whether the reported immediate improvement after MUF in our study and others[4–16] was due to the filtration itself or to any one of many rapidly changing variables that exist in the first hour after separation from CPB. During CPB, total lung collapse is present. Microatelectasis and macroatelectasis may gradually resolve in the early post-CPB period, causing significant changes in the serial measurements of lung function. Resolution of airway secretions and/or improvement in airway reactivity with positive airway pressure could also explain why there was no better significant clinical impact was observed with the use of MUF. The above-mentioned variables would have improved the lung function 15 to 20 min after separation of CPB in the control group

In conclusion, our results demonstrated that the use of MUF after CPB in patients weighing 5 to 10 kg can produce an improvement in lung compliance and gas exchange capacity, which may effectively minimize pulmonary dysfunction postbiventricular repair of congenital heart disease. However, these improvements are not sustained for the first 6 h postoperatively and do not lead to a decrease in the duration of intubation, ICU stay, or total hospital stay postoperatively. Aggressive CUF during CPB may be enough in this subgroup of patients.

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