Pediatr Nephrol (2002) 17:61–69

PRACTICAL PEDIATRIC NEPHROLOGY

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Choice of dialysis modality for management of pediatric acute renal failure

Received: 13 July 2001 / Revised: 25 September 2001 / Accepted: 26 September 2001

Abstract Acute renal failure in children requiring dialysis can be managed with a variety of modalities, including peritoneal dialysis, intermittent hemodialysis, and continuous hemofiltration or hemodiafiltration. The choice of dialysis modality to be used in managing a specific patient is influenced by several factors, including the goals of dialysis, the unique advantages and disadvantages of each modality, and institutional resources. This review will examine these aspects of acute renal failure management, with the goal of providing practical guidance regarding modality selection to the physician involved in the management of pediatric acute renal failure.

Keywords Acute renal failure · Hemofiltration · Hemodialysis · Peritoneal dialysis

Introduction

Today a wide variety of dialysis modalities are available for management of patients with acute renal failure (ARF). The recent development of continuous therapies, including hemofiltration and related techniques, has facilitated the provision of dialysis to more-complicated and unstable patients than in the past [1, 2, 3, 4, 5, 6]. Indeed, such therapies are finding increasing use in the treatment of ARF, as illustrated by recent surveys [7, 8].

However, it is important to recognize that these newer therapies may not be necessary for all patients with ARF. Similarly, these therapies may not be available in all clinical settings. This review will assess the advantages and disadvantages of available dialysis modalities for ARF and will guide the practitioner to make informed, rational choices in the management of ARF.

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Pediatric ARF

The etiologies of ARF in infants and children are well known and have been reviewed elsewhere [9, 10, 11, 12, 13, 14]; representative published series from several centers are summarized in Table 1. Variations in etiology will be seen according to the type of institution surveyed, with units in more-specialized centers seeing a greater proportion of ARF related to surgery or sepsis than those in less-specialized centers [15, 16, 17, 18, 19]. However, as advanced medical technology becomes more widely available across the globe, it is likely that the type of patient with ARF will continue to become more complex and difficult to care for than in the past. This will clearly have a significant impact not only on the need for dialysis in the management of their renal failure, but also on the ultimate outcome of such children.

It should be stated at the outset that, despite the advances in the ability to provide dialysis to children with ARF discussed later in this paper, the outcome of pediatric ARF remains surprisingly poor overall, with reported mortality rates for children requiring dialysis ranging between 35% and 73% in recent series [15, 16, 17, 18, 20,

Table 1 Etiology of pediatric acute renal failure (ARF)[a]

Cause	*n*	%
Hemolytic-uremic syndrome	108	21.0
Glomerulonephritis	65	12.6
Acute tubular necrosis[b]	120	23.3
“Intrinsic renal disease”[b]	44	8.5
Urinary obstruction	17	3.3
Postoperative	35	6.8
Sepsis	32	6.2
Ischemic/Prerenal	23	4.5
Other[c]	71	13.8
Total	515	100

[a] Compiled from references [15, 16, 17, 18, 20, 22, 26]
[b] Specific causes not specified
[c] Including metabolic disorders, renal venous thrombosis, hepatorenal syndrome, complications of organ transplantation, and other miscellaneous causes

21, 22]. These mortality rates are higher than those recently reported for ARF in adults, which have ranged from 22% to 47% [23, 24]. Mortality was increased in children with sepsis, who were status post cardiac surgery, who had multiple organ failure, or who experienced a delay in referral for care. Other important predictors of outcome from ARF that have been highlighted in recent reports include hypotension and the need for vasopressor therapy, the need for mechanical ventilation, and young patient age. Some of these factors probably also explain the failure of improvement in outcome from ARF despite the introduction of new dialysis modalities, as extremely ill patients are now receiving dialysis who would not have received it in the past. Unfortunately, there are few data available regarding the survival of children with uncomplicated ARF not requiring dialysis, who most likely have better outcomes than those who required dialysis.

The long-term outcome of children who survived ARF has also received little study. Data that are available seem to indicate that even those children who required dialysis for ARF have reasonably good outcome in terms of renal function, but these reports are limited by relatively small patient numbers, and by center effect [20, 21, 22, 25]. In addition, other series have indicated that these children may have a significant incidence of chronic renal sequelae [26]. Ideally, multi-center studies involving larger numbers of patients should be conducted in order to generate more-reliable information on the long-term outcome of survivors of pediatric ARF.

Factors influencing dialysis modality choice

From a clinical standpoint, the two most-important factors that influence choice of a dialysis modality are the indication for dialysis and the overall clinical status of the patient. Indications for dialysis are well known and are summarized in Table 2. Each of these problems can be managed to some extent by conservative measures, but dialysis will become necessary when conservative measures fail to keep these problems under adequate control [10, 27, 28]. In addition, occasional patients may benefit from the institution of dialytic support in order to provide the necessary nutrition to aid in their recovery from ARF or its underlying cause [29, 30, 31]. Furthermore, dialysis will also be indicated in patients with certain inborn areas of metabolism, or who are suffering from certain intoxications [32, 33, 34].

The second major determinant of both the need for dialysis and the choice of dialysis modality is the overall clinical status of the patient. The status of major organ systems should be assessed. From a respiratory standpoint, such assessment would include whether or not the patient is receiving mechanical ventilation, and whether or not there is pulmonary edema present. Pertinent cardiovascular factors would include blood pressure, the need for inotropic support, and the presence or absence of arrhythmia. From a renal standpoint, whether or not there is urine output present, and the quantity of such output, are important considerations. Other aspects of the patients' condition, including their mental status and the presence or absence of dysfunction of other organ systems (including the skin and gastrointestinal tract), should be assessed.

Table 2 Indications for dialysis in ARF

Fluid overload with pulmonary edema and/or respiratory failure
Uremia with encephalopathy or bleeding
Metabolic derangements: hyperkalemia, acidosis, hyperphosphatemia
Intoxications: lithium, methyl alcohol, salicylate
Inborn errors of metabolism: urea cycle defects
Nutritional support (?)

These clinical factors interact in important ways. For example, the patient who is mildly fluid overloaded, but not experiencing respiratory compromise or significant pulmonary edema, may not require rapid fluid removal, and therefore, might be able to be managed with a gradual modality such as peritoneal dialysis (PD). On the other hand, a patient with significant metabolic acidosis and hypotension requiring inotropic support would likely be a poor candidate for intermittent hemodialysis (HD), but could potentially be managed by either hemofiltration or PD. The goal of such a comprehensive patient assessment, therefore, would be to determine the major need to be filled by dialysis for that patient (i.e., ultrafiltration vs. solute clearance), as well as what is feasible or possible given the overall clinical status of the patient. Institutional considerations may also play a part in determining dialysis modality. These will be addressed later.

A final important issue is the timing of initiation of dialysis. While the indications for dialysis are well understood, there are essentially no data regarding when to intervene with dialysis: should the physicians caring for the child with ARF wait for symptoms or complications of renal failure to occur, or should dialysis be initiated prior to the appearance of symptoms? Would earlier initiation of dialysis result in improved outcome? This may be especially important with respect to continuous renal replacement modalities, which are essentially still in their infancy. It is possible that earlier initiation of hemofiltration, for example, might result in better survival than that reported recently [35]. This is an important issue that clearly is ripe for further study. In the absence of data, it is probably advisable to consider initiating dialysis at the earliest sign that it may be needed.

Advantages and disadvantages of specific dialysis modalities

Peritoneal dialysis

PD has long been considered an effective dialysis modality for children with ARF, and continues to be employed in the management of these patients at many centers [15,

Table 3 Cost of dialysis equipment (in U.S. dollars)

Modality	Manual peritoneal dialysis	Manual peritoneal dialysis	Automated peritoneal dialysis	Intermittent hemodialysis	Continuous hemofiltration
Device	Dialy-Nate Manual PD set	Ultra Set (Y-set)	Freeedom Cycler	C3	Prisma
Manufacturer	Utah Medical Products	Baxter	Fresenius	Gambro	Gambro
Cost per unit[a]	$88.75[b]	$6.95[c]	$12,295.00	$18,000.00	$25,000.00
Cost of additional supplies	1.5% Dianeal (Baxter) $24.43/2.0L	Peritoneal dialysate as at left	Pediatric tubing set $32.00 each Peritoneal dialysate as at left	100HG dialyzer $50.00 each; pediatric bloodlines $11.40 each	M60 hemofilter set (includes filter and bloodlines) $160.00 each Normocarb dialysate concentrate (Dialysis Solutions) $20.00/3.0L

[a] Manufacturer's list price
[b] New set required every 24–72 h
[c] New unit required for each exchange

16, 17, 18, 21, 22, 36, 37, 38, 39, 40]. Major reasons for this are the technical simplicity and therapeutic advantages of this modality. For the most part, access for PD can be achieved quite easily and quickly. Even in the most unstable patients, a percutaneous PD catheter can usually be placed at the bedside in a short period of time [41]. While such catheters do have in disadvantages, including the tendency to leak, their use makes PD possible even in those patients who are too unstable to undergo a surgical procedure. For patients who are more stable, it is probably advisable to arrange for a surgical PD catheter placement. This may even be the optimal approach in unstable patients, if appropriate surgical support is available in the institution [37, 42, 43].

Similarly, dialysate for PD is widely available from commercial vendors. For those patients who have a contraindication to the use of standard, lactate-buffered dialysate (for example, patients with severe lactic acidosis or hepatic failure), a “custom,” bicarbonate-based dialysate can be easily prepared in the hospital pharmacy [6, 40, 44, 45]. Once access has been established, little other specialized equipment is absolutely necessary to provide PD. If an automated cycler is not available, then manual PD can be performed, utilizing either the common two-bag, so-called Y-set (Baxter Healthcare, Deerfield, Ill., USA), or the Dialy-Nate system (Utah Medical Products, Midvale, Utah, USA) for infants. Because of these minimal technical requirements, PD can usually be instituted within a short time of the decision to do so. From a price standpoint, PD is fairly inexpensive compared with other modalities (Table 3), and does not require additional nursing personnel other than intensive care unit (ICU) nurses.

PD also has several therapeutic advantages. One of the most important of these is that PD can be successfully performed even in patients who are hypotensive. This was recently demonstrated in a retrospective study performed at the University of Michigan in which several dozen children with ARF who were also significantly hypotensive and requiring vasopressor support were successfully managed with PD despite the expected poor efficiency of PD in such patients because of compromised circulation [40]. The ability to perform PD in such patients, as well as those with multiple organ system failure [46], is an important factor to consider when choosing a dialysis modality for unstable patients.

Other important advantages of PD from a therapeutic standpoint include the continuous and gradual provision of both ultrafiltration and solute clearance. This mimics to some extent the function of the kidney itself, and is clearly one of the major contributing factors to the success of PD in patients with cardiovascular instability. Finally, the dialysate can also act as a source of supplemental calories for the patient undergoing PD, and can therefore enhance the patients' nutritional support [47, 48].

The gradual nature of PD, however, while providing the benefits alluded to above, is also one of its major drawbacks. The fact that both ultrafiltration and solute clearance occur rather slowly in patients undergoing PD means that it may not be the optimal modality for patients with severe volume overload who require rapid ultrafiltration, or for patients with severe life-threatening hyperkalemia who require rapid reduction of their serum potassium. In such patients, PD would be a poor modality choice, especially when compared with the rapidity of both ultrafiltration and solute removal provided by intermittent HD. These factors also make PD a poor choice for treatment of intoxications.

In addition, certain underlying medical conditions can prevent the use of PD, or prevent it from being used effectively. A good example of this would be a patient with somewhat tenuous pulmonary function, who may not tolerate large volumes of dialysate in the abdomen because of the resultant increased intra-abdominal pressure, which may inhibit pulmonary function [49, 50]. A history of extensive abdominal surgery may also be a contraindication to PD, although such patients need to be assessed on a case-by-case basis in conjunction with a surgeon. On the other hand, the presence of a ventriculo-peritoneal shunt, or the underlying diagnosis of prune-belly syndrome should not be considered contraindications to the use of PD, as PD has been successfully reported in children with these problems. Patients with severe lactic acidosis may not be good candidates for PD, especially if a bicarbonate-based dialysate solution cannot be prepared. Such patients would probably benefit from intermittent HD with bicarbonate-based dialysate. Finally, although the dextrose used as the osmotic agent in peritoneal dialysate can be a source of additional calories, hyperglycemia has been reported as an occasional complication of PD [36], necessitating correction with insulin.

Table 4 Complications of dialysis by modality

Modality	Complication
All	Volume depletion Removal of drugs and nutrients Electrolyte imbalance Access infection Access malfunction (leak/hemorrhage, obstruction/thrombosis)
Peritoneal dialysis	Hyperglycemia Hydrothorax Infection (exit site, peritonitis) Hypothermia Hyponatremia
Hemodialysis	Disequilibrium syndrome Membrane bioincompatibility
Continuous hemofiltration	Hyperglycemia (if peritoneal dialysate used) Hypothermia Membrane bioincompatibility

Intermittent HD

The major advantage of intermittent HD in the treatment of ARF is its rapid rate of both solute clearance and ultrafiltration. This has its clear advantages, not only in the examples cited earlier, but also in situations such as the patient with a urea cycle defect who is admitted with severe hyperammonemia. In such situations, intermittent HD is clearly the optimal method of ammonia clearance [51, 52]. Other advantages of intermittent HD include the ability to adjust the composition of the dialysate in order to treat certain electrolyte abnormalities such as hypernatremia [53]. Furthermore, the HD machine can be adjusted to provide isolated ultrafiltration for patients who require additional ultrafiltration, or ultrafiltration without solute clearance.

From a technical standpoint, HD access is usually quite easy to achieve. Utilizing the Seldinger technique, a double-lumen HD catheter can almost always be inserted at the bedside in a relatively short amount of time. Such catheters can also be inserted in the operating suite if surgical support is available, or can be inserted by interventional radiologists under fluoroscopic guidance. A variety of catheter types are available [54], allowing for provision of HD even to small infants. In addition to the ease of achieving access, equipment for HD is usually widely available in larger hospitals, in contrast to hemofiltration, where equipment may not be available because of cost considerations (Table 3) or inexperience.

Of course, while these technical aspects of HD usually do not present major obstacles, in some cases they will. For example, in small infants it may be difficult to achieve adequate access to provide optimal dialysis [55]. In addition, while the necessary equipment for HD may be widely available, some centers may not have this technology available because of the cost of HD machines (Table 3). Finally, provision of HD does represent a level of technological specialization that may not be present in some centers, especially with respect to the specialized staff required (dialysis nurses, support technicians).

From a patient management standpoint, treatment of ARF with intermittent HD usually necessitates some degree of fluid restriction because many patients will not tolerate removal of large volumes of fluid over the short treatment times typically utilized in intermittent HD. Daily intermittent HD may help in this regard, but will not completely eliminate the need for fluid restriction, which in turn will frequently lead to limitations on the amount of nutritional support that a patient may receive, particularly if they are receiving large volumes of other intravenous fluids such as inotropic agents or antibiotics. (A potential method of avoiding fluid restriction is to utilize prolonged intermittent HD [56], a modality that has not yet been reported in children). Finally, the capacity of intermittent HD for ultrafiltration will be further limited if the patient is significantly hypotensive. In such patients, HD may need to be terminated early or may not be able to be provided at all. In such patients, either PD or hemofiltration may be superior options because of the more gradual fluid removal provided by these modalities.

Unique complications of intermittent HD to be considered in patients with ARF include both disequilibrium syndrome and membrane bioincompatibility (Table 4; [57, 58]). Disequilibrium syndrome can occur because of the rapid osmolar shifts that may occur during HD. Without careful monitoring of the patient and perhaps provision of osmotically active substances such as mannitol during the HD treatment, these osmolar shifts can produce cerebral edema, leading to a variety of complications, including mental status changes and seizures [57, 59].

The topic of membrane bioincompatibility in patients with ARF has received much attention [58] in recent years, with some studies demonstrating that choice of dialysis membrane may affect outcome, and other studies demonstrating no effect [60, 61]. Certain dialysis membranes do result in complement activation, which may lead to cytokine release and other adverse effects that can worsen the patient's overall status, perhaps also prolonging their ARF [58]. At present, although this issue has not been completely resolved in the literature, it is probably wise to use only biocompatible membranes such as cellulose acetate in children with ARF.

Continuous hemofiltration

Continuous hemofiltration[1] has a number of distinct advantages in the management of patients with ARF. Chief among these is that it provides continuous solute clearance and ultrafiltration, thereby mimicking to some extent the functions of the normal kidney [1, 3]. The gradual nature of fluid removal provided by hemofiltration makes it an ideal modality for many patients with cardiovascular instability and hypotension. Furthermore, since fluid is removed on a continuous basis, fluid restriction is usually unnecessary in patients being treated with hemofiltration, which provides much greater freedom than HD to provide large volumes of nutritional support, either enteral or parenteral. On the other hand, at least one study has demonstrated increased losses of amino acids in patients undergoing hemofiltration [62]; increasing the amino acid content of the total parenteral nutrition (TPN) solution can usually minimize this problem.

Hemofiltration may also have specific metabolic advantages compared with other dialysis modalities. Because the composition of the dialysate is adjustable in many hemofiltration systems, a wide variety of metabolic derangements can be easily corrected with hemofiltration, including severe metabolic acidosis, lactic acidosis, and electrolyte abnormalities such as hyperkalemia. It has been reported that hemofiltration provides superior control of uremia than intermittent HD [63]. Hemofiltration can also be adapted to gradually correct hyperosmolar states [64], and may be less likely to lead to cerebral edema than intermittent HD [58]. In addition, several authors have recently begun to explore the possible benefits from hemofiltration with respect to removal of mediators of inflammation [65, 66]. Such substances, which contribute to the pathogenesis of the sepsis syndrome, appear to be cleared to some extent by hemofiltration, due to the relatively small size of these molecules and the properties of the membranes used for hemofiltration. The studies exploring this topic have by no means provided definitive data [66], but early promising reports [67] may eventually lead to a specific application for hemofiltration in the care of patients with sepsis, perhaps in combination with immunoadsorption [68].

From a technical standpoint, hemofiltration has unique requirements. As with HD, access to the central circulation is necessary to achieve adequate blood flow. Establishment of such access should be straightforward in centers that are used to performing HD. This may be more difficult in infants, but this is not an insurmountable barrier [41]. It should be noted that venovenous techniques of hemofiltration are now used nearly exclusively in pediatrics because of the more-predictable blood flows and clearances achieved compared with the older approach of arteriovenous hemofiltration. One unique drawback of hemofiltration in the care of infants with ARF is the relatively large extracoporeal circuit volume, which necessitates the use of a blood prime before initiating treatment (a smaller circuit has been developed and should soon be widely available). Case reports have emerged of a severe hypotensive reaction to the AN-69 membrane found in some hemofilters in infants treated with hemofiltration when a blood prime is used [69]. However, a method of preventing this reaction has been developed [69], which should hopefully reduce the complications of hemofiltration in this age group.

A more significant drawback to the use of hemofiltration is the technological complexity and high cost of this therapy. The equipment is amongst the most expensive on the market as far as dialysis equipment is concerned (Table 3), and some centers may not be able to afford to establish hemofiltration programs for this reason. In addition to the expensive equipment, a specialized nursing staff is usually required, with dialysis nurses initiating the hemofiltration treatments in most pediatric centers, and ICU nurses taking over once the patient has been stabilized on the hemofiltration circuit. This increases the labor cost for hemofiltration compared with other modalities [70], as not only is a skilled ICU nurse required, but also a skilled dialysis nurse. However, the dialysis nursing time may be less with hemofiltration compared with HD, potentially resulting in a cost savings compared with daily HD. Finally, until recently, many hemofiltration programs required extensive support from their hospital pharmacies to prepare large volumes of custom dialysate [71]. With the recent development of commercially available dialysate solutions for hemofiltration [72], this requirement has been alleviated to some extent.

It is important to note that despite the technological advance represented by hemofiltration, this modality has yet to improve the outcome of children with ARF [15, 35, 73, 74]. Although this may reflect the fact that hemofiltration is being applied to patients who are more complex and critically ill than those dialyzed in the past [74], it may also be a reminder that older dialysis modalities remain appropriate for many patients. In addition, the issue of timing of initiation of hemofiltration may also play a role in the failure of improvement in outcome.

Guidance from the literature

Ideally, it should be possible to turn to the medical literature to obtain guidance regarding the choice of dialysis modality. However, few studies have been performed

[1] In this paper, the term "hemofiltration" is used to refer to all of the many forms of continuous renal replacement therapy

that have compared different dialysis modalities in children with ARF. For example, there have been no studies comparing PD with intermittent HD in pediatric ARF. This is most likely because prior to the advent of hemofiltration, almost every paper on dialysis in pediatric ARF utilized PD, probably because of a perception in the past that HD was technically difficult in infants and young children. Although successful HD in infants has subsequently been reported [75], and may now be considered routine in many centers, no pediatric study comparing these modalities in ARF has been conducted.

Since the advent of hemofiltration, however, several studies have appeared in the pediatric ARF literature that have compared hemofiltration with other dialysis modalities. Before reviewing selected papers from this literature, it is important to point out that all of these studies suffer from significant limitations, including retrospective, single-center study designs, small patient numbers (some studies), and homogeneous patient populations that do not allow for generalization of study results. Despite these flaws, however, these studies do provide useful insights.

Fleming et al. [76] performed an important comparison of PD and hemofiltration in 1995. They retrospectively compared 42 children who required renal replacement therapy (RRT) following repair of congenital heart disease. Indications for RRT in the study included oliguria, fluid overload, hyperkalemia, and provision of TPN. Twenty-one patients received PD and 21 patients received hemofiltration, with 9 of those receiving arteriovenous hemofiltration and 12 venovenous; 34 patients received RRT for more than 24 h. Time of initiation of RRT was not standardized, and consequently varied significantly among the patients. Of the 42 patients in the study, 90% required inotropic support, 36% required repeat operation for their congenital heart disease, and 18% had sepsis. Survival was identical for patients treated with PD compared with those treated with hemofiltration (38%). However, fluid removal, urea and creatinine clearance, and caloric intake were superior in the hemofiltration groups compared with the group who received PD. From these data, the authors concluded that hemofiltration was superior to PD in this clinical setting. While this conclusion may be true for children who develop oliguria following open-heart surgery, these results may not apply to patients with other underlying diagnoses. In addition, although caloric intake and solute clearance were superior in the group that received hemofiltration, the data did not indicate that these benefits conferred any survival advantage. Thus, as indicated in other recently published series [39, 77, 78], PD remains a viable modality option for this type of patient.

A comparison of HD and hemofiltration in pediatric ARF was published by Maxvold et al. in 1997 [74]. They retrospectively studied 122 children with ARF, 58 who underwent intermittent HD, and 64 who underwent hemofiltration. Clinical characteristics of the two groups were similar in terms of patient age and patient weight. There was a higher percentage of children with primary renal disease in the HD group, compared with a higher percentage of patients with sepsis in the hemofiltration group. Similarly, hypotension and the need for vasopressor support were more common in the hemofiltration group, suggesting a greater severity of underlying illness in those children. This was reflected in the patient survival, which was much greater in the HD group (83%) than in the hemofiltration group (48%). Most dramatically, survival was 96% for patients with primary renal disease treated with HD compared with 31% for sepsis-related ARF treated with hemofiltration, again reflecting the greater severity of illness in the hemofiltration group. Other aspects of the modality comparison included a similar rate of complications in patients treated with HD and hemofiltration, the most common of which was hypotension. Patients underwent RRT longer in the HD group, most likely because of the greater survival in this group. The authors concluded from this study that although survival was somewhat better in the HD group, provision of hemofiltration most likely contributed to the survival of many patients who might not have survived had hemofiltration not been available.

Finally, there has been one study that has directly compared all three dialysis modalities in children with ARF. This was a retrospective review, again by investigators at the University of Michigan, of 279 children who received RRT over a 7-year period for treatment of ARF and/or inborn areas of metabolism; 59 of the children received PD, 140 hemofiltration, and 80 intermittent HD. Overall patient survival was 53%, with some variation in survival among modalities for certain diagnoses. For example, while overall survival in patients with ARF following bone marrow transplant was 42%, such patients treated with intermittent HD had a survival of 78% compared with survivals of 33% for those treated with PD and 21% for those treated with hemofiltration. Conversely, patients with ARF following repair of congenital heart disease had an overall survival of 39%, with 100% survival for those treated with intermittent HD, 33% survival for those treated with PD, and 50% survival for those treated with hemofiltration. Hemodynamic instability was felt to not only affect patient outcome, but also was predictive of modality choice: patients who were the most hemodynamically unstable were usually treated with either hemofiltration or PD, whereas stable patients were usually treated with intermittent HD.

The importance of underlying diagnosis and severity of illness as determinants of outcome was confirmed in a recent analysis of RRT in adult ARF [79]. In this study, 350 patients with ARF treated with either intermittent HD or hemofiltration were retrospectively reviewed. While initial analysis seemed to demonstrate a greater risk of death in patients undergoing hemofiltration, multivariate analysis controlling for severity of illness actually demonstrated that outcome for the two modalities was similar.

The common themes from these studies appear to be that severity of illness (especially hemodynamic stabili-

Table 5 Suggested modality choice in pediatric ARF

Goal of dialysis	Hemodynamic status	Modality
Ultrafiltration	Normotensive	Intermittent hemodialysis (with isolated ultrafiltration)
	Hypotensive	Continuous hemofiltration or peritoneal dialysis
Urea clearance	Normotensive	Intermittent hemodialysis or peritoneal dialysis
	Hypotensive	Continuous hemofiltration or peritoneal dialysis
Treatment of hyperkalemia	Either normotensive or hypotensive	Intermittent hemodialysis
Correction of metabolic acidosis[a]	Normotensive	Any
	Hypotensive	Continuous hemofiltration or peritoneal dialysis
Treatment of hyperphosphatemia	Either normotensive or hypotensive	Any; continuous hemofiltration possibly superior

[a] Bicarbonate dialysate preferred in patients with hepatic failure and/or lactic acidosis

ty), the specific indication for RRT, and the underlying cause of ARF are the most important factors to consider when choosing a modality for RRT in children with ARF. This approach is summarized in Table 5, which provides guidelines for modality choice for the various types of patients with ARF commonly seen in modern ICUs. For example, the hemodynamically stable patient with significant fluid overload requiring ultrafiltration only would best be treated by intermittent HD (with isolated ultrafiltration). However, the hemodynamically unstable patient with severe metabolic acidosis would be best treated with hemofiltration. In settings where hemofiltration is not available for financial or technological reasons, carefully performed PD would certainly be a viable therapeutic option in the hemodynamically unstable patient.

Conclusions

The physician involved in the care of children with ARF has numerous options available when RRT is indicated. Since there are few data available at present comparing the outcomes achieved with different dialysis modalities, the choice of modality to be used in a specific patient will have to be empirical, taking into consideration the patient's underlying illness, severity of illness, and the advantages and disadvantages of the various modalities available locally. Further studies should be conducted to better define the outcome of ARF in children, to further delineate the advantages and disadvantages of the available RRT modalities, and also to better define the costs involved with specific dialysis modalities.

Acknowledgements Presented in part at the 12th Annual Symposium on Pediatric Dialysis, New Orleans, La., USA, February 2001. The author would like to thank Elaine Guarascio for assistance with preparation of the manuscript.

References

1. Bunchman TE, Donckerwolcke RA (1994) Continuous arterial-venous hemodiafiltration and continuous veno-venous hemodiafiltration in infants and children. Pediatr Nephrol 8:96–102
2. Ellis EN, Pearson D, Belsha CW, Berry PL (1997) Use of pump-assisted hemofiltration in children with acute renal failure. Pediatr Nephrol 11:196–200
3. Forni LG, Hilton PJ (1997) Continuous hemofiltration in the treatment of acute renal failure. N Engl J Med 336:1303–1309
4. Mehta RL (1994) Therapeutic alternatives to renal replacement for critically ill patients in acute renal failure. Semin Nephrol 14:64–82
5. Murray P, Hall J (2000) Renal replacement therapy for acute renal failure. Am J Respir Crit Care Med 162:777–781
6. Parekh RS, Bunchman TE (1996) Dialysis support in the pediatric intensive care unit. Adv Ren Replace Ther 3:326–336
7. Belsha CW, Kohaut EC, Warady BA (1995) Dialytic management of acute renal failure: a survey of North American pediatric nephrologists. Pediatr Nephrol 9:361–363
8. Warady BA, Bunchman T (2000) Dialysis therapy for children with acute renal failure: survey results. Pediatr Nephrol 15:11–13
9. Ellis D, Gartner C, Galvis AG (1981) Acute renal failure in infants and children: diagnosis, complications and treatment. Crit Care Med 9:607–617
10. Karlowicz MG, Adelman RD (1992) Acute renal failure in the neonate. Clin Perinatol 19:139–158
11. Sehic A, Chesney RW (1995) Acute renal failure: diagnosis. Pediatr Rev 16:101–106
12. Stewart CL, Barnett R (1997) Acute renal failure in infants, children and adults. Crit Care Clin 13:575–590
13. Airede A, Bello M, Weerasinghe HD (1997) Acute renal failure in the newborn: incidence and outcome. J Paediatr Child Health 33:246–249
14. Flynn JT (1998) Causes, management approaches, and outcome of acute renal failure in children. Curr Opin Pediatr 10:184–189
15. Bunchman TE, Smoyer WE, Valentini RP, Kershaw DB, Gregory MJ, Sedman AB (1994) Modality and mortality in pediatric renal replacement therapy (abstract). J Am Soc Nephrol 5:436
16. Arora P, Kher V, Rai PK, Singhal MK, Galati S, Gupta A (1997) Prognosis of acute renal failure in children: a multivariate analysis. Pediatr Nephrol 11:153–155
17. Kandoth PW, Agarwal GJ, Dharnidha VR (1994) Acute renal failure in children requiring dialysis therapy. Indian Pediatr 31:305–309
18. Wong W, McCall E, Anderson B, Segedin E, Morris M (1996) Acute renal failure in the paediatric intensive care unit. N Z Med J 109:459–461
19. Liano F, Pascual J and the Madrid Acute Renal Failure Study Group (1996) Epidemiology of acute renal failure: a prospective, multicenter, community-based study. Kidney Int 50:811–818
20. Acharya UT, Singla PN, Singh RG, Usha Mishra OP (1996) Outcome of dialysed patients with acute renal failure. Indian Pediatr 33:387–390

21. Blowey DL, McFarland K, Alon U, McGraw-Houchens M, Hellerstein S, Warady BA (1993) Peritoneal dialysis in the neonatal period: outcome data. J Perinatol 13:59–64
22. Gong W-K, Tan T-H, Foong P-P, Murugasu B, Yap H-K (2001) Eighteen years experience in pediatric acute dialysis: analysis of predictors of outcome. Pediatr Nephrol 16:212–215
23. Baretti P, Soares VA (1997) Acute renal failure: clinical outcomes and causes of death. Ren Fail 19:253–257
24. Thadhani R, Pascual M, Bonventre JV (1996) Acute renal failure. N Engl J Med 334:1448–1460
25. Georgaki-Angelaki HN, Steed DB, Chantler C, Haycock G (1989) Renal function following acute renal failure in childhood: a long-term follow-up study. Kidney Int 35:84–89
26. Niaudet P, Haj-Ibrahim M, Gagnadoux M-F, Broyer M (1985) Outcome of children with acute renal failure. Kidney Int 28 [Suppl 17]:S148–S151
27. Mendley SR, Langman CB (1997) Acute renal failure in the pediatric patient. Adv Ren Replace Ther 4 [Suppl 1]:93–101
28. Sehic A, Chesney RW (1995) Acute renal failure: therapy. Pediatr Rev 16:137–141
29. Sponsel H, Conger JD (1995) Is parenteral nutrition therapy of value in acute renal failure patients? Am J Kidney Dis 25:96–102
30. Ikizler TA, Himmelfarb J (1997) Nutrition in acute renal failure patients. Adv Ren Replace Ther 4 [Suppl 1]:54–63
31. Riella MC (1997) Nutrition in acute renal failure. Ren Fail 19:237–252
32. Balsam L, Coritsidis GN, Feinfeld DA (1991) Role of hemodialysis and hemoperfusion in the treatment of intoxications. In: Hoffman RS, Goldfrank LR (eds) Critical care toxicology. Churchill Livingstone, New York, pp 61–79
33. Brophy PD, Flynn JT, Kershaw DB, Smoyer WE, Mottes T, Maxvold NJ, Bunchman TE (1999) Pediatric overdose: effective treatment with high-efficiency hemodialysis (abstract). J Am Soc Nephrol 10:137A
34. Meyer RJ, Flynn JT, Brophy PD, Smoyer WS, Kershaw DB, Custer JR, Bunchman TE (2001) Hemodialysis followed by continuous hemofiltration for treatment of lithium intoxication in children. Am J Kidney Dis 37:1044–1047
35. Goldstein SL, Currier H, Graf JM, Cosio CC, Brewer ED, Sachdeva R (2001) Outcome in children receiving continuous venovenous hemofiltration. Pediatrics 107:1309–1312
36. Reznik VM, Griswold WR, Peterson BM, Rodarte A, Ferris ME, Mendoza SA (1991) Peritoneal dialysis for acute renal failure in children. Pediatr Nephrol 5:715–717
37. Alarabi AA, Peterson T, Danielson BG, Wikstrom B (1994) Continuous peritoneal dialysis in children with acute renal failure. Adv Perit Dial 10:289–293
38. Kholi HS, Arora P, Kher V, Gupta A, Sharma RK, Bhaumik SK (1995) Daily peritoneal dialysis using a surgically placed Tenckhoff catheter for acute renal failure in children. Ren Fail 17:51–56
39. McCulloch B, Eley B, Zühlke L, Sinclair P, Reyonolds L, Argent A (2000) Peritoneal dialysis as a form of continuous renal replacement therapy for infants less than 5 kg in a developing country (abstract). Pediatr Nephrol 14:C136
40. Flynn JT, Kershaw DB, Smoyer WE, Brophy PD, McBryde KD, Bunchman TE (2001) Peritoneal dialysis for management of pediatric acute renal failure. Perit Dial Int 21:390–394
41. Bunchman TE (1996) Acute peritoneal dialysis access in infant renal failure. Perit Dial Int 16 [Suppl 1]:S509–S511
42. Kohli HS, Barkataky A, Kumar RS, Sud K, Jha V, Gupta KL, Sakhuja V (1997) Peritoneal dialysis for acute renal failure in infants: a comparison of three types of peritoneal access. Ren Fail 19:165–170
43. Chadha V, Warady BA, Blowey DL, Simckes AM, Alon US (2000) Tenckhoff catheters prove superior to Cook catheters in pediatric acute peritoneal dialysis. Am J Kidney Dis 35:1111–1116
44. Vaziri ND, Ness R, Wellikson L, Barton C, Greep N (1979) Bicarbonate-buffered peritoneal dialysis. An effective adjunct in the treatment of lactic acidosis. Am J Med 67:392–396
45. Nash MA, Russo JC (1977) Neonatal lactic acidosis and renal failure: the role of peritoneal dialysis. J Pediatr 91:101–105
46. McCulloch MI, Gilbert RD (1999) Acute peritoneal dialysis in children (abstract). Perit Dial Int 19 [Suppl 1]:S74
47. Grostein GP, Bluemkrantz MJ, Kopple JD, Moran JK, Coburn JW (1981) Glucose absorption during continuous ambulatory peritoneal dialysis. Kidney Int 19:564–567
48. Podel J, Hodelin-Wetzel R, Saha DC, Burns G (2000) Glucose absorption in acute peritoneal dialysis. J Ren Nutr 10:93–97
49. Gotloib L, Garmizo L, Varak I, Mines M (1981) Reduction of vital capacity due to increased intra-abdominal pressure during peritoneal dialysis. Perit Dial Bull 1:63–64
50. Bunchman TE, Meldrum MK, Meliones JE, Sedman AB, Walters MB, Kershaw DB (1992) Pulmonary function variation in ventilator dependent critically ill infants on peritoneal dialysis. Adv Perit Dial 8:75–78
51. McBryde KD, Gregory MJ, Brophy PJ, Maxvold NJ, Gardner JJ, Mottes TA, Bunchman TE (2000) Renal replacement therapy in metabolic diseases (abstract). J Am Soc Nephrol 11:108A
52. Mathias RS, Kostiner D, Packman S (2001) Hyperammonemia in urea cycle disorders: role of the nephrologist. Am J Kidney Dis 37:1069–1080
53. Pazmino PA, Pazmino BP (1993) Treatment of acute hypernatremia with hemodialysis. Am J Nephrol 13:260–265
54. Bunchman TE, Gardner JJ, Kershaw DB, Maxvold NJ (1994) Vascular access for hemodialysis or CVVH(D) in infants and children. Dial Transplant 23:314–318
55. Coulthard MG, Sharp J (2001) Haemodialysing infants: theoretical limitations, and single versus double lumen lines. Pediatr Nephrol 16:332–334
56. Schlaeper C, Amerling R, Manns M, Levin NW (1999) High clearance continuous renal replacement therapy with a modified dialysis machine. Kiney Int 56 [Suppl 72]:S20–S23
57. Arieff AI (1994) Dialysis disequilibrium syndrome: current concepts on pathogenesis and prevention. Kidney Int 45:629–635
58. Himmelfarb J, Hakim RM (1997) The use of biocompatible dialysis membranes in acute renal failure. Adv Ren Replace Ther 4 [Suppl 1]:72–80
59. Ronco C, Bellomo R, Brendolan A, Pinna V, La Greca G (1999) Brain density changes during renal replacement in critically ill patients with acute renal failure. Continuous hemofiltration versus intermittent hemodialysis. J Nephrol 12:173–178
60. Hakim RM, Wingard RL, Parker RA (1994) Effect of the dialysis membrane in the treatment of patients with acute renal failure. N Engl J Med 331:1338–1342
61. Jörres A, Gahl GM, Dobis C, Polenakovic MH, Cakalaroski K, Rutkowski B, Kisielnicka E, Krieter DH, Rumpf KW, Guenther C, Gaus W, Hoegel J (2000) Haemodialysis-membrane bioincompatibility and mortality of patients with dialysis-dependent acute renal failure: a prospective randomised multicentre trial. Lancet 354:1337–1341
62. Maxvold NJ, Smoyer WE, Cuter JR, Bunchman TE (2000) Amino acid loss and nitrogen balance in critically ill children with acute renal failure: a prospective comparison between classic hemofiltration and hemofiltration with dialysis. Crit Care Med 28:1161–1165
63. Clark WR, Mueller BA, Alaka KJ, Macias WL (1994) A comparison of metabolic control by continuous and intermittent therapies in acute renal failure. J Am Soc Nephrol 4:1413–1420
64. McBryde KD, Brophy PD, Kudelka TL, Pasko DA, Bunchman TE (2000) Continuous veno-venous hemodiafiltration for the treatment of hyperosmolar disturbances (abstract). Pediatr Nephrol 14:C136
65. Hoffmann JN, Hartl WH, Deppisch R, Faist E, Jochum M, Inthorn D (1995) Hemofiltration in human sepsis: evidence for elimination of immunomodulatory substances. Kidney Int 48:1563–1570
66. Silvester W (1997) Mediator removal with CRRT: complement and cytokines. Am J Kidney Dis 30 [Suppl 4]:S38–S43

67. Pearson G, Khandelwal PC, Naqvi N (2000) Early filtration and mortality in meningococcal septic shock? Arch Dis Child 83:508–509
68. Tetta C, Gianotti L, Cavaillon JM, Wratten ML, Fini M, Braga M, Bisagni P, Giavaresi G, Bolzani R, Giardino R (2000) Coupled plasma filtration-adsorption in a rabbit model of endotoxic shock. Crit Care Med 28:1526–1533
69. Brophy PD, Mottes TA, Kudelka TL, McBryde KD, Gardner JJ, Maxvold NJ, Bunchman TE (2001) AN-69 membrane reactions are pH-dependent and preventable. Am J Kidney Dis (in press)
70. Reznik VM, Randolph G, Collins CM, Peterson BM, Lemire JM, Mendoza SA (1993) Cost analysis of dialysis modalities for pediatric acute renal failure. Perit Dial Int 13:311–313
71. Smoyer WE, Sherbotie JR, Gardner JJ, Bunchman TE (1995) A practical approach to continuous hemofiltration in infants and children. Dial Transplant 24:633–640
72. Zimmerman D, Cotman P, Ting R, Karanicolas S, Tobe SW (1999) Continuous veno-venous haemodialysis with a novel bicarbonate dialysis solution: prospective cross-over comparison with a lactate buffered solution. Nephrol Dial Transplant 14:2387–2391
73. Bunchman TE, Brophy PD, Flynn JT, Kershaw DB, Maxvold NJ, Smoyer WE (1999) Pediatric renal replacement therapies: diseases, modalities and outcome (abstract). J Am Soc Nephrol 10:138A
74. Maxvold NJ, Smoyer WE, Gardner JJ, Bunchman TE (1997) Management of acute renal failure in the pediatric patient: hemofiltration versus hemodialysis. Am J Kidney Dis 30 [Suppl 4]:S84–S88
75. Sadowski RH, Harmon WE, Jabs K (1994) Acute hemodialysis of infants weighing less than five kilograms. Kidney Int 45:903–906
76. Fleming F, Bohn D, Edwards H, Cox P, Geary D, McCrindle BW, Williams WG (1995) Renal replacement therapy after repair of congenital heart disease in children: a comparison of hemofiltration and peritoneal dialysis. J Thorac Cardiovasc Surg 109:322–331
77. Werner HA, Wensley DF, Lirenmen DS, LeBlanc JG (1997) Peritoneal dialysis in children after cardiopulmonary bypass. J Thorac Cardiovasc Surg 113:64–68
78. Sorof JM, Stromberg D, Brewer ED, Feltes TF, Fraser CD Jr (1999) Early initiation of peritoneal dialysis after surgical repair of congenital heart disease. Pediatr Nephrol 13:641–645
79. Swartz RD, Messana JM, Orzol S, Port FK (1999) Comparing continuous hemofiltration with hemodialysis in patients with severe acute renal failure. Am J Kidney Dis 34:424–432