

METABOLIC AND NUTRITION ISSUES IN PATIENTS RECEIVING CONTINUOUS RENAL REPLACEMENT THERAPY

Jennifer L. Ash, Pharm.D., BCNSP; and Cathy L. Worrall, BSN, Pharm.D.,
BCPS, BCNSP, FAPhA

Reviewed by Judy W.M. Cheng, Pharm.D., MPH, FCCP, BCPS (AQ Cardiology); and Katherine H. Chessman,
Pharm.D., FCCP, BCPS, BCNSP

Learning Objectives

1. Apply an understanding of continuous renal replacement therapy (CRRT) modalities when designing nutrition regimens for adult patients receiving CRRT.
2. Appropriately assess the nutritional status of adult patients receiving CRRT.
3. Design an appropriate plan for providing parenteral or enteral nutrition to adult patients receiving CRRT.
4. Develop an appropriate plan for managing electrolytes, vitamins, and trace elements in adult patients receiving CRRT.
5. Design a plan to appropriately manage the acid-base status of adult patients receiving CRRT.
6. Develop a monitoring plan for nutrition therapy in adult patients receiving CRRT.

Introduction

Continuous renal replacement therapy (CRRT) was developed in the 1980s as an alternative to hemodialysis in patients who were too unstable hemodynamically to tolerate traditional hemodialysis sessions. Today, CRRT is widely used in intensive care units (ICUs). The continuous removal of fluids and toxins from the body that occurs with CRRT results in unique challenges related to the metabolic management of patients receiving this therapy. This chapter addresses the pathogenesis and treatment of the metabolic abnormalities seen in patients receiving CRRT and offers guidance to pharmacists involved in managing the metabolic needs of these patients.

Continuous Renal Replacement Therapy

Acute Renal Failure and CRRT

Acute renal failure (ARF) is commonly encountered in critically ill patients and may be attributable to prerenal, intrinsic, or postrenal causes. The ARF seen in ICU patients

is often multifactorial and associated with a high mortality rate. The mortality rate is even higher when ARF occurs concomitantly with sepsis. The prevalence of ARF in patients in ICUs is increasing secondary to an aging population and a higher prevalence of chronic kidney disease.

Acute renal failure has historically been managed using intermittent hemodialysis, which results in a rapid removal of fluid and electrolytes. Traditional hemodialysis (e.g., 4 hours per session) or even extended daily dialysis (e.g., 6 or more hours/day) has limited effectiveness and often results in hemodynamic instability in the critically ill patient.

Continuous renal replacement therapy is an extracorporeal dialysis using highly porous filters that mimic the function of the native kidney to gradually remove solutes and waste products 24 hours/day. Because of the slow fluid shift that occurs, CRRT is ideal for critically ill patients. The goals of CRRT include minimization of hemodynamic instability, correction of metabolic disturbances, restoration of electrolyte balance, restoration of normal fluid balance by gradual removal of excess fluid, and enhanced recovery of native kidney function.

Indications for renal replacement are often remembered using the mnemonic AEIOU: A = acidosis, E = electrolyte abnormalities, I = (drug) intoxication, O = (fluid) overload, and U = uremia. Patients with one of these indications, a high acuity of illness, and hemodynamic instability are appropriate candidates for CRRT.

Access for CRRT

Access for CRRT is either arteriovenous or venovenous. In arteriovenous access, an arterial catheter carries blood to the extracorporeal filter using systemic blood pressure; blood is returned to the patient using a venous catheter. An advantage of this setup is that an extracorporeal blood pump is not needed. However, systemic anticoagulation is required and, in the setting of hypotension, bloodflow may be unreliable. For venovenous access, either two venous catheters or a single, double-lumen venous catheter is placed for delivery to and return from the extracorporeal circuit. An external blood pump is required for this access system. Advantages of this setup include an avoidance of arterial access and a more reliable bloodflow. Many institutions

Abbreviations in This Chapter

ARF	Acute renal failure
CAVH	Continuous arteriovenous hemofiltration
CAVHD	Continuous arteriovenous hemodialysis
CAVHDF	Continuous arteriovenous hemodiafiltration
CRRT	Continuous renal replacement therapy
CVVH	Continuous venovenous hemofiltration
CVVHD	Continuous venovenous hemodialysis
CVVHDF	Continuous venovenous hemodiafiltration
ICU	Intensive care unit
SCUF	Slow continuous ultrafiltration
UUN	Urine urea nitrogen

prefer venovenous access for patients receiving CRRT because of the high risk of complications (e.g., limb ischemia, embolization, pseudoaneurysm) with arteriovenous access.

Principles of CRRT

Diffusion is the movement of particles from an area of high concentration to an area of lower concentration. In CRRT, diffusion occurs through the hemofilter, which is a semipermeable membrane. Convection is the movement of solvent (i.e., plasma) and dissolved, low-molecular-weight solutes across a semipermeable membrane. Convection-based solute removal in CRRT is dependent on the membrane's pore size and the solute's molecular size. Continuous renal replacement therapies use dialysis (diffusion based) or filtration (convection based) to remove solutes and fluid.

Continuous Renal Replacement Modalities Slow Continuous Ultrafiltration

Slow continuous ultrafiltration (SCUF) provides slow, continuous fluid removal through ultrafiltration without using fluid replacement. Ultrafiltration uses convection-based solute removal with transmembrane pressure, thus separating low-molecular-weight solutes from whole blood. If the solute's diameter is less than that of the membrane pores, the solute will be removed. Therefore, solute removal is dependent on the ultrafiltration rate and the membrane's permeability. In general, because of the usual slow rate of ultrafiltration in SCUF, this modality is used primarily for patients who are fluid overloaded when solute removal is neither needed nor desired.

Continuous Hemofiltration

The convection-based solute removal principles used in SCUF are essentially the same as those used in continuous venovenous hemofiltration (CVVH) and continuous arteriovenous hemofiltration (CAVH). However, the ultrafiltration flow rates are much higher than those used in SCUF. Hence, CVVH and CAVH will efficiently remove middle-molecular-weight solutes and fluid. However, because

of the high flow rates, many solutes that are needed by the body will be inadvertently removed. To prevent electrolyte and fluid deficiencies, replacement fluid is administered either pre- or postfilter in patients undergoing CVVH and CAVH.

Continuous Hemodialysis

Continuous venovenous hemodialysis (CVVHD) and continuous arteriovenous hemodialysis (CAVHD) use principles of both diffusion and ultrafiltration. A dialysate solution is run at a low rate countercurrent to the flow of blood, thus maximizing diffusion-based solute removal. In CVVHD and CAVHD, ultrafiltration is run at a slow rate to prevent hypotension. As a result, fluid removal is typically slower than CVVH or CAVH; therefore, replacement fluid generally is not needed. In contrast to CVVH and CAVH, the diffusion-based principles of CVVHD and CAVHD result in a greater solute removal. Continuous hemodialysis efficiently removes low-molecular-weight solutes and is used clinically to regulate the serum concentration of small solutes such as urea, creatinine, and electrolytes.

Continuous Hemodiafiltration

Continuous venovenous hemodiafiltration (CVVHDF) and continuous arteriovenous hemodiafiltration (CAVHDF) combine principles of diffusion and convection. Similar to continuous hemodialysis, CVVHDF and CAVHDF use a dialysate solution for diffusion. In contrast to continuous hemodialysis, continuous hemodiafiltration uses high rates of ultrafiltration to achieve convection-based solute removal. Because of the high ultrafiltration rates in CVVHDF and CAVHDF, pre- or postfilter replacement fluid is needed to maintain euvolemia. Continuous hemodiafiltration has the greatest efficiency of all the CRRT modalities in the removal of middle-molecular-weight solutes and fluid.

Nutritional Assessment in Patients Receiving CRRT

Anthropometrics

Malnutrition is defined as an imbalance between nutritional intake and what is required to maintain health. This imbalance applies to both weight gain and loss. Body weight is a simple, easy, and quickly obtained parameter used in the assessment of a patient's nutritional status. A weight history (gains or losses) is valuable in the assessment. An involuntary weight loss or gain of 10% of baseline body weight or greater within 6 months, or of 5% or more within 1 month, is considered a risk factor for malnutrition. In addition, a body weight that is 20% or more above or below the ideal body weight is a risk factor for malnutrition.

Although a weight history is valuable in many patients, difficulties arise when interpreting patient weight in the setting of ARF and critical illness; weight is rapidly changing in these patients and is thus unreliable as a nutrition assessment tool. It is not uncommon to see drastic weight changes (e.g., 2–3 kg) within a relatively short period (24–48 hours) in a critically ill patient. These weight changes may be related to fluid administration or drainage, edema, or a reduced ability to produce urine. In this setting, a patient's

“usual weight” should be used for nutritional assessment and nutritional requirement determination. If the patient has chronic kidney disease and is receiving intermittent hemodialysis, the patient’s “dry weight,” or target weight postdialysis, should be used.

The tricep skinfold thickness, midarm circumference, and midarm muscle circumference techniques are used to estimate subcutaneous fat stores and skeletal muscle mass. These techniques are difficult to use in patients with ARF because of their sensitivity to fluid shifts and hydration status.

Bioelectrical Impedance Analysis

Bioelectrical impedance analysis uses electrical resistance and reactance to assess the lean body mass and total body water of patients. Hydration status and electrolyte abnormalities of patients with ARF may produce unreliable results. Therefore, using bioelectrical impedance analysis in patients receiving CRRT is of limited value.

Laboratory Assessment

Serum albumin has traditionally been used as a marker of nutritional status. Because albumin has a half-life of 18–20 days, changes reflective of nutritional status will not be seen for about 1 month. Albumin is a negative acute-phase protein, which means that serum albumin concentrations will decrease in response to stress and infection. In addition, serum albumin concentration is dependent on hepatic production and fluid status. These characteristics limit the clinical value of serum albumin concentration in the nutrition assessment of patients with ARF.

Serum prealbumin has a much shorter half-life (1–2 days) compared with albumin and is therefore a good marker of short-term nutritional status. Like albumin, the production of prealbumin is dependent on hepatic function. Because prealbumin is renally eliminated, the serum concentration is falsely elevated in the setting of both acute and chronic renal failure. It is unknown if and to what extent prealbumin is removed by CRRT. Because of these factors, the clinical utility of serum prealbumin concentrations is limited in patients with renal failure.

Nutrition Considerations in Patients Receiving CRRT

Metabolic Needs and Macronutrients Energy Requirements

Energy requirements are often increased in critically ill patients because of their hypermetabolic and hypercatabolic state, which may be caused by multiple organ dysfunction syndrome, sepsis, trauma, and burns. Consideration should be given to any underlying pathophysiology, because isolated ARF results in negligible changes in energy requirements.

Blood circulating outside the body during venovenous CRRT and room temperature dialysate and replacement solutions contribute to heat loss and may result in hypothermia. Hypothermia leads to a hypometabolic response and thus reduces basal metabolic rate and energy needs. In addition, hypothermia has been associated with decreased immunocompetence and increased mortality in

critically ill patients. Hypothermia may be prevented in these patients by using a fluid warmer in conjunction with the CRRT machine.

Indirect calorimetry remains the preferred method of determining energy requirements for patients with ARF and receiving CRRT. If indirect calorimetry is not available, most clinicians will provide 25–35 kcal/kg daily to patients receiving CRRT, which is consistent with the current American Society for Parenteral and Enteral Nutrition guidelines.

Dextrose

In patients with ARF, increased gluconeogenesis, decreased glycogen synthesis, and decreased insulin clearance and secretion lead to glucose intolerance. In addition, increased concentrations of glucagon, growth hormone, and catecholamines, which are insulin antagonists, produce insulin resistance. Many aspects of CRRT must be considered when evaluating dextrose requirements in patients. Exogenous sources of glucose include dextrose containing dialysate and replacement fluids. Table 1-1 compares fluids used in CRRT.

It is estimated that 35% to 45% of the dextrose from the dialysate solution used in CRRT is absorbed. If the dialysate contains high amounts of dextrose (i.e., 1.5% to 2.5%), glucose absorption is significant and should be considered in the specialized nutrition support regimen. For this reason, high-dextrose dialysate solutions are not recommended. Newer dialysate formulations designed specifically for CRRT have lower dextrose concentrations (0.1% to 0.11%) and parallel physiologic glucose concentrations. These low-dextrose dialysate solutions will not contribute significant calories to the patient’s intake. If dextrose-free dialysate solutions are used, a net glucose loss will occur because of diffusion and a shift of glucose from the serum into the dialysate. The amount of calories lost because of the dialyzed dextrose is clinically insignificant, and the use of dextrose-free dialysate may actually assist in glycemic control.

If replacement solutions containing 5% dextrose are used, the nutrient contribution must be accounted for in the specialized nutrition support regimen. Because of the potentially large volume of replacement fluids used, the dextrose and caloric intake may be significant. As an alternative, dextrose-free replacement fluids (e.g., 0.45% NaCl) or commercially available solutions with dextrose concentrations of about 100 mg/dL (0.1%) may be used.

Lipids

Patients with ARF may present with hypertriglyceridemia secondary to a decreased breakdown and an increased synthesis of triglycerides from free fatty acids. Lipids are not lost to any appreciable degree in CRRT. Only trace amounts of triglycerides and cholesterol are present in the CRRT ultrafiltrate.

In general, lipids should make up 30% to 40% of nonprotein calories. The pharmacist should consider lipid calories obtained from drugs such as propofol (1.1 kcal/mL) when determining lipid needs.

Protein Requirements

Patients with ARF have increased protein catabolism and, as a result, urea accumulates. Therefore, protein is

Table 1-1. Comparison of Commercially Available CRRT Solutions

Manufacturer	Product	Product	Sodium (mEq/L)	Potassium (mEq/L)	Lactate (mEq/L)	Bicarbonate (mEq/L)	Chloride (mEq/L)	Calcium (mEq/L)	Magnesium (mEq/L)	Dextrose (mg/dL)	
Baxter Healthcare Corporation, Deerfield, IL	Premixed dialysate for CVVHDF	5B7860	140	2	30	—	117	3.5	1.5	100	
		Accusol	5B9248	140	4	—	35	113.5	3.5	1.0	100
		Dialysis Solution for CRRT	5B9249	140	2	—	35	111.5	3.5	1.0	100
			5B9250	140	—	—	35	109.5	3.5	1.0	—
			5B9251	140	2	—	30	116.3	2.8	1.5	100
		5B9252	140	2	—	30	113.5	—	1.5	100	
Gambro Renal Products, Inc., Lakewood, CO	PrismaSate dialysate	BK0/3.5	140	—	3	32	109.5	3.5	1.0	—	
		BGK2/0	140	2	3	32	108	—	1.0	110	
		BGK4/0/1.2	140	4	3	32	110.2	—	1.2	110	
		BGK4/2.5	140	4	3	32	113	2.5	1.5	110	
		B22GK4/0	140	4	3	32	120.5	—	1.5	110	
		BK2/0	140	2	3	32	108	—	1.0	—	
	PrismaSol replacement solution	BK0/3.5	140	—	3	32	109.5	3.5	1.0	—	
		BGK2/0	140	2	3	32	108	—	1.0	100	
		BGK2/3.5	140	2	3	32	111.5	3.5	1.0	100	
		BGK4/2.5	140	4	3	32	113	2.5	1.5	100	
		BGK4/0	140	4	3	32	110.5	—	1.5	100	
		BGK0/2.5	140	—	3	32	109	2.5	1.5	100	
		BGK0/0	140	—	3	32	106.5	—	1.5	—	

CRRT = continuous renal replacement therapy; CVVHDF = continuous venovenous hemodiafiltration.

commonly restricted in patients who have renal insufficiency and are not receiving dialysis. Renal replacement therapies will remove urea and allow a more liberalized provision of protein. With CRRT, an estimated 10% to 17% of amino acids infused are lost in the effluent fluids. The extent of protein loss is dependent on the free serum amino acid concentrations and the ultrafiltration rate. Protein losses are greater in convection-based modalities (CVVH and CVVHDF) than diffusion-based modalities (CVVHD). As a result, CRRT requires the provision of protein exceeding that typically provided to patients with normal renal function.

Patients receiving CRRT have traditionally been given 1.5–2 g of protein per kilogram per day. However, recent evidence demonstrates that providing 2.5 g of protein per kilogram per day achieves normalized serum amino acid concentrations and a neutral nitrogen balance.

Glutamine

Glutamine plays an important role in muscle function, enteric mucosa preservation, acid-base balance, and immune function. Glutamine is a conditionally essential amino acid in the setting of acute illness, and decreased serum concentrations have been described in critically ill patients. Because protein loss in CRRT is dependent on serum amino acid concentrations and glutamine is the most abundant serum amino acid, glutamine losses may be great in critically ill patients receiving CRRT. Glutamine losses caused by CRRT have been estimated to be 25% to 35% of serum concentrations, and they often exceed 4 g/day. Glutamine supplementation (0.3–0.5 g/kg/day) should be considered for patients receiving CRRT. This supplemental protein should be included in the calculation of the patient's

daily protein intake. Intravenous glutamine is not available in the United States, but glutamine powder is available for enteral administration. The clinical benefits of glutamine supplementation in this patient population are yet to be determined.

Specialized Amino Acid Formulations

Parenteral nutrition allows the possibility of using specialized intravenous amino acid formulations. The urea recycling theory was based on the idea that only essential amino acids need to be provided to patients with renal failure because urea passing into the gastrointestinal tract will be degraded by bacterial urease into ammonia, which is then reabsorbed and converted by the liver into nonessential amino acids. Studies comparing essential amino acid to essential–nonessential amino acid combinations in the patient receiving CRRT are lacking. The pharmacist should be aware that there is a lack of clinical evidence to support the benefits of essential amino acid–only parenteral solutions in patients with ARF.

Fluids

Oliguric and anuric renal failure are characterized by a decreased renal water excretion. Fluid overload, edema, and pulmonary congestion often result. Fluid status should be monitored using daily weights, intake/output, and physical examination findings. Invasive monitoring of fluid status using central venous pressure or pulmonary artery occlusion pressure may be necessary. Additional considerations are important in assessing the fluid status of a patient receiving CRRT. The fluid intake consists of not only fluids from the typical intravenous and enteral routes, but also fluids from

CRRT dialysate and replacement solutions. The fluid output in patients receiving CRRT includes urine, gastrointestinal losses, insensible losses, and fluid removed by the CRRT itself (e.g., dialysate, replacement fluid, other parenteral infusion volume removed from the patient). Continuous renal replacement therapies using both convection and diffusion (e.g., CVVHDF) will remove greater amounts of fluid than modalities using only one principle.

When designing a specialized nutrition support regimen for the patient receiving CRRT, minimization of fluid intake is often desired. The replacement fluid used in the setting of CVVH or CVVHDF is typically a crystalloid fluid (e.g., 0.9% NaCl) or a commercially available or pharmacy-compounded replacement solution. The administration rate of this replacement fluid is adjusted to the patient's hemodynamic response. Enteral and parenteral feeding formulations are rarely, if ever, used as the modality for replacing fluids in patients receiving CRRT. Because CRRT is often used to remove excess fluids, minimization of fluid delivery is desired. Therefore, concentrated enteral feeding formulas (e.g., 2 kcal/mL) or maximally concentrated parenteral feeding formulations are used when designing a specialized nutrition support regimen. If the treatment goals for an individual patient receiving CRRT do not include fluid removal, a more liberalized fluid delivery may be appropriate.

Micronutrient Considerations

Electrolytes

There are many electrolyte abnormalities encountered in patients with ARF. Continuous renal replacement therapy may be indicated for the treatment of these electrolyte disorders. However, CRRT also induces many electrolyte disorders, which must be carefully monitored for and treated aggressively in the setting of CRRT. Most institutions will manage electrolyte abnormalities outside the specialized nutrition support regimen by using replacement solutions, dialysate, or boluses or continuous infusions of electrolytes. Other institutions may prefer to use parenteral nutrition feeding formulations to manage electrolyte abnormalities. Using the parenteral nutrition solution as a replacement vehicle in patients with consistently low electrolyte values can save nursing and pharmacy preparation and administration time and reduce the cost of care. Electrolyte trends must be followed closely and the parenteral nutrition formulation adjusted, as needed, to avoid electrolyte imbalances.

Sodium

Sodium is the major extracellular cation of the body and is responsible for water homeostasis. The patient who is fluid overloaded and a candidate for CRRT will often present with hyponatremia secondary to dilution. This patient, however, may have an increased, decreased, or normal total body sodium concentration. Because hypernatremia may cause additional fluid retention in patients already edematous because of ARF, sodium intake should be restricted. However, 0.9% NaCl infusions are often needed for fluid resuscitation in patients who are hemodynamically unstable. In addition, 0.9% NaCl is often used as the replacement solution for CVVH and CVVHDF. Sodium concentrations in ultrafiltrate are very similar to usual serum sodium concentrations (i.e., 135–145 mEq/L).

Accordingly, replacement solutions for CRRT contain sodium in concentrations similar to serum (Table 1-1). When designing a parenteral nutrition feeding formulation, sodium concentrations should also be adjusted to mimic normal serum sodium concentrations. Sodium is often ordered in milliequivalents per day (not milliequivalents per liter) when writing parenteral nutrition orders. The prescriber must consider the feeding formulation's final volume when adjusting the sodium content in the parenteral nutrition solution.

Potassium

Potassium is the major intracellular cation of the body and is renally excreted. Acute renal failure results in hyperkalemia and may, consequently, result in life-threatening cardiac arrhythmias. Potassium removal occurs in CRRT but is highly variable and difficult to predict; therefore, serum potassium concentrations should be monitored often in patients receiving CRRT. Replacement fluids for CRRT typically contain 3–4 mEq/L of potassium to prevent hypokalemia. Dialysate solutions used in CRRT also have potassium concentrations ranging from 2 mEq/L to 4 mEq/L to prevent hypokalemia. If serum potassium concentrations are appropriately maintained with the replacement or dialysate solution in CRRT, potassium will not be needed in the parenteral nutrition feeding formulation.

Magnesium

Magnesium is primarily eliminated by the kidneys. In the setting of ARF, hypermagnesemia and the resulting neuromuscular, cardiovascular, and neurologic complications may develop. However, it is estimated that 70% of plasma magnesium is filterable, and an estimated 1–2.2 mEq/hour of magnesium is lost through CRRT. As a result, replacement and dialysate solutions for CRRT typically contain 1–1.5 mEq/L of magnesium to maintain a normal serum magnesium concentration of 1.6–2.3 mg/dL. Magnesium concentrations should be monitored frequently and replaced as needed. If regular replacement is required to maintain serum magnesium concentrations within the reference range, magnesium may be added to the parenteral nutrition feeding formulation.

Calcium

Calcium is necessary for bone formation and neuromuscular function. Around 40% to 60% of serum calcium is bound to albumin. Therefore, calcium concentrations should be interpreted with respect to serum albumin concentration and can be estimated using the following equation:

$$\text{calcium}_{\text{corrected}} \text{ (mg/dL)} = \text{calcium}_{\text{measured}} \text{ (mg/dL)} + 0.8 [4 - \text{albumin}_{\text{measured}} \text{ (g/dL)}]$$

where 4 is the usual serum albumin concentration. Several studies question the reliability and sensitivity of this correction equation and recommend measuring serum ionized calcium concentrations to assess calcium status more accurately. The ionized calcium represents the unbound, or active, calcium in the body and will, therefore, give a more appropriate representation of total calcium.

Calcium abnormalities are relatively uncommon in patients with ARF. However, about 60% of serum calcium is filterable in CRRT. As a result, replacement fluids with around 3 mEq/L of calcium are needed to replace the calcium lost in the ultrafiltrate.

Regional citrate anticoagulation with trisodium citrate or anticoagulant citrate dextrose is often used to prevent clotting of the CRRT filter; citrate anticoagulation works by chelating ionized calcium, which is a component of the coagulation cascade. In regional anticoagulation, the citrate is administered prefilter, and the resulting citrate-calcium complex is filtered. To prevent resultant hypocalcemia and maintain serum ionized calcium concentrations between 1.14 mg/dL and 1.29 mg/dL, calcium chloride is infused postfilter. The infusion rate should be adjusted to maintain serum ionized calcium concentrations within the reference range. A standard amount of calcium (e.g., 2 g/day) may also be added to the parenteral nutrition feeding formulation.

Phosphorus

In contrast to peritoneal dialysis and intermittent hemodialysis, phosphorus is removed by CRRT. It has been estimated that 90% of circulating phosphorus is filterable; thus, hypophosphatemia in CRRT is likely. Hypophosphatemia may result in respiratory failure, muscle weakness, hemolysis, and glucose intolerance. Because of its incompatibility with other components, phosphorus is not included in any commercially produced replacement or dialysate solutions. Phosphorus must be replaced intermittently or may be added to the parenteral nutrition feeding formulation to maintain serum phosphorus concentrations between 2.4 mg/dL and 4.7 mg/dL.

Vitamins

Vitamin requirements in patients with ARF are not well defined. Water-soluble vitamins, with the exception of vitamin B₁₂, are lost in CRRT and should be replaced by the administration of an enteral renal multivitamin or through standard multivitamins added to the parenteral nutrition feeding formulation. Fat-soluble vitamins (A, D, E, and K) are not lost to any significant degree during CRRT.

Thiamine

Thiamine (vitamin B₁) is important in glucose metabolism. Significant amounts of thiamine are lost during CRRT. Although the thiamine body stores are about 30 mg, it has been estimated that as much as 4 mg/day of thiamine is lost in patients receiving CRRT. Without supplementation, thiamine depletion could occur after only 1 week of CRRT. Although the amount of thiamine provided by standard multivitamin supplementation with parenteral nutrition therapy (6 mg of thiamine per day) may be sufficient for many patients receiving CRRT, it may not meet the thiamine needs of patients on high ultrafiltration rates or more efficient CRRT modalities (i.e., CVVHDF). In this situation, thiamine may be supplemented at dosages of 50–100 mg/day. Supplemental doses may be added to the parenteral nutrition feeding formulation. For patients not receiving parenteral nutrition, thiamine may be supplemented daily by intravenous or enteral administration.

Folic Acid

Folic acid removal during CRRT is reported to be 650 nmol/day, which is a 12.6% daily reduction in the serum folic acid concentration. Standard multivitamin supplementation in parenteral nutrition provides 600 mcg of folic acid daily. Additional folic acid (1 mg/day) may be added to the parenteral nutrition feeding formulation or given enterally to patients with a functional gastrointestinal tract.

Vitamin C

Vitamin C (ascorbic acid) is known to have significant antioxidant activity. About 500 µmol/day of vitamin C is lost in the CRRT filtrate. The clinical significance of this loss is unknown.

Trace Elements

Selenium

Selenium is a trace element with antioxidant activity. It is part of selenocysteine, an essential amino acid needed for glutathione peroxidase activity. For this reason, selenium has generated much interest among critical care clinicians. An adult needs 40–120 mcg/day of selenium to maintain a serum concentration of 0.01–0.34 mcg/dL. Selenium will accumulate in patients with ARF not receiving dialysis; therefore, selenium intake should be reduced, if possible, to prevent selenium toxicity. However, dialysis will remove selenium, and selenium supplementation should be provided to these patients at daily intakes similar to those for patients without renal insufficiency. Serum selenium concentrations are decreased in patients receiving CRRT. Selenium deficiency may lead to muscle weakness, pain, or cardiomyopathy and can interfere with the body's antioxidant defenses. Supplemental selenium (50–100 mcg/day) should be provided to patients undergoing CRRT. Some adult multitrace element solutions added to parenteral nutrition formulations provide 60 mcg of selenium; therefore, additional supplementation is not necessary in patients receiving parenteral nutrition supplemented with these solutions. Patients receiving enteral nutrition should receive supplementation.

Copper

A loss of around 6.5 µmol/day of copper occurs with CVVHDF, accounting for about 30% of typical daily parenteral nutrition supplementation. The clinical significance of this loss is unknown. Because copper is excreted by the biliary tract, additional copper supplementation should be avoided in patients with hepatic dysfunction to prevent the development of copper toxicity.

Chromium

Chromium losses in CRRT have been reported to occur at a rate of about 0.36 µmol/day. No clinical effects of chromium toxicity have been reported in the general population. Additional chromium supplementation may be provided, although the clinical implications of chromium loss and benefits of supplementation in patients receiving CRRT remain unknown.

Zinc

Less than 3% of plasma zinc is filtered by CRRT. Despite reports of zinc loss in the ultrafiltrate, serum zinc concentrations in patients receiving CRRT were mildly

increased in one study. This positive zinc balance may have been caused by the zinc content of replacement fluids given in large quantities. The clinical implications of zinc loss and retention are unknown at this time.

Acid-Base Balance

Metabolic acidosis occurs in oliguric and anuric ARF secondary to the kidney's decreased synthesis and reabsorption of bicarbonate and impaired ability to excrete hydrogen and ammonium ions. Acidosis will encourage protein breakdown and muscle wasting and affect nutritional status. One of the goals of CRRT is to restore acid-base balance.

Historically, dialysate solutions used for intermittent hemodialysis or peritoneal dialysis were used as the replacement fluids and dialysate in CRRT. These solutions typically used lactate, which is converted to bicarbonate by the liver, as a buffer for the correction of acidosis. Subsequently, reports of hyperlactatemia and a worsening of acidosis were seen among critically ill patients with ARF. In addition, lactate can have a negative effect on cardiac function and mean arterial pressure. Lactate-buffered solutions should be avoided in patients with severe hepatic failure or hemodynamic instability.

As a result, many manufacturers now produce CRRT solutions that use bicarbonate as the primary buffer. These bicarbonate-buffered solutions have been used successfully and are well tolerated by critically ill patients, even in the setting of multiple organ dysfunction syndromes. Using bicarbonate solutions has also been associated with less protein catabolism than lactate solutions. However, bicarbonate solutions present some logistic problems. For stability reasons, commercial bicarbonate-buffered solutions are provided in a two-compartment bag (an electrolyte solution and a buffer solution) that must be mixed just before administration. Because magnesium and calcium may precipitate with bicarbonate to form carbonate salts, the magnesium and calcium components of these solutions are typically reduced compared with lactate-buffered CRRT solutions (Table 1-1). Therefore, supplemental magnesium and calcium, in addition to phosphorus, often must be administered to the patient outside the replacement and dialysis solutions to maintain adequate serum concentrations of these electrolytes.

The chloride and acetate content of the parenteral nutrition formulation should be adjusted based on the patient's acid-base status. Acetate is converted in the liver to bicarbonate; therefore, maximizing the acetate in the parenteral nutrition formulation may assist in correcting metabolic acidosis. However, bicarbonate from other sources in CRRT (e.g., dialysate and replacement solutions) also must be considered.

Glycemic Control

Glycemic control in critically ill patients has received a lot of attention in recent years. However, specific guidelines and recommendations for many other patient populations are lacking, including those for patients with ARF receiving CRRT. Despite this lack of guidance, it may be reasonably concluded that keeping the serum glucose at or near usual physiologic serum concentrations is desired to support optimal clinical outcomes.

Many factors contribute to the development of hyperglycemia in the critically ill patient, including stress-related increases in circulating counterregulatory hormones, cytokines, and endogenous catecholamines; increased gluconeogenesis; and administration of endogenous catecholamines and other drugs. In addition to these factors, when attempting to achieve glycemic control in patients receiving CRRT, the clinician must consider the glucose being provided by replacement and dialysate solutions.

A continuous intravenous infusion of regular insulin is the preferred therapeutic intervention for achieving blood glucose control in patients receiving CRRT. In the event CRRT is interrupted because of filter clotting or other factors, dextrose-containing dialysate and replacement fluids will also be discontinued. Including insulin in the parenteral nutrition formulation puts the patient at risk of developing hypoglycemia in the absence of these ongoing glucose sources. Therefore, intravenous insulin infusions represent the safest approach to glycemic control in this patient population.

Nutritional Intervention

Enteral Nutrition

Enteral nutrition stimulates the gastrointestinal tract, avoids risk associated with intravenous catheter placement, is more physiologic, and is associated with a decreased infection rate compared with parenteral nutrition. It has been established that enteral nutrition is preferred over parenteral nutrition in many disease states, and the same is true for specialized nutrition support in patients with ARF.

Because most patients receiving CRRT are hemodynamically unstable at least intermittently, the safety of enteral feeding in a hypotensive patient should be addressed. During a hypotensive state, shunting of bloodflow away from the gastrointestinal tract to more critical organs occurs and may put the patient at risk of bowel ischemia and necrosis. Careful and diligent monitoring of the patient and of enteral feeding tolerance is required.

Enteral feeding formulas designed specifically for patients with renal insufficiency are not necessarily needed in patients receiving CRRT. The reduced electrolyte content of these disease-specific enteral formulations is not generally required. Concentrated enteral formulations (e.g., 2 kcal/mL) may be useful in patients receiving SCUF and CVVHD. However, concentrated formulations may exacerbate gastroparesis, which is common in this patient population. Patients receiving CRRT are critically ill and stressed. As such, immune-enhancing enteral formulations may have a role in therapy, but literature support is currently lacking. Specialized renal formulations now on the market must be supplemented with a modular protein supplement to meet the high protein intake recommendations for patients receiving CRRT.

Parenteral Nutrition

Parenteral nutrition should only be used in patients receiving CRRT if the gastrointestinal tract cannot be used for nutrition support. If parenteral nutrition is indicated, the design of the parenteral feeding formulation requires accounting for amino acid losses and dextrose absorption

during CRRT. In general, the nonprotein calorie component should be 60% to 70% dextrose and 30% to 40% lipid.

Monitoring Nutrition Support Therapy

Nutrition support therapy is complex and involves many aspects including macronutrients, micronutrients, vitamins, and trace elements. In general, patients receiving CRRT require frequent monitoring of electrolytes and fluid status. Table 1-2 summarizes monitoring parameters and suggested frequency for patients receiving CRRT and nutrition support.

Nitrogen Balance

Nitrogen balance is used to assess the adequacy of protein repletion. Nitrogen released from protein catabolism is converted to urea and excreted in the urine as urine urea nitrogen (UUN). The UUN value is obtained from a 24-hour urine collection and represents 85% to 90% of total nitrogen excretion. Nitrogen balance is calculated by the following equation:

$$\begin{aligned} \text{nitrogen balance (g N/day)} &= \text{nitrogen intake (g N/day)} - \text{nitrogen loss (g N/day)} \\ &\text{where nitrogen intake} \\ &= \text{protein intake (g/day)/6.25; and nitrogen loss} \\ &= [\text{UUN (g N/day)} + \text{insensible losses (2-4 g N/day)}] \end{aligned}$$

Using CRRT complicates the assessment of the nitrogen lost per day because in addition to the usual losses, the nitrogen lost during CRRT must be considered. Total daily nitrogen losses in patients receiving CRRT can be estimated by the following equation:

$$\begin{aligned} \text{nitrogen loss (g N/day)} &= \text{effluent urea nitrogen (g N/day)} \\ &+ \text{amino acids lost across the CRRT membrane (g N/day)} \\ &+ \text{UUN (g N/day)} + \text{insensible losses (2-4 g N/day)} \end{aligned}$$

where effluent urea nitrogen (g N/day) = total effluent ultrafiltrate (L) × average ultrafiltrate urea nitrogen (g N/L); and amino acids lost across the CRRT membrane = 1.5 g N/day for an ultrafiltrate flow rate of 1 L/hour and 2 g N/day for an ultrafiltrate flow rate of 2 L/hour. The total effluent ultrafiltrate includes the volume of dialysate, the replacement fluid, and any other parenteral infusion volume removed from the patient. The average ultrafiltrate urea nitrogen is obtained by sampling fluid from the effluent bag.

Prealbumin

Prealbumin serum concentrations are commonly used in the inpatient setting to monitor nutrition support regimens. Because prealbumin is eliminated by the kidney, and there are no available reports of clearance by CRRT, serum concentrations may be falsely elevated and therefore may not reflect adequate nutrition status in the patients receiving CRRT. A reasonable goal for prealbumin serum concentrations in patients receiving CRRT is 30 mg/dL or higher. However, the trend in serum prealbumin concentration is likely to be more useful than the absolute value and should be monitored weekly.

Table 1-2. Monitoring Parameters for Patients Receiving CRRT and Parenteral Nutrition

Monitoring Parameter	Suggested Frequency
Basic metabolic panel, ^a Mg, Phos	Baseline, then every 6 hours
Peripheral and postcell ionized calcium ^b	Every 6 hours
Arterial blood gas	Baseline, then as needed
Liver function tests	Baseline, then weekly
Complete blood count	Daily
Serum triglycerides	Baseline, then weekly
Prealbumin	Baseline, then weekly
Weight	Daily, if possible
Intake and output	Daily
Nitrogen balance	Weekly, if feasible
Indirect calorimetry	Weekly, if available

^aIncludes sodium, potassium, chloride, CO₂ content, glucose, blood urea nitrogen, creatinine, and calcium.

^bFor patients receiving citrate anticoagulation. CRRT = continuous renal replacement therapy.

Triglycerides

While receiving intravenous lipids, if serum triglyceride concentrations exceed 400 mg/dL, lipids should be held and administered only intermittently (e.g., 200 mL of 20% lipid emulsion 3 days/week) to prevent essential fatty acid deficiency.

The Role of the Pharmacist

The pharmacist is an integral member of the ICU team, the nephrology team, and the nutrition support team. For patients receiving CRRT, the pharmacist's role is not limited to medication dosing and adjustments but rather encompasses many aspects of patient care including electrolyte, fluid, and nutrition management. The pharmacist working in an ICU setting where CRRT is used should have an in-depth knowledge of the various CRRT modalities and their effects on electrolyte, acid-base, macronutrient, and micronutrient balance. The pharmacist will then be able to assist the team in the appropriate provision of these therapies to avoid complications and improve patient outcomes.

Annotated Bibliography

1. A.S.P.E.N. Board of Directors and The Clinical Guidelines Task Force. Guidelines for the use of parenteral and enteral nutrition in adult and pediatric patients. *JPEN J Parenter Enteral Nutr* 2002;26S:1SA-6SA.

These published guidelines from the American Society for Parenteral and Enteral Nutrition (A.S.P.E.N.) offer the reader a concise review of pertinent literature and recommendations for nutrition therapy in patients with acute and chronic renal

failure. Guidelines included apply to the patient with acute or chronic renal failure receiving continuous ambulatory peritoneal dialysis, intermittent hemodialysis, or CRRT. Recommendations include provision of at least 1 g of protein per kilogram per day for patients undergoing continuous hemofiltration and use of a balanced mixture of essential and nonessential amino acids. For severely malnourished or hypercatabolic patients, 1.5–1.8 g of protein per kilogram per day is recommended in addition to adequate energy substrates (25–35 kcal/kg/day). Supplementation of water-soluble vitamins is recommended for all patients undergoing dialysis. These guidelines provide excellent evidence-based information for the clinician designing specialized nutrition support regimens in patients with ARF. Updated guidelines are expected in early 2009.

2. Wooley JA, Btaiche IF, Good KL. Metabolic and nutritional aspects of acute renal failure in critically ill patients requiring continuous renal replacement therapy. *Nutr Clin Pract* 2005;20:176–91.

This review article is a good resource that describes the pathophysiology of common fluid, electrolyte, acid-base, vitamin, and trace element abnormalities that occur in patients with ARF receiving CRRT. In addition, the article provides a good review of CRRT including the principles of therapy, indications for its use, and the various modalities available. Attention is given to the clinical impact that dialysate, replacement fluids, and anticoagulation have on nutritional decisions and recommendations. Nutrition assessment, energy and protein requirements, enteral and parenteral nutrition, and monitoring parameters are reviewed. The result is an important reference and an easy-to-understand review of a difficult topic.

3. Liu KD, Stralovich-Romani A, Chertow GM. Nutrition support for adult patients with acute renal failure. In: Merritt R, ed. *The A.S.P.E.N. Nutrition Support Practice Manual*, 2nd ed. Silver Spring, MD: American Society for Parenteral and Enteral Nutrition, 2005:281–6.

This reference, written by nutrition support practitioners and published by A.S.P.E.N., offers a brief yet comprehensive review of nutrition support for the adult patient with ARF. This book chapter focuses on clinical practice recommendations and explanations that the pharmacy practitioner will undoubtedly find useful. The chapter is organized in an easy-to-follow outline format with useful tables. Sections focus on various aspects of nutrition support including assessment, energy and protein requirements, and enteral and parenteral nutrition for adult patients with ARF. A revised nitrogen balance equation for patients receiving CRRT is also discussed.

4. Scheinkestel CD, Adams F, Mahony L, Bailey M, Davies AR, Nyulasi I, et al. Impact of increasing parenteral protein loads on amino acid levels and balance in critically ill anuric patients on continuous renal replacement therapy. *Nutrition* 2003;19:733–40.

This observational study evaluated 11 patients with glucose and amino acid losses during CRRT. All patients were critically ill, anuric, mechanically ventilated, and receiving parenteral nutrition. Energy requirements were determined using basal energy expenditure estimates with a stress factor adjustment. Nonprotein calories were provided as about 70% dextrose and 30% lipid. Protein was provided at 1 g/kg/day and increased at 24-hour intervals by 0.25 g/kg/day to a goal of 2.5 g/kg/day. Investigators reported that at all protein intakes less than 2.5 g/kg/day, 14% to 57% of all amino

acid concentrations measured were below the lower limit of reference ranges. When protein intake reached 2.5 g/kg/day, all measured blood amino acid concentrations were within reference ranges. Furthermore, investigators determined that 17% of infused amino acids and 4% of infused glucose were lost across the hemofilter. This study was an important justification for increased protein supplementation of 2.5 g/kg/day in patients with ARF receiving CRRT.

5. Scheinkestel CD, Kar L, Marshall K, Bailey M, Davies A, Nyulasi I, et al. Prospective randomized trial to assess caloric and protein needs of critically ill, anuric, ventilated patients requiring continuous renal replacement therapy. *Nutrition* 2003;19:909–16.

This prospective, randomized study was based on previous research by the investigators (see reference 4). This study evaluated 50 critically ill, mechanically ventilated patients receiving CRRT. Control patients (n=10) received 2 g of protein per kilogram per day during the entire 6-day study period. The study group (n=40) received protein at a dosage of 1.5 g/kg/day for 2 days, 2 g/kg/day for 2 days, and 2.5 g/kg/day for 2 days. Energy intake was constant throughout the study period and was based on indirect calorimetry, when available. Parenteral nutrition was used only when enteral nutrition was not possible. The presence of enteral feeds (either alone or in combination with parenteral nutrition) had a beneficial effect on patient outcome (p=0.028). Positive nitrogen balance was more common with protein intakes greater than 2 g/kg/day (p=0.0001). Of interest, nitrogen balance was independently associated with ICU outcome (p=0.02) and hospital outcome (p=0.03). This study showed a 21% increase in survival for each 1-g increase in nitrogen balance (p=0.03). This trial supports providing a protein intake of at least 2 g/kg/day in patients receiving CRRT. Of interest, this study is one of only a few that proves a correlation between improved nitrogen balance and survival.

6. Klein CJ, Moser-Veillon PB, Schweitzer A, Douglass LW, Reynolds HN, Patterson KY, et al. Magnesium, calcium, zinc, and nitrogen loss in trauma patients during continuous renal replacement therapy. *JPEN J Parenter Enteral Nutr* 2002;26:77–92.

This observational study compared blood concentrations of magnesium, calcium, zinc, and urea in critically ill trauma patients with ARF receiving CRRT (n=6) and those not with ARF and not receiving CRRT (n=6). All study patients received parenteral nutrition for at least 24 hours and were provided with 30 kcal/kg and 1.5 g of protein per kilogram per day. Electrolytes were measured in both urine and CRRT effluent. The authors reported significantly greater magnesium losses and lower serum magnesium concentrations in patients receiving CRRT compared with patients not receiving CRRT (23.9 ± 3.1 mmol/day vs. 10.2 ± 1.2 mmol/day, respectively; p<0.01; 0.75 ± 0.04 mmol/L vs. 0.90 ± 0.03 mmol/L, respectively; p<0.01). Significantly greater calcium losses were reported in the patients receiving CRRT compared with those not receiving CRRT (69.8 ± 2.7 mmol/day vs. 2.9 ± 2.5 mmol/day, respectively; p<0.01). A net positive zinc balance was observed in both groups. This study provides laboratory evidence of CRRT removal of magnesium and calcium, thus supporting the need for supplementation. The clinical impact of positive zinc balance is unknown, but further research is needed in this area. Although the study's participants were all men, similar results should be expected in women; however, this needs to be verified by additional study.

7. Berger MM, Shenkin A, Revelly JP, Roberts E, Cayeux MC, Baines M, et al. Copper, selenium, zinc, and thiamine balances during continuous venovenous hemodiafiltration in critically ill patients. *Am J Clin Nutr* 2004;80:410–6.

This prospective, randomized, crossover trial evaluated the balance of copper, selenium, zinc, and thiamine in patients with ARF receiving lactate-based or bicarbonate-based replacement solutions as part of CVVHDF therapy. Eleven patients participated and received the two different replacement solutions during two consecutive 24-hour periods. Both solutions contained nonmeasurable concentrations of copper and similar concentrations of selenium. Zinc concentrations were significantly higher in the bicarbonate-based replacement solution. There were no significant differences in copper, selenium, and thiamine effluent concentrations between the two groups. Zinc losses, however, were greater in the bicarbonate-based solution group, likely because of increased circulating serum concentrations. This study is helpful because it provides estimates of losses for copper, selenium, and thiamine. In addition, it demonstrates insignificant differences in the losses of these trace elements solely because of replacement fluid selection.

8. Story DA, Ronco C, Bellomo R. Trace element and vitamin concentrations and losses in critically ill patients treated with continuous venovenous hemofiltration. *Crit Care Med* 1999;27:220–3.

The authors of this prospective study compared trace element and vitamin concentrations among critically ill patients receiving CRRT, critically ill patients not requiring CRRT, and healthy controls. Blood concentrations of trace elements and vitamins were measured in all groups, and ultrafiltrate concentrations were evaluated in the CRRT group. This study demonstrated no detectable amounts of fat-soluble vitamins in the CRRT ultrafiltrate. There were no significant differences in concentrations of selenium, zinc, vitamin E, and vitamin C when blood samples were compared in the CRRT and ICU groups. However, there were significantly lower blood concentrations of selenium ($p < 0.001$), zinc ($p < 0.01$), vitamin E ($p < 0.05$), and vitamin C ($p < 0.001$) in the CRRT group compared with the healthy controls. Detectable amounts of vitamin C, copper, and chromium were measured in the CRRT ultrafiltrate. The study design was appropriate because it gave consideration to the changes in trace element and vitamin concentrations because of being critically ill, which the authors reason is likely because of oxidative stress. This study is also useful because it highlights that trace element and vitamin losses in the ultrafiltrate are not necessarily correlated to serum concentrations.

9. Fortin MC, Amyot SL, Geadah D, Leblanc M. Serum concentrations and clearances of folic acid and pyridoxal-5-phosphate during venovenous continuous renal replacement therapy. *Intensive Care Med* 1999;25:594–8.

This prospective, observational study compared vitamin losses of critically ill patients with ARF treated with CVVH ($n = 5$) with those treated with CVVHDF ($n = 5$). No supplemental vitamins were given beyond those typically provided in specialized nutrition support. Serum concentrations of folic acid and pyridoxal-5-phosphate, the active component of vitamin B₆, were evaluated. The estimated daily blood losses of folic acid and pyridoxal-5-phosphate were 0.29 mg/day and 0.02 mg/day, respectively. Although this study evaluated serum only and not ultrafiltrate concentrations, it provides insight into other water-soluble vitamins. This study

demonstrates that pyridoxal-5-phosphate and folic acid (both water-soluble vitamins) are removed by CRRT. Therefore, it can be reasoned that other water-soluble vitamins would also be removed. Data regarding specific water-soluble vitamin losses are lacking, so this study provides valuable insight into other likely vitamin losses and deficiencies.

10. Kierdorf HP, Leue C, Arns S. Lactate- or bicarbonate-buffered solutions in continuous extracorporeal renal replacement therapies. *Kidney Int Suppl* 1999;72:S32–6.

This review article evaluates the laboratory and clinical differences that occur with either lactate-buffered or bicarbonate-buffered CRRT solutions. It also presents the reasoning for the shift in clinical practice from lactate-based to bicarbonate-based solutions. The authors conclude that bicarbonate-based solutions control uremia as well as lactate-based solutions with no negative effect on hemodynamic status. The concern about hyperlactatemia when using lactate-based solutions is discussed, as are logistic considerations when bicarbonate-based solutions are used.

11. Bihorac A, Ross EA. Continuous venovenous hemofiltration with citrate-based replacement fluid: efficacy, safety, and impact on nutrition. *Am J Kidney Dis* 2005;46:908–18.

Citrate is commonly used for anticoagulation in patients receiving CRRT to prevent filter clotting. The practice of using citrate rather than heparin for anticoagulation has steadily increased during recent years, often because of concern about the development of heparin-induced thrombocytopenia. However, few studies have evaluated the use of citrate not only as an anticoagulant but also as the buffer in CRRT, especially at the high ultrafiltrate rate used in this retrospective study. This study proves citrate-based solutions are a viable option for replacement fluid in CRRT. Although there were no clinical signs of citrate toxicity, investigators did not measure serum citrate concentrations, which would have been useful to interpret the metabolism of citrate in the body.

SELF-ASSESSMENT QUESTIONS

Questions 1–5 pertain to the following case.

B.A., a 67-year-old man (weight 90 kg; height 70") with a history of chronic heart failure, was admitted to the coronary care unit after suffering a myocardial infarction. On admission, B.A.'s family reported that he weighed 70 kg at his last cardiologist visit 6 months ago, but his usual weight is 82 kg. After his myocardial infarction, B.A. developed cardiogenic shock requiring fluid resuscitation, dobutamine, and norepinephrine. He is receiving continuous renal replacement therapy (CRRT) using citrate anticoagulation.

- Which one of the following is the most likely reason that B.A. required CRRT?
 - Hypernatremia secondary to cardiogenic shock.
 - Hyperkalemia secondary to acute renal failure (ARF).
 - Hyperphosphatemia secondary to ARF.
 - Hypermagnesemia secondary to ARF.
- Which one of the following is the best assessment of B.A.'s nutritional risk?
 - His body mass index is within normal limits; therefore, he is not at risk of nutrition-related complications.
 - He experienced a weight loss of more than 10% of his body weight in the past 6 months; therefore, he is at risk of nutrition-related complications.
 - His current weight is more than 20% above his ideal body weight; therefore, he is at risk of nutrition-related complications.
 - His body mass index is increased; therefore, he is not at risk of nutrition-related complications.
- Which one of the following trace elements would not require supplementation if B.A. were started on parenteral nutrition while receiving CRRT?
 - Copper.
 - Chromium.
 - Selenium.
 - Zinc.
- Which one of the following is the best estimate of B.A.'s daily caloric requirement?
 - 1230 kcal/day.
 - 1640 kcal/day.
 - 2460 kcal/day.
 - 3280 kcal/day.
- If B.A. develops metabolic alkalosis, which one of the following changes in his CRRT regimen would be best?
 - Lactate solutions should be used to correct B.A.'s alkalosis.
 - Bicarbonate-based solutions should be used to correct B.A.'s alkalosis.

- Bicarbonate administration should be decreased because of B.A.'s citrate anticoagulation.
- Acetate solutions should be added to correct B.A.'s alkalosis.

Questions 6–12 pertain to the following case.

J.G., a 42-year-old woman (weight 60 kg), was admitted to the intensive care unit (ICU) after a motor vehicle collision. She developed ARF secondary to hypovolemic shock. J.G. is currently receiving continuous venovenous hemodialysis (CVVHD) and has a small bowel obstruction requiring parenteral nutrition. She requires a propofol infusion at 30 mcg/kg/minute (11 mL/hour) to maintain the desired sedation level. This morning, J.G.'s serum triglyceride concentration was 250 mg/dL. The dialysis solution she receives is a lactate-based solution with dextrose 2% running at 1 L/hour. Trisodium citrate is being used for regional anticoagulation. The CRRT machine does not use a blood warmer.

- Which one of the following factors will increase J.G.'s energy requirements compared with those of a healthy adult?
 - ARF.
 - Traumatic injury.
 - Female sex.
 - Hypothermia.
- To provide J.G. an appropriate nutrition support regimen, which one of the following best represents the degree to which dextrose in the parenteral nutrition regimen should be adjusted?
 - Decrease dextrose about 200 g/day.
 - Decrease dextrose about 480 g/day.
 - Increase dextrose about 200 g/day.
 - Increase dextrose about 480 g/day.
- To provide J.G. an appropriate nutrition support regimen, which one of the following best represents the degree to which lipid in the parenteral nutrition regimen should be adjusted based on her current therapies?
 - Decrease lipid emulsion by 29 g/day.
 - Increase lipid emulsion by 29 g/day.
 - Decrease lipid emulsion by 53 g/day.
 - Increase lipid emulsion by 53 g/day.
- Which one of the following vitamins should be supplemented in J.G.'s parenteral nutrition feeding formulation?
 - Vitamin A.
 - Vitamin D.
 - Thiamine (vitamin B₁).
 - Ascorbic acid (vitamin C).
- Which one of the following daily protein intakes is best to help J.G. achieve normalized serum amino acid concentrations and a neutral nitrogen balance?

- A. 60 g/day.
 - B. 90 g/day.
 - C. 120 g/day.
 - D. 150 g/day.
11. Which one of the following types of amino acid formulation would be best to use in compounding J.G.'s parenteral nutrition feeding formulation?
- A. Essential amino acid–only formulation.
 - B. Nonessential amino acid only–formulation.
 - C. Essential plus nonessential amino acid combination formulation.
 - D. Modular protein formulation.
12. J.G.'s current condition and therapies put her at risk of calcium and phosphorus imbalances. Which one of the following statements best summarizes the primary concern for J.G. at this time?
- A. Citrate anticoagulation will likely induce hypercalcemia, thus requiring a reduction in the amount of J.G.'s calcium intake.
 - B. Calcium balance should be frequently assessed by monitoring J.G.'s serum ionized calcium and serum phosphorus concentrations.
 - C. Hypocalcemia is rare in patients with ARF receiving CRRT such as J.G.; therefore, calcium supplementation will not be required.
 - D. Calcium supplementation in J.G. should only occur if her serum phosphorus concentration is within the reference range.

Questions 13–16 pertain to the following case.

M.T., a 28-year-old woman, was admitted to the hospital with ARF secondary to an acute drug overdose. She does not yet meet criteria for dialysis. Her medical history is significant only for depression. Tube feeding is being initiated today because of her altered mental status and decreased oral intake. Arterial blood gas results from this morning are as follows: pH 7.35, pCO₂ 35 mm Hg, and HCO₃ 18.4 mmol/L. Other laboratory results include prealbumin 22 mg/dL and albumin 2.5 g/dL.

13. Which one of the following best describes M.T.'s current metabolic state compared with her usual metabolic state?
- A. Resting energy expenditure is greatly increased.
 - B. Gluconeogenesis is decreased.
 - C. Protein catabolism is decreased.
 - D. Metabolism is unchanged.
14. Which one of the following enteral formulations is best for M.T. at this time?
- A. A low-electrolyte renal disease–specific product.
 - B. An immune-enhancing product.
 - C. A calorie-dense product.
 - D. A high-nitrogen product.
15. Based on M.T.'s serum albumin and prealbumin concentrations, which one of the following statements best describes her metabolic status?
- A. Her serum prealbumin concentration is falsely elevated secondary to ARF.
 - B. She is not malnourished because her serum prealbumin concentration is within the reference range.
 - C. She is malnourished because her serum albumin concentration is decreased.
 - D. Her serum albumin concentration is within the reference range; therefore, she is not malnourished.
16. Which one of the following best identifies M.T.'s acid-base disorder as evidenced by her arterial blood gas?
- A. Metabolic acidosis.
 - B. Metabolic alkalosis.
 - C. Respiratory acidosis.
 - D. Respiratory alkalosis.

Questions 17–20 pertain to the following case.

W.G., a 57-year-old man, was admitted to the ICU postoperatively after a small bowel resection for Crohn's disease. He is currently being treated for bacteremia and sepsis resulting from a central venous catheter–related infection. He has received outpatient dialysis every Monday, Wednesday, and Friday for oliguric renal failure for the past 5 years because of uncontrolled hypertension and diabetes mellitus. Because of his current hypotension and vasopressor requirement, W.G.'s intermittent hemodialysis was discontinued, and CRRT was initiated. During the past 24 hours, replacement fluids ran at 1500 mL/hour, dialysate fluid ran at 500 mL/hour, and 8 L of parenteral infusion volume was removed from W.G. A sample sent from the effluent bag showed an average urea nitrogen concentration of 51 mg/dL. W.G. is currently anuric. He is tolerating enteral nutrition with additional protein supplementation, which is providing 175 g of protein per day.

17. Which one of the following would be the best change to make to W.G.'s regimen now that he is receiving CRRT rather than intermittent hemodialysis?
- A. Oral phosphate binder should be discontinued.
 - B. Oral renal vitamin formulation should be discontinued.
 - C. If parenteral nutrition becomes necessary, selenium should be removed from the formulation.
 - D. If parenteral nutrition becomes necessary, zinc should be removed from the formulation.
18. W.G.'s serum glucose concentration has been consistently elevated. Which one of the following is the best approach for managing his hyperglycemia?
- A. Administer insulin glargine subcutaneously every night.
 - B. Administer insulin aspart according to a sliding scale.
 - C. Add regular insulin to the parenteral nutrition formulation.
 - D. Start regular insulin by continuous intravenous infusion.

19. Which one of the following is the best estimate of W.G.'s nitrogen balance? Estimate 4 g of nitrogen for insensible losses.
- A. Negative 9 (-9) g of N.
 - B. Negative 6.5 (-6.5) g of N.
 - C. Negative 1.5 (-1.5) g of N.
 - D. Positive 1 (+1) g of N.
20. Which one of the following enteral feeding formulations is best for W.G. at this time?
- A. A low-electrolyte, renal disease-specific product.
 - B. An immune-enhancing product.
 - C. A calorie-dense product.
 - D. A high-nitrogen product.