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Continuous arteriovenous hemofiltration in children

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Abstract. Continuous arteriovenous hemofiltration (CAVH) is an extracorporeal technique for the treatment of hypervolemia and electrolyte disturbances in the critically ill patient with oligoanuria. The patient's cardiac output provides the blood flow through the circuit; no pumps are necessary. A range of hemofilters is now available extending the applicability of CAVH to the pediatric population, including premature newborns. In this report the treatment of 15 neonates and 8 older children is described. Fluid overload was reduced in all cases. Reflecting the very grave clinical conditions of these patients, 15 of the 23 treated children ultimately died. Due to failure to control uremia, four patients required treatment with dialysis. CAVH was found to be generally safe and effective even in the hemodynamically unstable critically ill child.

Key words: Continuous arteriovenous hemofiltration – Acute renal failure – Oligoanuria – Pediatric critical care – Hypervolemia

Introduction

Continuous arteriovenous hemofiltration (CAVH) refers to the continuous generation of an ultrafiltrate of plasma by a hemofilter in a short, extracorporeal circuit; concomitant administration of a replacement solution is usually required. The driving force for blood flow through the circuit is provided by the difference between the patient's arterial and venous pressures. This technique was pioneered by P. Kramer from 1977 onward, as a treatment for oligoanuric patients in the intensive care unit [1]. With the highly water-permeable artificial membranes currently available large volumes of fluid can be removed from the patient even at subnormal blood pressure (down to mean arterial pressure of 60 mmHg) without the use of a blood pump. Equipment suitable for use in infants has recently become available, facilitating the application of this technique even in premature neonates [2]. Instead of the highly efficient solute removal by diffusion that occurs with dialysis, hemofiltration utilizes the less efficient mass transfer process of convection. The filters are permeable to non-protein-bound solutes below a molecular size of approximately 10,000 daltons [3].

The removal of smaller fluid volumes from oliguric, diuretic-resistant patients has been termed slow continuous ultrafiltration (SCUF) [4]. At these slower rates of fluid removal, the need for large volumes of replacement solution is obviated, but the biochemical manifestations of uremia are less likely to be controlled. Continuous venovenous hemofiltration (CVVH) has also been employed, although a blood pump becomes necessary with this technique [3]. A recent trial of a system adding a slow continuous flow of dialysate through the ultrafiltrate compartment, continuous arteriovenous hemodiafiltration (CAVHDF), has been shown to augment urea clearance [5]. With the utilization of filters with larger effective pore

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sizes, continuous arteriovenous plasma exchange is possible.

Comparison with alternate modes of treatment

Traditionally, peritoneal dialysis (PD) has been the technique employed in the newborn intensive care unit for infants requiring more than conservative therapy for acute renal failure (ARF). This technique was selected because neither vascular access nor sophisticated equipment was necessary, minimal staff training and monitoring were required, treatment could be initiated quickly without the need to coordinate services with a dialysis unit, and it was not hemodynamically stressful [6]. However, PD has various disadvantages: it is relatively inefficient with low solute clearances; it can cause respiratory compromise from mechanical restriction of the diaphragmatic excursions or from the risk of hydrothorax; there can be problems related to catheter insertion (risk of trauma to intraabdominal contents, aggravated in the presence of intraabdominal pathology or coagulopathy); only limited ultrafiltration is possible, and the additional potential complications of hyperglycemia, dialysate leak, peritonitis, and protein loss must also be borne in mind.

Hemodialysis (HD) is highly efficient and typically can achieve high rates of ultrafiltration, but also has several disadvantages. Specialized equipment and highly trained personnel from a dialysis unit are required. The acutely ill infant is placed at further risk by the potential complications of disequilibrium, hemodynamic compromise, decreased PO_2, and the need for anticoagulation. Furthermore, adequate vascular access must be obtained and substantial extracorporeal blood volume (usually necessitating blood priming) and flow are required [7]. This technique is considered to be arduous for the newborn.

CAVH has the advantage of being a continuous rapidly initiated treatment, hemodynamically "gentle", yielding excellent ultrafiltration rates and requiring only a small extracorporeal volume [8, 9]. Only minimal equipment and staff training are necessary. The ease of removal of large fluid volumes facilitates the concomitant administration of obligatory i. v. fluids such as those required when giving pressor drugs or hyperalimentation solutions. However, continuous monitoring and vascular access are necessary. The need for continuous anticoagulation is the chief disadvantage of this technique. An increased risk of bleeding for example in the immediate postoperative period, and/or increased potential for injury resulting from such hemorrhagic incidents as an intracerebral hemorrhage in premature newborns constitute relative contraindications for the performance of CAVH.

Table 1 compares the expected solute and fluid clearances averaged over 24 h for a 3-kg infant treated with either HD, PD, or CAVH. The HD treatment is administered over only 4 of the 24 h, while PD and CAVH are each administered over the entire 24-h period. Under the assumptions used in constructing Table 1, the net 24-h urea clearance with CAVH is somewhat less than that for either HD or PD. However, tolerable fluid removal is much greater with CAVH.

Table 1. Predicted effects of three modes of treatment over a 24-h period in a 3 kg infant

	Treatment mode		
	HD	PD	CAVH
Urea clearance (l/24 h)	2.1	2.4	1.6
Ultrafiltration (l/24 h)	0.2	0.6	1.6

HD = hemodialysis; PD peritoneal dialysis; CAVH = continuous arteriovenous hemofiltration

Principles of CAVH

The extracorporeal circuit (Fig. 1) provides for the delivery of blood from an arterial access to the hemofilter driven by the force of the patient's own cardiac output. Blood returns to the patient through the venous line. Ultrafiltrate forming across the membrane in the ultrafiltrate compartment of the filter is conducted by tubing to a metered collection container. Heparin can be administered by either repeated bolus or continuous infusion (depending on the patient's coagulation status) into a connector on the arterial side of the hemofilter. Replacement solution, hyperalimentation fluid, and drugs are typically administered into the venous line. An alternate hemofiltration mode involves the pre-filter dilution of blood with substitution fluid.

The forces governing ultrafiltration are described mathematically in the Appendix and shown in schematic form in Fig. 2. Ultrafiltration involves the balance of hydrostatic and oncotic forces across the filter membrane. Favoring ultrafiltration are the positive pressure of systemic blood pressure in the blood compartment and the negative pressure induced by the gravity drainage of ultrafiltrate on its side of the membrane. Op-

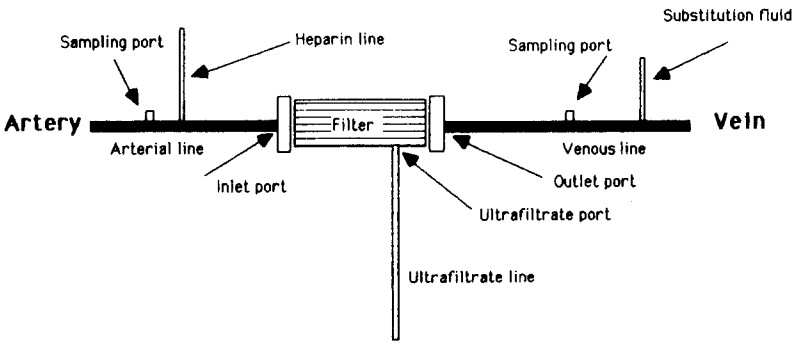

Fig. 1. CAVH extracorporeal circuit. Reproduced with permission from Bosch (1986) [17]

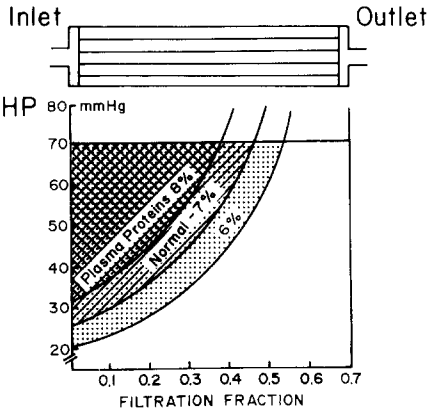

Fig. 2. Intrafilter pressure profiles demonstrating the relationship between filtration fraction and plasma inlet protein concentration. With lower inlet protein concentration filtration pressure equilibrium occurs closer to the filter outlet and filtration fraction increases. *HP,* hydrostatic pressure in the filter; *curved lines,* oncotic pressure values for different protein inlet concentrations; *shaded areas,* transmembrane pressure. Reproduced with permission from Lauer A. et al. [8]

posing ultrafiltration is the oncotic pressure in the blood chamber generated by the plasma proteins. At the inlet to the hemofilter hydrostatic pressure exceeds oncotic pressure and ultrafiltrate forms. As a consequence, blood is hemoconcentrated as it traverses the filter. The increasing protein concentration increases oncotic pressure, and simultaneously hydrostatic pressure decreases due to the resistance to blood flow through the device; the filtration fraction increases. Thus, transmembrane pressure decreases along the filter, and the rate of ultrafiltration falls. When filtration pressure equilibrium occurs, i. e., transmembrane pressure equals 0, ultrafiltration ceases. Depending on the operational characteristics of the hemofilter, filtration pressure equilibrium may not develop during clinical applications.

The above description is highly reminiscent of glomerular hemodynamics, and the hemofilter may be appropriately referred to as a large extracorporeal glomerulus. Further analogy to the glomerular basement membrane is suggested by the sieving coefficients for various solutes observed in a typical hemofilter membrane (Table 2). Small solutes (including drugs) that are not protein-bound are freely filtered. Protein-bound and larger molecules are able to penetrate the membrane less easily. Since this "glomerulus" has no tubule (hence no reabsorption or secretion) the clearance of any solute is given by the ultrafiltrate to plasma concentration ratio multiplied by the ultrafiltrate flow rate. A significant clearance of medium-sized molecules would be expected.

Based on these operating principles, higher ultrafiltration rates would be expected with higher blood pressure and with increased negative pressure in the ultrafiltrate line. This could be accomplished either by lowering the collection container below the hemofilter or by the application of suction to the ultrafiltrate port [9]. These factors increase the mean transmembrane pressure and favor ultrafiltration. Lower plasma total protein concentration (such as would be expected in new-

Table 2. Solute ultrafiltrate-to-plasma concentration ratios

Approximately 1	Less than 1	Markedly less than 1
Sodium	Calcium	Albumin
Potassium	Creatine	Other serum proteins
Chloride	phosphokinase	Total bilirubin
Creatinine		Direct bilirubin
Urea		Indirect bilirubin
Bicarbonate		
Phosphorus		
Uric acid		
Glucose		
Inulin		

Table 3. Available hemofilters

	Fiber material	Fiber diameter (μm)	Fiber length (cm)	No. of fibers	Area (m^2)	Priming volume (ml)	UFR[a] (ml/min)
Amicon							
Minifilter (prototype)	Polysulfone	1000	7.5	25	0.005	2	5–2
Minifilter	Polysulfone	1000	8.5		0.015	6	8–1.5
Diafilter-20	Polysulfone	200	12.5	5000	0.25	20	5–13
Diafilter-10	Polysulfone	200	9.5	6000	0.2	25	6–12
Gambro							
FH22	Polyamide	215	11.5	2100	0.16	11	2–5
FH55	Polyamide	215	14.0	6200	0.60	43	8–20

[a] Ultrafiltration rate with a blood flow of 50–100 ml/min and mean transmembrane pressure of 50–100 mmHg

borns) would also increase ultrafiltration and increase filtration fraction (Fig. 2). Conversely, increased arterial blood line resistance (small tubing diameter, increased length, kinks, etc.) reduces CAVH performance. The high hematocrits seen in newborns also decrease performance through an effect on blood viscosity and decreased plasma flow for any given whole blood flow.

Comparison of available hemofilters

As can be seen in Table 3, the Amicon Minifilter and the Gambro FH22, by virtue of their low priming volumes, are attractive for the treatment of newborns: the Diafilter-20 has also been used for infants [10]. The fewer fibers and hence lower surface area of the Minifilter probably accounts for that device's lower ultrafiltration rate. The Diafilter-10 represents an interesting enhancement of the Diafilter-20, the essential difference being a decrease in the length of the fibers to reduce the likelihood of filtration pressure equilibrium with the resultant high hematocrits causing sludging and intrafiber clotting.

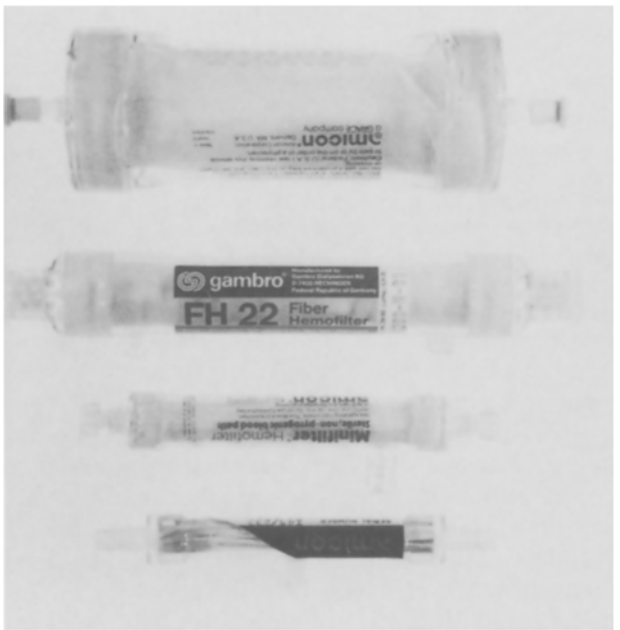

Fig. 3. Hemofilters available. From *top* to *bottom*: Amicon Diafilter-20, Gambro FH22, Amicon Minifilter, Amicon prototype Minifilter

Results from an animal model

Table 4 presents some preliminary data comparing the functional parameters of the Amicon

Table 4. Comparison of performance of two hemofilters when used on 1 kg rabbits

	Amicon Minifilter	Gambro FH22
P_f (mmHg)	35	35
Δ P (mmHg)	0.7	4.4
$\bar{P}$ (mmHg)	30.7	15.5
Hct_i/Hct_o (%)	36.3/39.1	24.4/44.1
$OSM_i/OSM_o/OSM_u$ (mmol/kg)	349/348/331	333/336/326
π_i/π_o (mmHg)	13.7/14.8	7.2/34.4
$\bar{\pi}$ (mmHg)	14.3	20.8
Q_f (ml/min)	0.3	1.5
Q_b (ml/min)	4.2	3.4
Q_p (ml/min)	2.7	2.6
FF (%)	11	59
R	0.24	1.76
Work	4.2	20.4
TMP_i/TMP_o	52.2/50.3	45.4/13.7
$\overline{TMP}$	51.4	29.7
K	0.006	0.05
k	0.4	0.3

See Appendix for explanation of abbreviations

Minifilter and the Gambro FH22 in a rabbit model. By virtue of their relatively small priming volumes, these filters appear to have particular advantages in the treatment of newborns. Hemoconcentration in the hemofilter is demonstrated by the increase in hematocrit and protein oncotic pressure from filter inlet to outlet. Consistent with the generation of an ultrafiltrate of plasma is the approximate equality of inlet, outlet, and ultrafiltrate osmolarity. Although plasma flow is almost identical, ultrafiltration rate is greater in the Gambro hemofilter, yielding a higher filtration fraction. The resistance to blood flow and hence the work needed to generate that flow are less in the Amicon hemofilter. Under these experimental conditions, both filters operate in a state of filtration pressure disequilibrium, allowing calculation of unique values for K_f. Factoring out the differences between the filters in ultrafiltration rate, transmembrane pressure and membrane surface area, it can be seen that the membrane ultrafiltration coefficients of polysulfone (Amicon) and polyamide (Gambro) are quite similar.

Clinical experience in the neonate

Indications for CAVH

Currently CAVH is the treatment of choice for fluid overload in the hemodynamically unstable neonate who has ARF and contraindications to peritoneal dialysis [11]. The indications for CAVH are broader, however. They include the control of other parameters of renal failure – azotemia, hyperkalemia, acidosis, and hypo- or hypernatremia. Optimum management of the acute uremic state, especially in the potentially highly catabolic acutely ill patient, necessitates high ultrafiltration rates with corresponding administration of large volumes of replacement solution. CAVH has also found application in the prevention and control of overhydration in patients who are resistant to diuretics. Examples include patients with states of low cardiac output following open heart surgery. CAVH has been utilized in the treatment of newborns with the following conditions: acute tubular necrosis (ATN) consequent upon perinatal shock/asphyxia, hydrops fetalis, congenital heart disease, sepsis, and in those requiring extracorporeal membrane oxygenation [1, 4–6, 14].

Results

The data in Table 5 are from the reports of Lieberman et al. [12], Leone et al. [10], Sabbagh et al. [13], and Ronco et al. [14]. Fifteen newborns as small as 1.1 kg and as young as 29 weeks of gestation have been treated for as long as 6.5 days. The main indication for treatment was clinically demonstrable fluid overload in the presence of renal failure. Various sites have been used for vascular access although, when present, the umbilical artery and vein are clearly the most convenient. Standard 5-F umbilical catheters provide adequate flow for efficient hemofiltration. The diagnoses listed (Table 5) are typical for acutely ill infants in a newborn intensive care unit. The one patient converted from PD to CAVH had a peritoneal fluid leak and peritonitis.

Table 5. Summary of clinical experience with CAVH in neonates

Number	15
Weight (kg)	1.1–4.7
Gestational age (weeks)	29 to 41
Age at treatment	1½ days to 5 months
Duration of treatment (h)	9–159 (6½ days)
Indications	Demonstrable fluid overload or to allow adequate fluid administration in the presence of oligoanuria Concurrent electrolyte or acid-base disturbance (hyperkalemia, metabolic acidosis)
Access	18–24 gauge, 3.5–5 f Arterial: umbilical, femoral, brachial, dorsalus pedis Venous: umbilical, femoral, internal jugular, external jugular
Diagnoses	ATN secondary to perinatal shock/asphyxia, sepsis; NEC; hydrops fetalis; CHF; low CO (S/P cardiac surgery for hypoplastic left ventricle); RDS; DIC; PD leak; peritonitis
Outcome	In 11 pts adequate CAVH therapy (1 switched from Amicon prototype mini to D-20, 1 with blood pump, 4 with suction) 3 pts to PD, 1 to HD-UFR 5 pts recovered renal function, alive 3 pts recovered renal function, dead 7 pts never recovered renal function, dead (in 1 pt, treatment electively discontinued) 2 pts experienced intracerebral hemorrhages during CAVH 1 pt cerebral edema reduced, improved BAER

BAER = brainstem auditory evoked response; CHF = congestive heart failure; CO = cardiac output; DIC = disseminated intravascular coagulation; HD-UFR = hemodialysis with sequential ultrafiltration; NEC = necrotizing enterocolitis; RDS = respiratory distress syndrome; S/P = status post

Table 6. Parameters indicating inadequate response to treatment using the Amicon prototype Minifilter [14] in patient 4

	Patient 1	Patient 4
Treatment time (min)	2880	2880
Ultrafiltration rate (ml/min)	1.1	0.7
Reinfusion rate (ml/min)	1.1	0.7
Urea generation rate (mg/min)	0.7	1.2
Total urea generation (mg/48 h)	2016	3456
Urea removal rate (mg/min)	0.5	0.5
Total urea removed (mg/48 h)	1440	1440
Changes in BUN concentration (mg/dl)	+4	+30

For most patients, CAVH provided adequate therapy with only four infants requiring transfer to other dialytic modalities. These conversions occurred during the investigators' early experience with the Amicon prototype Minifilter. An example of inadequate solute clearance with this hemofilter is illustrated in Table 6. Values for ultrafiltration rate and urea clearance were similar in both of these patients. This resulted in progressive azotemia only in patient 4, because of this infant's higher urea generation rate, evidence of a severely catabolic state (sepsis).

The values shown in Table 7 are from the same patients as in Table 5. Of the smaller hemofilters, the Gambro FH22 provided the most consistent, high ultrafiltration rates. The highest ultrafiltration rate translates into a solute clearance for small molecules, such as urea or creatinine, of 20.5 ml/min per 1.73 m^2. This compares quite favorably with the normal premature newborn range of glomerular filtration rate of 20–40 ml/min per 1.73 m^2 [15]. An ultrafiltration rate of 2 ml/min would be expected to provide adequate solute clearance for the majority of even anuric newborns.

Outcome

Although CAVH provided adequate therapy in 11 of the 15 patients (Table 5), 10 of the infants treated ultimately died. This, in part, reflects the very grave clinical condition of these neonates that precipitated the need for treatment. Eight patients recovered renal function.

Heparin administration in the critically ill neonate remains a problem. An initial bolus of 40 units/kg followed by a continuous infusion of 10 units/kg per h is probably appropriate for most patients. In the presence of an increased susceptibility to dangerous bleeding, with an underlying coagulopathy, dose reduction is clearly indicated (e. g., bolus of 10 units/kg, then 5 units/kg per h). Serial monitoring of either the activated partial thromboplastin time or the activated clotting time is recommended. Thrombocytopenia is an indication for reduced heparin dosage.

Despite such precautions, we observed two infants who were noted to have new intracerebral hemorrhages after treatment. These could have been secondary to continuous anticoagulation during CAVH. Interestingly, one infant was noted to have reduced cerebral edema (as determined by intracranial sonography) after treatment, with improvement in brain stem auditory evoked response.

Experience with CAVH in older children

Older children in a general pediatric intensive care unit setting have also been treated with CAVH (Table 8) [10, 16]. The Amicon D20 was utilized for most of these patients. Ultrafiltration rates of at least 200 ml/h were achieved even in the smaller children. Satisfactory ultrafiltration continued as long as systolic blood pressure remained above 50 mmHg. In order to limit excessive fluid losses, Leone et al. [10] have advocated connecting an adjustable roller pump (I-Med infusion pump) to the ultrafiltrate line to control ultrafiltration rate.

Acute renal failure complicating sepsis with disseminated intravascular coagulation constitut-

Table 7. Effectiveness of different filters in treatment of neonates

	n	Total UF[a] (ml)	Av. Q_f (ml/min)	Av. Q_b (ml/min)	Av. FF (%)	Clearance (ml/min per 1.73 m^2)
Amicon Minifilter (prototype)	10	36–5676	0.04–1.1	0.9–28	4–33	0.4–11.9
Amicon Diafilter-20	2	1050–2886	0.5 –2.0	4.3– 5.0	30–58	18.0
Gambro FH22	4	360–2880	0.25–2.5			3.6–20.5

[a] UF = ultrafiltration. Other abbreviations as in Appendix

Table 8. A summary of data recorded in older children treated with CAVH

Case no.	Age (years)	Wt (kg)	Indication	Filter	Duration (h)	UFR (ml/h)	Outcome
1.	$3\ ^{11}/_{12}$	15.3	Leukemia; sepsis; ARF	D20	45	244 – BP 80/ 86 – BP 50/	Expired
2.	4	24.6	SLE; nephrosis; ARF; acute pulmonary failure – ventilator	D20	111	53[a]	Improved ventilatory and cardiovascuar status, extubated
3.	$^{8}/_{12}$	8.3	Sepsis/DIC; ARF	D20	84	240	Expired
4.	10	30	Polycystic kidney disease; congential hepatic fibrosis; renal and hepatic failure; massive ascites	D20	24	600	Anasarca markedly reduced, expired
5.	17	58	Lymphoma; sepsis; ARF	D20	52	720	Expired
6.	14	45	a. Post renal trauma	FH55	96	600	Electively switched to regular HD
			B. CRF; lost regular vascular access; failed PD; fluid overload	D20	72	700	Back to regular HD
7.	$^{5}/_{12}$	6.7	AIDS; multiple organ failure	FH22	11	37	Expired
				D10	31	84	
8.	$^{9}/_{12}$	11	Post-burn sepsis; anasarca; poor diuretic response	D20	60	200	Edema eliminated

Cases 1 – 3 are taken from [10]; case 8, from [16]
[a] Screw clamp on UF tubing to decrease UFR

ed the most frequent indication for CAVH in this group. Systemic fluid overload in the presence of an inadequate response to diuretics was another important indication. In these patients we have seen marked improvement in both cardiac function and ventilatory status with amelioration of pulmonary edema during CAVH. The patient with renal and hepatic failure (case 4) was able to receive effective treatment, with reduction of massive ascites. In case 6a the patient was treated following exploratory laparotomy for trauma during which traumatic rupture of one kidney (with nephrectomy) and total thrombosis of the contralateral renal artery (with attempted salvage by saphenous vein bypass) were discovered. The patient's pulmonary edema, metabolic acidosis, and hyperkalemia were effectively corrected using CAVH. Continuing hemofiltration during the immediate postoperative period facilitated the administration of blood products (as well as other fluids) and prevented advancing azotemia while maintaining a stable hemodynamic profile, despite total anuria. Subsequently, while receiving regular hemodialysis, the same patient (case 6b) lost his usual vascular access (Hickman catheter removed because of sepsis). After PD failed to control fluid overload, a Scribner shunt was placed and utilized for CAVH. The already existing shunts and fistulas of patients with end stage renal failure can be readily utilized for the rapid initiation of CAVH in emergencies. Patients with central venous catheters can be treated with CVVH, although this necessitates a blood pump.

Conclusion

CAVH is an effective treatment for fluid overload in the presence of acute renal failure in the critically ill child. The biochemical manifestations of uremia can also be controlled in many patients with this modality. Diuretic-resistant edema-forming states can also be managed effectively. A further pediatric application might be the reduction of hyperammonemia or acidosis in various metabolic diseases. Further investigation of the many variations of continuous flow extracorporeal circuits (pre- vs. post-filter dilution CAVH, suction-assist CAVH, CAVH with pump-regulated/-limited ultrafiltration, CVVH, and CAVHDF) is needed to define optimum therapy in various clinical settings. More data are also needed concerning the pharmacokinetics of drugs commonly

used in the neonatal intensive care unit in the patient undergoing CAVH. It is hoped, especially with the judicious administration of adequate hyperalimentation, that the application of CAVH can decrease the historically high mortality rate of critically ill infants and children with ARF.

Appendix

Equations governing ultrafiltration

$$\overline{P} = \frac{P_i + P_o}{2} \qquad \overline{\pi} = \frac{\pi_i + \pi_o}{2} \qquad Q_b = \frac{Qf \cdot Hct_o}{Hct_o - Hct_i}$$

$$Q_p = Q_b \cdot \frac{(1 - Hct_i)}{100} \qquad FF = \frac{Qf}{Q_p} = 1 - \frac{Prot_i}{Prot_o} \qquad \overline{TMP} = \overline{P} + P_f - \overline{\pi}$$

$$Q_f = K \cdot \overline{TMP} \qquad \text{Solute clearance} = Q_f \text{ X } 1.73/SA$$
$$K = kS$$

$$Q_b = \frac{\Delta P}{R} \qquad R \approx \frac{\mu L}{Nr^4} \qquad \text{Work} = Q_b \cdot \Delta P = Q_b^2 \cdot R$$

$\overline{P}$	mean hydrostatic pressure	$Prot_o$	total plasma protein, filter outlet
P_i	hydrostatic pressure, filter inlet	P_f	ultrafiltrate pressure (height of ultrafiltrate column, 1 cm H_2O = 0.74 mmHg)
P_o	hydrostatic pressure, filter outlet	ΔP	arterial – venous hydrostatic pressure difference
$\overline{\pi}$	mean oncotic pressure	R	filter resistance
π_i	oncotic pressure, filter inlet	N	number of fibers
π_o	oncotic pressure, filter outlet	μ	blood viscosity
Q_b	blood flow	L	fiber length
Q_f	ultrafiltrate flow	r	fiber radius
Q_p	plasma flow	K	membrane permeability coeffici
Hct_i	hematocrit, filter inlet	S	membrane surface area
Hct_o	hematocrit, filter outlet	k	ultrafiltration coefficient
FF	filtration fraction	$\overline{TMP}$	mean transmembrance pressure
$Prot_i$	total plasma protein, filter inlet		

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