SURGERY FOR CONGENITAL HEART DISEASE

PERITONEAL DIALYSIS IN CHILDREN AFTER CARDIOPULMONARY BYPASS

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Objective: **We reviewed 5 years' experience with peritoneal dialysis in children with acute renal failure after cardiac operations. We hypothesized that peritoneal dialysis is safe and effective in children with low-output cardiac failure after cardiac operations.** ***Results:*** **Mortality in these patients with renal failure (*n* = 32) was 46.9%. Fluid removed by peritoneal dialysis was 48 ± 28 ml/kg per 24 hours. Most complications of peritoneal dialysis were minor, hyperglycemia being the most frequent (53.1%). Peritoneal infection was suspected in 25%. Bowel perforation developed in two patients. None of the complications required early termination of dialysis. Hemodynamics and pulmonary function improved continuously during the study period.** ***Conclusion:*** **The early institution of peritoneal dialysis in acute renal failure and low cardiac output after cardiac operations not only removes fluid, thus easing fluid restriction, but may also improve cardiopulmonary function. (J Thorac Cardiovasc Surg 1997;113:64-70)**

Acute oliguric/anuric renal failure (ARF) develops in up to 5% of children after cardiac operations.[1-7] The vast majority of these patients have low-output cardiac failure. Treatment alternatives are (1) slow continuous fluid removal, such as in hemofiltration or peritoneal dialysis (PD), or (2) severe fluid restriction and drug-induced diuresis. Fluid restriction is more conservative and less invasive. However, absolute requirements for electrolyte and drug infusions frequently lead to fluid accumulation despite aggressive diuretic therapy. This may further compromise depressed cardiorespiratory function. In addition, fluid restriction makes adequate nutrition impossible.

Recent evidence suggests that active fluid removal in patients with ARF and low cardiac output after cardiopulmonary bypass (CPB) may improve hemodynamic parameters,[8, 9] as well as arterial oxygenation.[8] Short-term intraoperative hemofiltration at the end of CPB in children has been shown to improve cardiac function[10] and respiratory mechanics.[11]

At our institution, children with ARF after cardiac operations are usually treated with PD. We reviewed our experience from 1986 through 1991 and describe fluid dynamics and cardiorespiratory function in 32 children treated with PD after cardiac operations. We hypothesized that PD is a safe and effective method of extrarenal fluid removal in children with severe cardiac and renal failure after CPB.

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Patients and methods

The review of records was approved by the Institutional Review Board of the British Columbia Children's Hospital. Between January 1986 and January 1991, 618 children (aged 1 day to 15 years, mean 24 months) underwent a cardiac operation with the use of CPB at British Columbia Children's Hospital.

The computerized database of the intensive care unit was searched for patients who required PD after a cardiac operation. Thirty-two children were identified who had low-output cardiac failure complicated by ARF requiring PD. *ARF* was defined as urine output of less than 0.5 ml/kg per hour for more than 4 hours, unresponsive to

Table I. *Patient data at day 1 of study*

	PD (n = 32)
Age (mo)	22 ± 35
Weight (kg)	9.2 ± 8.9
Sex	18 male, 14 female
MAP (mm Hg)	55 ± 9.9
CVP (mm Hg)	15 ± 3.6
Inotrope score	5.2 ± 1.9
P_{AW}	11 ± 3.2
PEEP	5.3 ± 1.6
Fio_2	0.7 ± 0.52
Pao_2 (mm Hg)	104 ± 51
A-aDo_2 (mm Hg)	353 ± 191
Diagnosis/operation	
Arterial switch	3
Tetralogy of Fallot	5
AV canal defect	5
VSD	5
Fontan	4
Aortic arch defect	4
Other	6
Mortality	15/32 (46.9%)

All values are expressed as mean ± standard deviation. *MAP,* Mean arterial pressure; *CVP,* central venous pressure; *P*AW, mean airway pressure; *PEEP,* positive end-expiratory pressure; *Fio_2,* fraction of inspired oxygen; *Pao_2,* arterial pressure of oxygen; *AV,* atrioventricular; *VSD,* ventricular septal defect; *A-aDo_2,* alveolar-arterial gradient for oxygen.

adjustment in fluid therapy, diuretics, inotropic support, or any combination thereof.

Low-output cardiac failure was defined as mean arterial pressure less than 60 mm Hg (<50 mm Hg in infants <4 weeks) on three or more separate recordings and requirement for two inotropic agents or more (two or more of the following: dopamine and/or dobutamine at ≥8 μg/kg per minute and/or epinephrine and/or norepinephrine at ≥0.1 μg/kg per minute).

Details of the operations and clinical courses were obtained from a review of all patients' hospital records. The following data were recorded: mean arterial and central venous blood pressures, mean airway pressure, positive end-expiratory pressure, inotropic drugs and dosages, arterial blood gases, urine output, and fluid balance. Alveolar-arterial gradient for oxygen (A-aDo_2) was calculated in all children without intracardiac shunt as follows:

$$\text{A-aDo}_2 \text{ (mm Hg)} = \text{Fio}_2 \times (760 - 47) - \text{Paco}_2/0.8 - \text{Pao}_2$$

where Fio_2 = fraction of inspired oxygen, $Paco_2$ = arterial partial pressure of carbon dioxide, and Pao_2 = arterial partial pressure of oxygen.

All patients' lungs were ventilated in a controlled mode with a Siemens Servo 900C ventilator (Siemens Medical Systems, Inc.). Mean airway pressure was recorded as displayed by the ventilator. Timing of mean airway pressure measurement was chosen randomly in regard to PD cycling. For each of the recorded parameters, three daily values were retrieved and the mean was calculated. Institution of PD was the beginning of the 5-day study period for each patient.

Table II. *Complications of PD**

Complication	No.	%
Hyperglycemia (3 requiring insulin)	17	53.1
Positive dialysate culture	12	37.5
Difficult drainage	5	15.6
Hemodynamic instability with drainage	5	15.6
Catheter site leakage	4	12.5
Asymptomatic hypokalemia	4	12.5
Pleural effusion requiring drainage	3	9.4
Bowel perforation	2	6.3

*More than one complication occurred in some.

PD. A standard peritoneal catheter for short-term use (Trocath, McGraw Labs) was inserted either in the intensive care unit or, in a few cases, during the primary surgical procedure, when postoperative hemodynamic and renal compromise was anticipated. Two children requiring prolonged PD later had cuffed Tenckhoff catheters inserted in the operating room. Dialysate solutions were standard commercial preparations (Dianeal, Travenol Labs). Heparin was added in a concentration of 500 units/L and potassium chloride was added as appropriate. Initial cycles were chosen to be 20 ml/kg dialysate with 40-minute dwell time and 20-minute drainage time. Dialysis schedule was altered on regular review of clinical and biochemical status.

Statistical analysis. Values are expressed as mean ± one standard deviation. Comparison between values was done by means of analysis of variance for repeated measures.

Results

Patient details are shown in Table I. Of 618 children undergoing cardiac operations, 32 had ARF and were treated with PD (5.2%). Fifteen of 32 children died (46.9%).

PD. The mean interval between the operation and initiation of PD was 2.6 ± 0.6 days. Fifteen children (46.9%) had ascites on clinical examination before PD. Mean duration of PD was 7.1 ± 8.3 days; one infant required long-term PD and subsequently underwent successful renal transplantation. PD removed fluid in all but four children, all of whom died of cardiac complications within 24 hours of starting PD. When these four were excluded, fluid removed by PD was 48 ± 28 ml/kg per day. The condition of all patients with acidosis or hyperkalemia improved—with pH and potassium returning to normal levels in 26 (81%).

PD complications. Dialysis complications are shown in Table II. Most were believed to be minor and were easily managed. Mediastinal or chest tube drainage (or both) increased by more than 25% after the institution of PD in 13 patients (41%). Positive dialysis cultures were obtained in 12 chil-

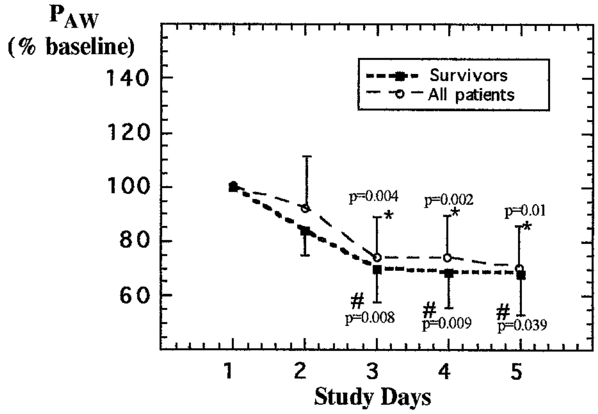

Fig. 1. Mean airway pressure *(P_{AW})* during 5 days of PD for all subjects *(open circles)* and for the group of survivors *(solid squares)*. *Bars* represent one standard deviation. *Different from day 1, all subjects ($p < 0.05$). #Different from day 1, survivors ($p < 0.05$).

dren (38%), with contamination suspected in four (cultures not reproducible, Gram stain of dialysate negative for cells and organisms, no clinical evidence of infection). A true infection of the peritoneum was suspected in the remaining eight (25%); *Pseudomonas maltophilia* ($n = 4$) and *Enterobacter cloacae* ($n = 3$) were the commonest organisms identified. Intraperitoneal antibiotics led to clinical improvement. Dialysate cultures remained intermittently positive in four until catheter removal. Infection was never an indication to discontinue PD. Bowel perforation developed in two patients. PD was continued in both. They were operated on for bowel repair when clinically stable and they recovered.

Hemodynamics. All children received infusions of two or more inotropic agents. The initial agent was usually dopamine, followed in order of frequency by epinephrine, dobutamine, and norepinephrine. Other vasoactive substances used were nitroprusside, isoproterenol, nitroglycerin, and prostaglandin E_1. Mean arterial pressure rose from 55.3 to 60.1 mm Hg after 2 days, and central venous blood pressure decreased from 15.5 to 12.0 mm Hg during that time (Table III), suggesting improvement in hemodynamic function during this period.

Pulmonary mechanics and gas exchange. Mean airway pressure and A-ADo$_2$ both decreased during the study period. Mean airway pressure on days 3, 4, and 5 (Fig. 1) and A-aDo$_2$ on days 4 and 5 (Table IV) were significantly different from their original values on day 1. Data for mean airway pressure and A-aDo$_2$ in the survivors followed identical trends and showed the same significant differences.

Discussion

We conducted a retrospective study of children with ARF after cardiac operations who were treated with PD. Low-output cardiac failure after CPB in combination with ARF continues to carry a poor prognosis. The group presented here had a 5.2% incidence of ARF requiring PD with a mortality of 46.9%. This is similar to other reports, in which the incidence of ARF requiring PD was between 2.4% and 5.3%[1-3, 5, 6] and mortality was between 33%[2] and 75%.[5]

Despite severely restricted cardiac function, PD was an effective technique of fluid removal in the children studied here. Vasoconstrictors did not prevent effective PD. Mean fluid removal of 2 ml/kg per hour (excluding the four sickest children, who died during the first day) allowed progressive reduction of hypervolemia while avoiding the need for most severe fluid restriction. We found this particularly helpful in the infants in whom severe fluid restriction would have otherwise limited the administration of nutrition and medications. Many centers have started to use postoperative hemofiltration as a slow continuous fluid removal technique in children who have had cardiac operations.[12, 13] Continuous venovenous hemofiltration has been shown to be better than arteriovenous hemofiltration.[13, 14] However, in contrast to PD, hemofiltration requires systemic anticoagulation with its inherent risks. The amount of fluid removed by PD was comparable with amounts from reports of hemofiltration in critically ill children after CPB.[12, 13] Recognizing the problem of excessive fluid accumulation, some cardiothoracic centers have chosen to insert a PD catheter during the operation for children at risk, such as in infants or in children who have had long CPB times.[15] The catheter can then be used not only for the institution of PD in the event of oliguria, but also for drainage of peritoneal fluid to reduce respiratory embarrassment.[15] In the event of uremia, hemofiltration appears to offer a more effective clearance of urea and creatinine in children after repair of congenital heart disease than PD.[13]

Although in this study the number of complications from PD appears high, the majority were minor and easily dealt with. Bowel perforation, seen in two children, is a potentially serious complication. It is unclear whether it occurred at catheter insertion or during dialysis. The condition of both chil-

Table III. *Hemodynamic indicators*

	Day 1	Day 2	Day 3	Day 4	Day 5
PD					
MAP (mm Hg)	55.3 ± 9.9	57.1 ± 11.2	60.1 ± 12.2	62.3 ± 10.4	59.9 ± 10.8
CVP (mm Hg)	15.5 ± 3.6	15.4 ± 5.3	12.0 ± 3.6	13.0 ± 3.6	12.1 ± 4.0

All values are expressed as mean ± standard deviation.

Table IV. *A-aDo$_2$ during 5 days of PD*

	Day 1	Day 2	Day 3	Day 4	Day 5
A-aDo$_2$ (mm Hg)					
All subjects	353 ± 191	283 ± 196	197 ± 161	158 ± 129*	147 ± 126†
Survivors	303 ± 149	191 ± 106	164 ± 127	132 ± 106‡	144 ± 134§

*Different from day 1 (p = 0.001).
†Different from day 1 (p = 0.001).
‡Different from day 1 (p = 0.003).
§Different from day 1 (p = 0.037).

dren stabilized, and both underwent uncomplicated repair. Infection rates were higher in this group with ARF than those reported in children with chronic renal failure undergoing PD.[16] We postulate that malnutrition and temporary immune dysfunction associated with critical illness are important factors in this increased susceptibility to infection. All infections were contained with appropriate intraperitoneal antibiotics. Slow dialysate drainage could often be improved by carefully positioning the child. Hypotension with drainage of the dialysate can be ameliorated by lengthening drainage time or decreasing the volume of dialysate. Dialysate may be displaced into the pleural space, possibly via a diaphragmatic leak at the sternal incision, and drains easily through the chest tubes.

The children undergoing PD had a continuous improvement in hemodynamics, as evidenced by rising mean arterial blood pressure and decreasing requirement for inotropic support. This may have been an effect of PD or of time. Zobel and associates[9] postulated that continuous arteriovenous hemofiltration had led to observed improvement in arterial pressure, central venous pressure, and need for inotropic agents on day 3 of hemofiltration in children with low cardiac output after operations involving CPB. However, neither that study nor ours was prospective or included a control group and thus the observed effect might have been due to time only.

We observed a marked decrease in mean airway pressure around the third day of PD. It might be argued that the drainage of peritoneal fluid by itself will lead to decreased ventilation pressures. However, only about half of our patients had appreciable ascites on clinical examination before PD. Furthermore, for ascites to be the major cause, fluid drainage should have caused an immediate drop in airway pressure. However, decreased airway pressure occurred on average on day 3 in the patients described here. Mean airway pressure may have improved for the entire group as a result of the sickest patients having died during the preceding days. We therefore analyzed data separately for the group of survivors and found them to show the same trends and significant differences, thus excluding this potential error (see Table IV and Fig. 1).

Decreased lung compliance and increased air flow resistance after CPB are caused primarily by increased extravascular lung water.[17, 18] Extrarenal fluid removal will lead to decreased extravascular lung water.[18] Zobel and coworkers[9] described improved oxygenation index after 59 hours of continuous arteriovenous hemofiltration in children with postoperative heart and renal failure. However, a control group without hemofiltration was not included; thus neither their study nor ours was controlled for the effect of time. Another group of authors recently reported improved pulmonary mechanics after rapid removal of large fluid volumes via modified ultrafiltration immediately after the termination of CPB.[11]

The A-aDo$_2$ was determined for all children with absent postoperative intracardiac shunt and was found to have decreased during the study period, both in the survivors and in the entire group. This finding also supports improvement in lung function during the course of the study. However, a statistical difference was detected only on days 4 and 5 (see Table IV). It is conceivable that a greater improvement in pulmonary gas exchange may have followed the reversal of pulmonary stiffness during PD but was not detected owing to small sample size and large standard deviation. Alternatively, pulmonary inflammation and endothelial injury caused by CPB[17] might have persisted despite removal of extravascular lung water, causing ongoing intrapulmonary shunt with desaturation. Again, the decrease of $A\text{-}aDo_2$ seen with PD may have been an effect of PD or of time alone.

Conclusion

Despite major advances in pediatric cardiac surgery and intensive care, the prevalence of postoperative ARF remains unchanged[1,2,6] and is unlikely to decrease soon.[19] We conclude that PD is a safe technique for infants or children in postoperative ARF. The technique is effective even in patients with low cardiac output. The early institution of PD after cardiac operations may not only remove fluid, ease fluid restriction, and thus allow better nutrition, but also improve pulmonary mechanics.

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Commentary: Con

Werner and colleagues argue in favor of relatively liberal use of peritoneal dialysis (PD) after cardiopulmonary bypass (CPB) in a pediatric population with a mean age of 24 months. The indication for PD in their retrospective study was oliguria irrespective of potassium, urea, or creatinine levels in the setting of low-output cardiac failure. Low-output cardiac failure was defined as mean arterial pressure less than 60 mm Hg during infusion of two inotropic agents. Others have recommended an even more liberal use of PD. Mee,[1] for example, places a dialysis catheter routinely "in neonates . . . and any patient in whom right-sided failure may occur." However, proponents of this approach have failed to provide convincing evidence that this method is more effective than a more traditional approach to the management of low cardiac output. What Werner and associates have demonstrated is that the technique may be associated with a significant risk of important complications: 47% of the patients died, 38% had positive dialysate cultures with true infection of the peritoneum being suspected in 25%, and 6% of patients had a perforation of the bowel. The only benefits demonstrated, namely some improvement in pulmonary mechanics and diffusion, might be explained by improved lung expansion resulting from drainage of ascites.

How is it possible that in the face of a high risk of complications some groups continue to believe strongly in the effectiveness of PD and apply it widely in their practices? The answer most likely lies in other aspects of the care of young patients undergoing repair of congenital cardiac anomalies. One important surgical variable, for example, is management of the foramen ovale. In patients who are at risk of postoperative right heart failure, for example, after repair of tetralogy of Fallot, closure of the foramen prevents right-to-left decompression at the atrial level and limits systemic cardiac output to the output achievable by the impaired right ventricle. Right atrial pressure will be significantly more elevated than in patients in whom the formen is deliberately left open. Pleural effusions, ascites, and oliguria are more likely to be seen and might prompt more frequent use of PD.

There are remarkable differences in perfusion protocol in various centers, which almost certainly influence the prevalence of fluid accumulation during and after CPB. The hematocrit value used varies from as low as 5% to 10% to as high as 35%.[2] Hemodilution affects not only red cell concentration but also colloid osmotic pressure. Use of a pure crystalloid prime is accompanied by a very low postoperative colloid osmotic pressure and greater fluid accumulation during CPB. Perfusion flow rate is probably also important. Mee's group uses the same high flow rate at deep hypothermic temperatures as other groups use at normothermia.[3] It could be argued that this not only potentially increases the transcapillary pressure gradient but also exposes a greater volume of blood every minute to foreign surfaces and might increase the release of inflammatory mediators that increase capillary permeability. Others will argue that the routine use of modified ultrafiltration will reduce the load of inflammatory mediators early after CPB and thereby reduce the risk of postoperative edema, leaky capillary syndrome, and therefore the need for PD.[4]

There is no argument that peritoneal drainage is immensely useful in the patient who has postoperative ascites to the extent that it is interfering with ventilation, necessitating high intrathoracic pressures, which further elevates right atrial pressure and exacerbates the production of ascites. PD is also effective in controlling high potassium and urea levels in the patient with established acute renal failure. However, the indications for its use for low cardiac output and third-space fluid remain to be defined by carefully designed prospective studies.

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Commentary: Pro

Excessive fluid accumulation in children and particularly neonates after cardiopulmonary bypass is common and delays progress through the intensive care phase of postoperative arrangement. Associated temporary impairment of renal clearance (particularly in those patients whose systemic venous pressures are above normal) associated with diminished response to diuretics contributes to fluid retention.

If a silicone rubber temporary peritoneal dialysis (PD) catheter is inserted during the operation, then it is relatively easy to use this as an additional tool for eliminating unwanted retained fluid, electrolytes, and probably other undesirable chemicals. Initially, the catheter is used simply as a drain, often signaling early the development of leaky capillary syndrome.

The decision to use PD becomes a very small one if the catheter is already in place, and hence PD tends to be used for considerably less than the traditional indications. The method of dialysis is also different. So that deleterious effects on ventilation can be avoided, small-volume (10 ml/kg) rapid-cycle (30 minutes) dialysis is used. The initial protocol calls for alternating isotonic (1.5%) and hypertonic (4.25%) standard dialysis solutions without added heparin, potassium, or antibiotics.

The indications for converting from drainage to minidialysis include serum potassium concentration greater than 5.0 mmol/L, anuria, low urine output (less than 2-3 ml/kg) despite 2 mg/kg of furosemide, low urine output per se in the presence of high filling pressures, obvious volume overload with inadequate renal response, rapidly rising core temperature, low cardiac output with acidosis, and so forth. All these indications are relative to the nature of the heart disease, the current status, anticipated problems, and the elapsed postoperative time.

When "leaky capillary syndrome" is clearly established and there is a large amount of peritoneal drainage, or a large negative dialysis balance, even if the patient appears edematous, intravascular volume must be maintained with replacement therapy. Under these conditions, the peritoneal effluent is usually rich in protein. An empirical replacement regimen used by our group since the early 1980s, and which appears to maintain the serum biochemistry, is based on a repeating 3-hour cycle. Fresh frozen plasma is used for the first hour, 5% albumin in a balanced electrolyte solution for the next hour, and for the third hour we administer one third of the intended volume replacement using 20% albumin. A decision is made to replace 40% to 100% of measured peritoneal loses, depending on other measured parameters.

Clearly, some patients do not require insertion of a PD catheter at operation, and the catheter proves unnecessary retrospectively in a moderate number of selected patients. Our protocol, which has not changed substantially since the early 1980s, is to insert a catheter in all neonates undergoing intracardiac operations and in neonates undergoing pulmonary artery banding via a midline sternotomy who were in the intensive care unit before the operation. In addition, we include all patients with potential for right heart failure after biventricular repair (tetralogy of Fallot, pulmonary atresia with intact ventricular septum, borderline inoperability because of pulmonary vascular obstructive disease) and all patients having Fontan-type operations.

In summary, a PD catheter is very easily and quickly inserted during midline sternotomy, is useful as a peritoneal cavity drain, provides an early alert to leaky capillary syndrome, makes fluid management (particularly in neonates and infants) easy, allows for a lower threshold for PD (low volume, rapid cycle is favored in the patient who has had cardiac surgery), may be used to control rapidly rising core temperature, is simple to manage, very low risk, and relatively inexpensive. Fluid removal by using minidialysis is relatively gentle, even in situations of borderline postoperative hemodynamics, and requires no specialist management.

I agree with the authors of this article but would have a significantly lower threshold for using PD.

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