Fluid and Electrolyte Therapy

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An understanding of pediatric fluid therapy is one of the most important advances in pediatric medicine and a cornerstone of current inpatient practice for children with a wide range of acute and chronic conditions.

Before beginning to calculate deficit fluid replacement and manage electrolyte disturbances, it is important to understand the pathophysiology behind water homeostasis and maintenance fluid calculations. Body water and sodium retention are regulated by the hormones antidiuretic hormone (ADH) and aldosterone in response to renin-angiotensin production. Renin and ADH are secreted in reaction to output from sensors detecting changes in circulating blood volume and serum osmolality. These volume receptors are located in the left atrium, carotids, and the aortic arch, and the osmolar receptors are located in the hypothalamus, as well as elsewhere in the body. There are also nonosmotic triggers of ADH secretion, such as pain, stress, vomiting, and a number of pulmonary processes, that in particular affect hospitalized patients. Because sodium is the predominant extracellular cation, its regulation is essential to maintaining water homeostasis. Disturbances in ADH, aldosterone, and sodium will therefore have significant effects on water and electrolyte homeostasis.[1]

MAINTENANCE FLUIDS

Infants kept without oral intake (NPO) for diagnostic studies frequently need maintenance intravenous fluids if they are not allowed to drink for more than 4 to 6 hours. Two methods commonly used to calculate maintenance requirements of fluid are the Holliday-Segar formula and use of the patient's body surface area (BSA). Both formulas assume that the patient is healthy and do not take ongoing losses or additional sources of metabolic stress, such as fever, into account. Furthermore, the Holliday-Segar formula bases fluid requirements on calorie expenditure in healthy children by calculating basal metabolic rates and total energy requirements during normal activity.

The Holliday-Segar method uses the caloric expenditure of the "average patient" to determine fluid needs. By adding up normal insensible water loss from the skin and lungs as a result of metabolic activity and losses in urine and the gastrointestinal tract and then subtracting net gain from water oxidation, essentially 1 mL of water is needed for each kilocalorie of energy expended. Because the metabolic rate is inversely proportional to weight (Fig. 58-1), younger infants and children have higher metabolic rates and therefore require more fluids per unit of body weight than adolescents and adults do.

The Holliday-Segar formula can be simplified and used to calculate fluids on a daily or hourly basis (Table 58-1). Note that the hourly calculation is often referred to as the "4-2-1" rule.[2-7]

The Holliday-Segar formula refers only to water requirements and does not take into consideration electrolyte losses and needs. In healthy children, most electrolyte loss is through urine. An average of 3 mEq of Na^+ and 2 mEq of K^+ is lost for every 100 kcal of energy expended or 100 mL of maintenance fluid required per 24 hours. Alternatively, one can estimate electrolyte requirements by BSA:

$$\text{BSA } (m^2) = \text{Height (cm)} \times \text{Weight (kg)}/3600$$

Using the BSA method, the electrolyte requirements are as follows:

Na^+ = 30 to 50 mEq/m^2/day
K^+ = 30 to 40 mEq/m^2/day
Cl^- = 30 mEq/m^2/day

Example: Maintenance Fluids

An 8-month-old needs to be NPO after midnight for his hernia repair tomorrow. What maintenance fluid would you order for him? He weighs 23 lb (10 kg).

Calculation

	Water	Sodium
Maintenance	1000 mL/day	30 mEq

We use the Holliday-Segar formula, which states that 100 mL of fluid is needed per day for the first 10 kg of body weight. Therefore he would need a total of 1000 mL/day (100 mL/kg/day × 10 kg). A total of 3 mEq of Na^+ is needed for every 100 mL of fluid, so he would need 30 mEq Na^+ (3 mEq/100 mL × 1000 mL). If this quantity of Na^+ were provided as NaCl in the 1000 mL of water, it would be 30 mEq/L. Since the concentration of Na^+ in normal saline (NS) is 154 mEq/L, ¼ NS should be used for this infant (30 mEq/L is close to 38.5 mEq/L in ¼ NS). Because 2 mEq of K^+ is needed per every 100 mL, 20 mEq of KCl is added per liter. To determine the hourly rate, we divide the total volume needed each day, 1000 mL, by 24.

Answer

Order: 5% dextrose (D5)/¼NS + 20 mEq KCl/L to run at 42 mL/hr.

It should be noted that much has been published regarding use of the Holliday-Segar formula for calculating maintenance fluids. Several authors have suggested that administration of isotonic fluid may help prevent many cases of iatrogenic hyponatremia. This is based in part on the recognition of nonosmotic stimulation of ADH secretion, especially in hospitalized ill children. Many centers are now reserving the use of hypotonic solutions such as

D5/$^1/_4$NS for children in the first several months of life and have changed to using D5/$^1/_2$NS as routine maintenance fluid.[8,9]

Ongoing Losses

In addition to maintenance needs of water and electrolytes, ongoing losses are also important to take into account during hospitalization. Losses may result from conditions in which one is continuing to lose fluid (e.g., ongoing diarrhea) or from conditions associated with increased insensible losses (e.g., fever, which results in a 12% increase in maintenance fluid requirements for every 1° C increase over 38° C) or injury to the skin (e.g., burns). Ongoing gastrointestinal losses are another common problem (e.g., continuing diarrhea). Table 58-2 gives the typical electrolyte content of various body fluids to help estimate salt and water losses from various gastrointestinal sites.[10,11]

Table 58-1 Fluid Requirements Based on the Holliday-Segar Formula

Patient Weight	24-Hour Calculation	Hourly Calculation
3-10 kg	100 mL/kg	4 mL/kg
>10 but <20 kg	1000 mL + 50 mL/kg*	40 mL + 2 mL/kg
>20 kg	1500 mL + 20 mL/kg†	60 mL + 1 mL/kg

*This additional amount for the weight >10 kg only.
†This additional amount for the weight >20 kg only.

Dehydration

In treating patients with dehydration, it is important to determine both the quantity (mild, moderate, or severe) and quality (hypo-osmolar, iso-osmolar, or hyperosmolar) of the fluid deficit.

In calculating fluid deficits it is useful to calculate the water component separately from the sodium component and combine them to determine the final fluid concentra-

Table 58-2 Electrolyte Content of Various Fluids

Site	Na^+ (mEq/L)	K^+ (mEq/L)	Cl^- (mEq/L)	HCO_3^- (mEq/L)
Gastric	20-80	5-30	100-140	0
Small intestine	100-140	5-25	90-135	0
Ileostomy	45-135	3-15	20-115	110
Diarrhea	50-100	5-80	10-110	15-50

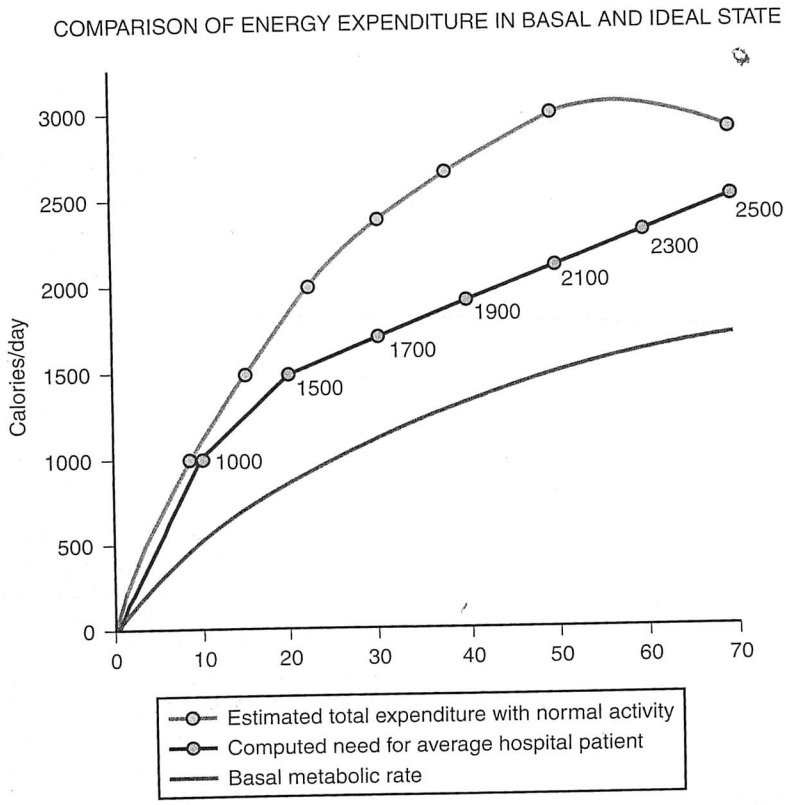

Figure 58-1 Comparison of energy expenditure and basal and ideal state. (From Holliday MA, Segar WE: The maintenance need for water in parenteral fluid therapy. Pediatrics 1957;19:823-832.)

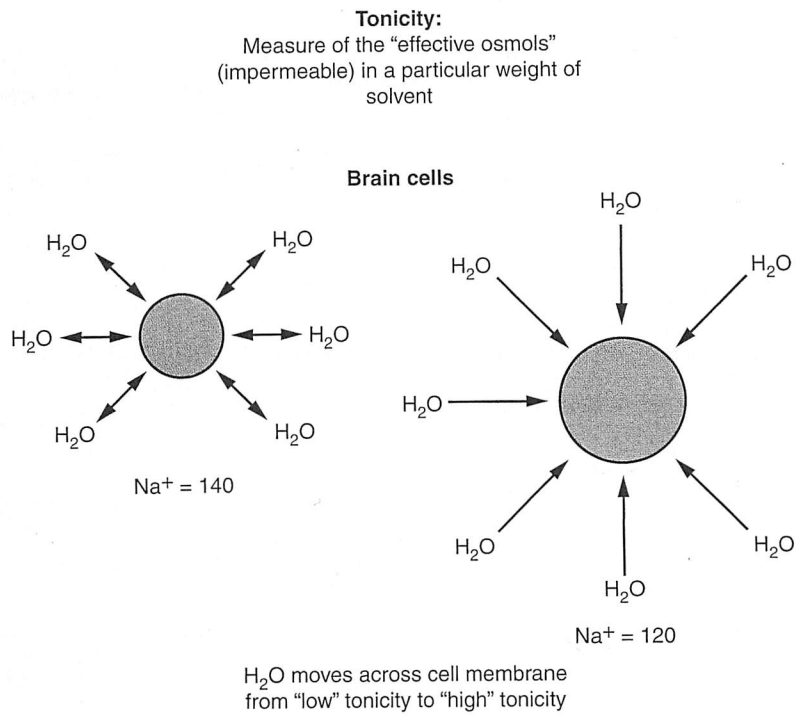

Figure 58-2 Changes in osmolarity can result in cerebral edema.

tion. To determine the rate of fluid administration after the initial bolus, the maintenance and deficit fluid volumes are combined and given at a fixed rate over the first 24 to 48 hours.[12]

Example: Isonatremic Dehydration

See Table 58-3.

OSMOLAR DISTURBANCES

Osmolality is a measure of all solute particles per weight of solvent and can be estimated according to the following formula:

$$2(Na^+) + (\text{Blood urea nitrogen}/2.8) + (\text{Glucose}/18)$$

Normal osmolality is 280 to 295 mOsm/kg. Generally, patients who are hypernatremic (Na^+ >150 mEq/L) will be hyperosmolar. Conversely, hyponatremic (Na^+ <130 mEq/L) patients will be hypo-osmolar. Water will shift from a low-osmolar space to a higher-osmolar space. This is important because rapid shifts in osmolality caused by correcting sodium disturbances too quickly (>0.5 mEq/hr) can cause fluid shifts within the brain that lead to brain injury (Fig. 58-2).

Hyponatremia

Clinical Presentation

Brain edema caused by fluid shifts with hypo-osmolarity is manifested as nausea, vomiting, muscular weakness, headaches, lethargy, ataxia, and psychosis in patients with moderate hyponatremia. Severe hyponatremia leads to increased intracranial pressure with seizures, coma, tentorial herniation, respiratory depression, and death. Certain disease states and pathogens, including pyloric stenosis and gastrointestinal pathogens such as rotavirus and cholera, are more likely to produce hyponatremic dehydration. Too rapid a correction of hyponatremic dehydration (>0.5 to 1 mEq/L/hr) may lead to central pontine myelinolysis characterized by a persistent "locked in" neurologic state.

Hyponatremia is usually caused by sodium loss in excess of free water loss. It is important to note that the serum sodium concentration does not accurately reflect total body sodium; rather, hyponatremia reflects a relative excess of free water. Although the cause of the hyponatremia is often obvious, it can be more of a diagnostic dilemma than is the case with hypernatremia. To determine the cause and treatment of hyponatremia, three factors are most important: the patient's volume status and urine sodium and osmolality.

Before beginning therapy it is important to determine whether "true" or hypo-osmotic hyponatremia is present. "Pseudohyponatremia" exists when serum is either isotonic, as in severe hyperlipidemia or hyperproteinemia, or hypertonic, as in hyperglycemia. In isotonic pseudohyponatremia caused by hyperlipidemia or hyperproteinemia, the volume of lipid or protein displaces plasma water so that a smaller volume of sodium-containing plasma is measured. In the past, chemistry laboratories used indirect potentiometry, in which the total volume of the specimen is used in calculating the sodium concentration, not just the aqueous sodium-containing portion. Now, virtually all laboratories measure sodium with ion-selective electrodes, and as a result, this error no longer occurs. In hypertonic or "dilutional" hyponatremia, hyperglycemia causes intracellular fluid to shift into the vascular space such that a decrease in serum Na^+ of 1.6 mEq/L occurs for every 100-mg/dL elevation in serum glucose (e.g., a serum glucose concentration of 800 results in a sodium concentration of 124; $800 - 100 = 700$, $1.6 \times 7 = 11$, $135 - 11 = 124$).[13]

Table 58-3 Example: Isonatremic Dehydration

A 7-year-old boy is admitted with a 2-day history of vomiting and diarrhea. He is estimated to be 7% dehydrated and vomited all attempts at oral rehydration in the emergency department. He was given a 20 mL/kg bolus of IV normal saline prior to transfer to the inpatient unit. His weight is 23 kg and his serum sodium level is 139 mEq/L.

	Water		Sodium	
	Calculation	Result	Calculation	Result
Maintenance 1st 10 kg = 100 mL/kg 2nd 10 kg = 50 mL/kg >20 kg = 20 mL/kg	10 kg × 100 mL/kg = 1000 mL 10 kg × 50 mL/kg = 500 mL 3 kg × 20 mL/kg = 30 mL	1560 mL	1560 mL × 3 mEq/100 mL	47 mEq
Total Fluid Deficit = weight × % dehydration × 1000 mL/kg or = (normal wt − dehydrated wt) × 1000 mL/kg	23 kg × 0.07 × 1000 mL/kg	1610 mL	—	—
ECF Na^+ Deficit = 0.6 × total fluid deficit × 140 mEq/L	—	—	1.61 L × 0.6 × 140 mEq/L	135 mEq
Correction for Sodium Derangement No sodium derangement	—	—	—	—
Total Requirements	—	3170 mL	—	182 mEq
Previous Replacement	23 kg × 20 mL/kg	−460 mL	0.46 L × 154 mEq/L	−71 mEq
Balance of Requirements	3170 mL − 460 mL	2710 mL	182 mEq − 71 mEq	111 mEq
Concentration of Saline Solution	111 mEq ÷ 2.71 L	41 mEq/L		

Note: numbers that are highlighted in blue are specific for the patient data provided in the example.

Maintenance:

This boy's maintenance water needs for the first 24 hours are 100 mL/kg for his first 10 kg of body weight (1000 mL) plus 50 mL/kg for the second 10 kg of body weight (500 mL) plus 20 mL/kg for the last 3 kg of body weight, which yields a total of 1560 mL. Only a current weight is available for this child but provides a sufficiently close approximation of his normal body weight to be used in these calculations. His daily maintenance sodium needs are 3 mEq for each 100 mL of water, or 47 mEq.

Total Fluid Deficit:

This child's weight loss is used to approximate his total fluid loss. Since he is estimated to be 7% dehydrated, the weight loss can be calculated by multiplying his body weight by the estimated percent of dehydration (23 kg × 0.07). Since each kilogram of weight loss is equivalent to 1000 mL, the total fluid loss would be 1610 mL.

ECF Sodium Deficit:

The sodium content of this total fluid deficit is based on the proportion of the fluid that is made up by the extracellular fluid (ECF), which is 60% of the total. The sodium concentration is normally 140 mEq/L; therefore the sodium content in the total fluid deficit is found by multiplying this concentration by the volume of ECF deficit (1.61 L × 0.6), which yields 135 mEq.

Correction for Sodium Derangement:

Since this child is isonatremic, no additional water or sodium deficits beyond that already approximated above are expected.

Total Requirements:

The total water requirements are equal to the sum of the maintenance (1560 mL) and volume of the total fluid deficit (1610 mL), which is 3170 mL. The total sodium requirements are the maintenance sodium needs (47 mEq) plus the amount of sodium in the ECF deficit volume (135 mEq), which is 182 mEq.

Previous Replacement/Balance of Requirements:

This boy received a bolus of 20 mL/kg of normal saline, which provided some portion of his total water and sodium needs. The total volume of water in this saline bolus is equal to the total volume (23 kg × 20 mL/kg = 460 mL = 0.46 L). Since the concentration of normal saline solution is 154 mEq/L, the amount of sodium in that volume is 71 mEq (= 0.46 L × 154 mEq/L). These amounts of water and sodium are subtracted from the total requirements, which leaves the balances of 2710 mL of water and 111 mEq of sodium.

Concentration of Saline Solution:

An appropriate concentration of intravenous saline would be 111 mEq of sodium in 2710 mL (2.71 L) of water, or 41 mEq/L. Since normal saline is 154 mEq/L, this would be proportional to approximately ¼ normal saline solution (41 mEq/L ÷ 154 mEq/L = 0.27 ≈ ¼).

The potassium needs are estimated by multiplying the daily maintenance potassium needs (2 mEq/100 mL) by the maintenance daily fluid requirements (1560 mL), which would be 31 mEq. This amount should be added to the balance of fluids that he will receive in the first day (2710 mL, or 2.71 L), which is equivalent to 11 mEq/L (31 mEq ÷ 2.71 L). A standard or "stock" solution that contains 10 or 20 mEq/L KCl can be used. Potassium should not be added routinely to an intravenous solution if renal failure is suspected.

To provide some caloric support and to deliver a more isotonic fluid through the vein, the saline is provided in a 5% dextrose solution. The hourly rate at which the fluids should be delivered is calculated by dividing the balance of the fluids needed in the first day (2710 mL) by 24 hours, or 113 mL/hour for the first 24 hours.

Answer: D5/¼ NS + 20 mEq/L KCl at 113 mL/hour (or D5/¼ NS + 10 mEq/L KCl at 113 mL/hour).

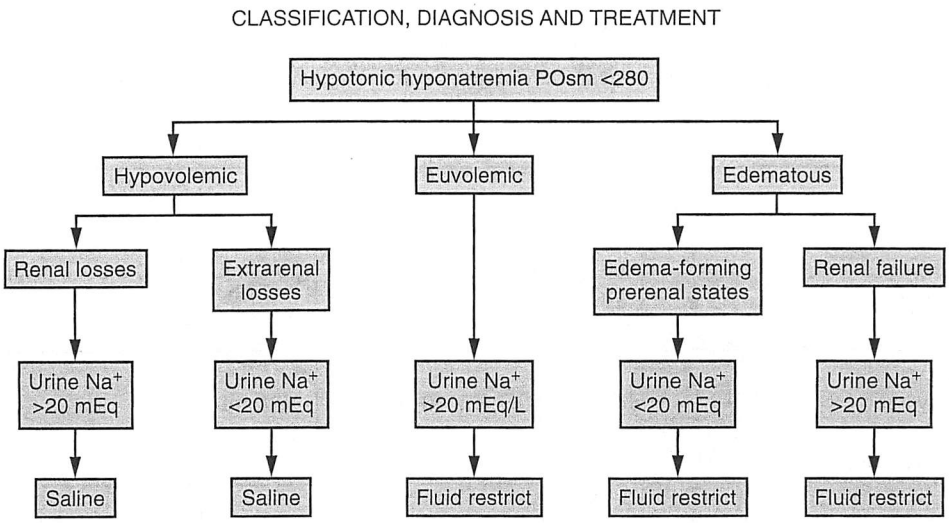

Figure 58-3 Diagnostic algorithm for hyponatremia. (From Berl T, Anderson RJ, McDonald KM, et al: Clinical disorders of water metabolism. Kidney Int 1976;10:117.)

True hyponatremia (Na^+ <130 mEq/L) occurs when serum is hypotonic. True hyponatremia may be associated with changes in total body water and categorized as hypovolemic, euvolemic, or edematous. A treatment algorithm for hyponatremia is presented in Figure 58-3.

Hyponatremic hypovolemia or dehydration occurs when there is a decrease in total body water, as well as sodium. Urine osmolality is greater than 100 mOsm/kg. If urine Na^+ is less than 20 mEq/L, hyponatremia is due to extrarenal losses such as vomiting and diarrhea. If urine Na^+ is greater than 20 mEq/L, renal losses are occurring as a result of diuretics, mineralocorticoid deficiency, salt-losing nephropathy, bicarbonaturia, ketonuria, or osmotic diuresis.

Treatment

In hyponatremic dehydration, aside from the sodium and water deficit that would be expected with isonatremic dehydration, an additional amount of sodium must be given to correct the sodium deficit. The following formula is used to calculate the additional sodium deficit that occurs:

$$0.6 \times \text{Wt} \times (\text{Desired } Na^+ - \text{Current } Na^+)$$

The "desired" sodium should be 12 to 14 mEq/L above the current sodium level so that a rapid shift in fluid does not ensue. Electrolytes should be monitored closely until serum sodium is in the 130-mEq/L range.

Example: Hypovolemic Hyponatremia

A 6-month-old girl presents with a 4-day history of vomiting and diarrhea. Her parents have been giving her apple juice for fluid replacement. Her weight is 8 kg, and she weighed 9 kg at her well-child visit 5 days ago.

Physical Examination

The girl's temperature is 36.7° C with a heart rate of 145, respiratory rate of 40, blood pressure of 78/44, and weight of 8.0 kg. She is difficult to arouse and has sunken eyes and dry, tacky mucous membranes. Her serum sodium is 122 mEq/L. The patient received 20 mL/kg of NS. What fluid order would you write? See Table 58-4 for an example calculation.

Hyponatremia with Edema

Edema exists when renal mechanisms inappropriately conserve excessive sodium and water. Urine osmolality is greater than 100 mOsm/kg. This may be due to acute or chronic renal failure with urine Na^+ greater than 20 mEq/L or due to decreased effective circulating blood volume because of decreased cardiac output (congestive heart failure) or decreased oncotic pressure (cirrhosis or nephrotic syndrome). In addition to treating the underlying disorder, hyponatremia is treated by sodium and fluid restriction and use of a loop diuretic and potentially an angiotensin-converting enzyme inhibitor.[14]

Hyponatremia with Euvolemia

Hyponatremia associated with euvolemia is most commonly seen in the syndrome of inappropriate antidiuretic hormone (SIADH) secretion, which may be due to glucocorticoid deficiency, hypothyroidism, stress (especially pain in the postoperative period), drugs (including selective serotonin reuptake inhibitors, antineoplastic agents, and anticonvulsants), or positive-pressure ventilation. Urine osmolality is greater than 100 mOsm/kg and urine Na^+ is greater than 20 mEq/L. Euvolemic hyponatremia with urine osmolality less than 100 mOsm/kg is due to water intoxication. Treatment should be focused on the underlying disease. Fluid restriction and administration of NS and a loop diuretic may be indicated.[15]

Emergency Treatment of Hyponatremia

Patients with significant hyponatremia can present with generalized seizure activity. If a patient's seizure activity is due to hyponatremia, raising Na^+ by 5 mEq/L or increasing the serum sodium level above 125 mEq/L will typically stop the seizure activity. Note that this rate of rapid correction of

Table 58-4 Example: Hypovolemic Hyponatremia

	Water		Sodium	
	Calculation	Result	Calculation	Result
Maintenance 1st 10 kg = 100 mL/kg 2nd 10 kg = 50 mL/kg >20 kg = 20 mL/kg	9 kg × 100 mL/kg	900 mL	900 mL × 3 mEq/100 mL	27 mEq
Total Fluid Deficit = weight × % dehydration × 1000 mL/kg or = (normal wt − dehydrated wt) × 1000 mL/kg	(9 kg − 8 kg) × 1000 mL/kg	1000 mL	—	—
ECF Na^+ Deficit = 0.6 × total fluid deficit × 140 mEq/L	—	—	1 L × 0.6 × 140 mEq/L	84 mEq
Correction for Sodium Derangement Sodium Deficit: = (desired Na^+ − current Na^+) × wt × 0.6	—	—	(134 − 122) × 9 kg × 0.6	65 mEq
Total Requirements	—	1900 mL	—	176 mEq
Previous Replacement	9 kg × 20 mL/kg	−180 mL	0.18 L × 154 mEq/L	−28 mEq
Balance of Requirements	1900 mL − 180 mL	1720 mL	183 mEq − 28 mEq	148 mEq
Concentration of Saline Solution	148 mEq ÷ 1.72 L	86 mEq/L		

Note: numbers that are highlighted in blue are specific for the patient data provided in the example.

Maintenance:

This child's maintenance water needs for the first 24 hours are 100 mL/kg for each of her 9 kg of body weight, or 900 mL. Her maintenance sodium needs for this time period are 3 mEq for each 100 mL of water, or 27 mEq.

Total Fluid Deficit:

Her total fluid deficit is calculated by the difference between her pre-illness weight (9 kg) and her weight at the time she presented with dehydration (8 kg), which is 1 kg. This indicates that she is 11% dehydrated, i.e., 1 kg is 11% of her pre-illness weight (9 kg). If a pre-illness weight were not available, estimates of degree of dehydration would be made based on physical findings (see Chapter 57). Since each 1000 mL weighs 1 kg, her total fluid deficit is 1000 mL.

ECF Sodium Deficit:

The sodium content of this total fluid deficit is based on the proportion made up by her extracellular fluid (ECF) compartment, which is 60% of the total fluid deficit. The sodium concentration in the ECF is normally 140 mEq/L; therefore this little girl's estimated sodium deficit is the product of her ECF deficit (expressed in liters) and the normal sodium concentration, or 84 mEq.

Correction for Sodium Derangement:

However, this child is hyponatremic; therefore she has an additional sodium deficit, beyond that already approximated above. The additional sodium deficit is estimated by the difference between her current serum sodium level and her desired serum sodium level for her whole body ECF compartment. The whole body ECF volume is 60% of the total body weight. Rather than target a complete correction of her serum sodium level, a desired sodium level 12 mEq/L higher than her current level, or 134 mEq/L, is used. Therefore, the sodium deficit is calculated by multiplying her ECF volume (body weight × 0.6) by the difference between her desired and current serum sodium level. For this example the sodium deficit would be 65 mEq.

Total Requirements:

The maintenance water (900 mL) and total fluid deficit (1000 mL) are added to determine the total water requirements for the first 24 hours (1900 mL). The total sodium requirements are the sum of the maintenance sodium needs (27 mEq), the amount of sodium in the ECF deficit (84 mEq), and the additional sodium deficit due to her hyponatremia (65 mEq), which is 176 mEq.

Previous Replacement/Balance of Requirements:

However, her initial resuscitation included 20 mL/kg of normal saline. This provided her with 180 mL of water and 28 mEq of sodium, which are subtracted from the total needs. This leaves the balances of water and sodium needed in the first 24 hours of 1720 mL and 148 mEq, respectively.

Concentration of Saline Solution:

If a saline solution containing the proportions of salt and water from the balance of requirements were prepared, it would yield a saline concentration of 79 mEq/L. Since normal saline is 154 mEq/L, this would be approximately equivalent to a ½ normal saline solution.

The potassium needs are approximated by multiplying the daily maintenance potassium needs (2 mEq/100 mL each day) by the maintenance fluid requirements (900 mL), which yields 18 mEq/day. This amount should be added to the balance of fluids that she will receive in the first 24 hours (1720 mL, or 1.72 L), which is equivalent to 10 mEq/L (18 mEq ÷ 1.72 L = 10 mEq/L). Potassium should not be added routinely to intravenous solutions if renal failure is suspected.

To provide some caloric support and to deliver a more isotonic fluid through the vein, the saline is provided in a 5% dextrose solution. The total volume should be delivered over 24 hours, so one would divide 1720 mL by 24 hours to provide a rate of 72 mL/hour.

Answer: D5/½ NS + 10 mEq/L KCl to run at 72 mL/hour.

For patients with hyponatremia secondary to excessive renal sodium loss, the underlying disorder should be corrected if possible. Mineralocorticoid supplementation should be given for deficient states such as congenital adrenal hyperplasia. Long-term oral sodium supplementation is often needed if the underlying defects cannot be completely corrected.

sodium is reserved only for patients presenting with seizure activity.[16] Usually, giving 1 mL/kg of hypertonic (3%) saline will raise serum Na^+ by approximately 1 mEq/L. Generally, 2 to 6 mL/kg of 3% saline administered IV over an hour is used to treat seizure due to hyponatremia.

Hypernatremia

Clinical Presentation

Patients with hypernatremia present with hyperpnea, muscle weakness, restlessness, a high-pitched cry, lethargy, coma, and convulsions. Hypernatremia equates with hyperosmolality and leads to cellular dehydration, and with resultant areas of ischemia secondary to blood vessel sludging or bleeding from tension on bridging vessels. Diabetes insipidus can also result in hyperosmolar dehydration if the patient is unable to drink enough to compensate for deficient levels of ADH. Breastfeeding failure, especially in older first-time mothers, has been associated with hypernatremic dehydration in the newborn. Severe hypernatremic dehydration is sometimes also associated with hyperglycemia and hypocalcemia. Too rapid a correction of hypernatremic dehydration may result in cerebral edema and brainstem herniation.

The goal in treatment is to avoid cerebral edema by decreasing serum sodium slowly, by 1 mEq/L/hr with acute hypernatremia or by 0.5 mEq/L/hr with chronic hypernatremia. Figure 58-4 presents a treatment algorithm for hypernatremia.[17-21]

Hypernatremia secondary to sodium and water loss results in hypertonic dehydration. In hypernatremic dehydration the skin may feel "doughy." In addition, in contrast to patients with hyponatremic dehydration, patients with hypernatremic dehydration have less prominent signs and symptoms of dehydration because circulating blood volume is preserved. Renal losses from osmotic diuresis, as in diabetes mellitus (mannitol, glucose, or urea), result in urine Na^+ less than 20 mEq/L. Extrarenal losses caused by vomiting and diarrhea, excessive sweating, or breastfeeding failure result in urine Na^+ less than 20 mEq/L.

Treatment

In hypernatremic dehydration, there is a loss of water and sodium as with isonatremic dehydration but there are additional free water losses. Maintenance and deficit needs are calculated as for isonatremic dehydration. The additional free water deficit is determined next, and is calculated as

$$(\text{Current } Na^+ - \text{Desired } Na^+) \times 4 \text{ mL/kg} \times \text{Patient weight}$$

In this formula, the desired sodium is generally 145 mEq/L to prevent overly rapid correction. The patient weight in the formula should be expressed in kilograms.

Generally, half the free water deficit, along with all of the maintenance and solute deficit, is administered in the first 24 hours.

When treating hypernatremic dehydration, one must take care not to correct the sodium by hydrating too quickly. Treat shock with 0.9% saline (20 mL/kg) administered over a 30-minute period, but do not give a bolus unless necessary. Although the formula for calculating the free water deficit is a good general staring point, the rate of decrease in serum sodium is not as predictable as the rate of rise is for hyponatremic dehydration. No formula can replace frequent reassessment of the patent's sodium level and mental status. It is important to check electrolytes frequently to be sure that the sodium level does not drop too quickly, that is, a rate of decrease no greater than 0.5 mEq/L per hour.

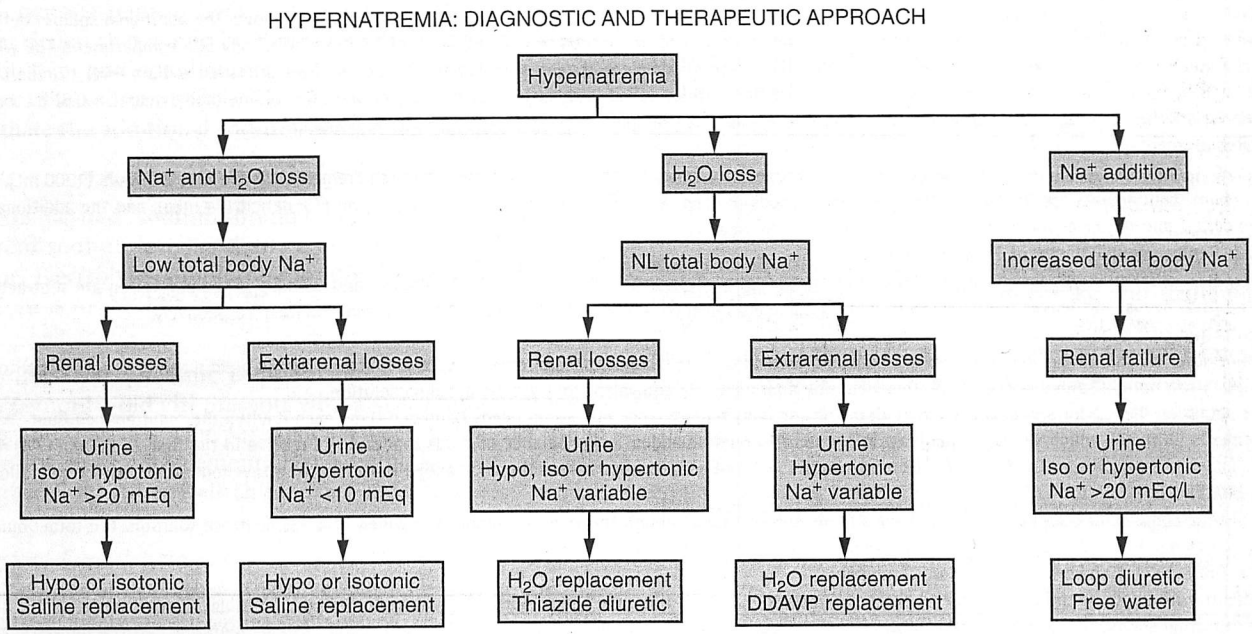

Figure 58-4 Diagnostic algorithm for hypernatremia. (From Berl T, Anderson RJ, McDonald KM, et al: Clinical disorders of water metabolism. Kidney Int 1976;10:117.)

The duration of correction is based on serum Na^+:

150 to 170 mEq/L: correct over a 48-hour period.
Greater than 170 mEq/L: correct over a 72-hour period.
Greater than 200 mEq/L: consider dialysis.

Patients with a serum sodium concentration higher than 170 should be managed in an intensive care unit (ICU) setting for close monitoring of electrolytes and cardiovascular and neurologic status.

Example: Hypernatremic Dehydration

A 5-month-old infant presents with vomiting and diarrhea. He weighed 7 kg at his last checkup 1 week ago. His current weight is 6.2 kg. The infant has a sunken fontanelle, decreased urine output, no tears, and dry lips, but his capillary refill time is well maintained and his skin feels "doughy." His serum Na^+ concentration is 155 mEq/L. What would your initial fluid order be? See Table 58-5.

Diabetes Insipidus

Hypernatremia secondary to water loss with normal total body sodium is due to inadequate secretion of ADH by the posterior pituitary gland (central diabetes insipidus) or inappropriate response by the renal collecting tubule to reabsorb water (nephrogenic diabetes insipidus). Central diabetes insipidus occurs more commonly and is often due to injury or destruction of the hypothalamus or posterior pituitary from meningitis or tumor (craniopharyngioma, histiocytosis X) and less commonly due to autosomal dominant or recessive defects in ADH synthesis and release. Nephrogenic diabetes insipidus may be due to an autosomal or sex-linked recessive defect in the membrane receptor protein. It may also be acquired as a result of an illness or insult that damages the renal medulla, such as from medication, obstructive uropathy, or electrolyte disturbances, including hypokalemia and hypercalcemia. Infants with nephrogenic diabetes insipidus may be febrile in association with hypernatremic dehydration.

The diagnosis is made by finding an inappropriately low urine osmolality (specific gravity <1.005, urine osmolarity of 50 to 200) with a low serum ADH level in the face of increased serum osmolality after a period of water deprivation.

Primary treatment is to administer free water. Inadequate endogenous ADH may be treated by replacement with desmopressin (DDAVP), a synthetic analogue. DDAVP is given as a nasal spray (3 months to 12 years of age, 5 to 30 μg/24 hr divided daily or twice daily with a maximum of 40 μg in 24 hours), orally (begin with 0.05 mg per dose daily or twice daily and titrate to achieve control of excessive thirst and urination), or intravenously/subcutaneously (children ≥ 12 years and adults, 2 to 4 μg/24 hr divided twice daily) as replacement therapy for central diabetes insipidus. Patients with nephrogenic diabetes insipidus may benefit from the addition of a thiazide diuretic. Hydrochlorothiazide dosing for neonates and infants younger than 6 months is 2 to 4 mg/kg/day in 2 divided doses (maximum daily dosage: 37.5 mg) and for older infants and children dosing is 2 mg/kg/day in 2 divided doses (maximum daily dosage: 200 mg).[22-26]

Hypernatremia with edema means that there is increased total body sodium and an increase in total body water. Urine Na^+ is greater than 20 mEq/L. The cause is usually iatrogenic and due to excessive administration of hypertonic dialysis fluid, $NaHCO_3$ or NaCl, or saline for therapeutic abortion. Primary hyperaldosteronism and Cushing syndrome are rare causes of edema and hypernatremia in childhood. Treatment is a loop diuretic along with administration of free water.

Potassium

Ninety-five percent of total body potassium is intracellular, mostly in muscle cells in a concentration of 150 mEq/L. Most (90%) potassium is excreted in urine under normal conditions. Renal excretion of potassium is very efficient, but unlike sodium, conservation is not efficient and occurs only in states of extreme deprivation. Aldosterone plays a critical role in potassium secretion in the distal tubule in exchange for sodium or hydrogen ions, or both. Delivery of sodium to the distal tubule for reabsorption is necessary for normal potassium excretion.

Most conditions resulting in dehydration cause depletion of total body potassium and sodium. Because potassium is an intracellular cation, serum potassium represents only 2% of total body potassium. Good general rules regarding potassium therapy are never to institute K^+ repletion until the patient has established urine output and not to exceed 4 mEq/kg/day of K^+ repletion. The potassium requirement for maintenance fluid in a patient with normal body potassium is approximately 2 mEq/100 kcal or per 100 mL of fluid. In practice, giving a patient 10 to 20 mEq/L of fluid provides adequate maintenance potassium.

Hyperkalemia

Clinical Presentation

True hyperkalemia is defined as serum K^+ greater than 5.5 mEq/L. Moderate to severe hyperkalemia (K^+ >6.1 to 6.9 mEq/L) is potentially life threatening because high serum potassium disrupts the normal electrical conduction system. Within the muscular system hyperkalemia causes skeletal muscle weakness and fatigue, whereas smooth muscle inhibition can cause respiratory depression. Most seriously, disruption of the cardiac conduction system, manifested as electrocardiographic changes such as prolongation of the PR interval, widening of the QRS complex, and peaked T waves, can lead to cardiac arrhythmias and ultimately to cardiac arrest.

Differential Diagnosis of Hyperkalemia

"Pseudohyperkalemia" is very common and usually due to inappropriate specimen collection, such as squeezing a digit too strenuously when obtaining a finger-stick blood draw, which causes the blood collected to be hemolyzed and release of potassium from red blood cells.

Severe leukocytosis greater than 70,000/cm^3 or thrombocytosis greater than 1,000,000/cm^3 can also result in pseudohyperkalemia.

True Hyperkalemia

True hyperkalemia most commonly results from a decrease in potassium excretion in the kidney or redistribution of potassium from the intracellular to the extracellular space (Table 58-6). A decrease in renal potassium excretion can occur in either acute or chronic renal failure, as a result

Table 58-5 Example: Hypernatremic Dehydration

	Water		Sodium	
	Calculation	Result	Calculation	Result
Maintenance 1st 10 kg = 100 mL/kg 2nd 10 kg = 50 mL/kg >20 kg = 20 mL/kg	7 kg × 100 mL/kg	700 mL	700 mL × 3 mEq/100 mL	21 mEq
Total Fluid Deficit = weight × % dehydration × 1000 mL/kg or = (normal wt − dehydrated wt) × 1000 mL/kg	(7 kg − 6.2 kg) × 1000 mL/kg	800 mL	—	—
ECF Na^+ Deficit = total fluid deficit × 0.6 × 140 mEq/L		—	0.8 L × 0.6 × 140 mEq/L	67 mEq
Correction for Sodium Derangement ½ free water deficit = (current Na^+ − desired Na^+) × wt × 4 mL/kg ÷ 2	(155 − 145) × 7 kg × 4 mL/kg ÷ 2	140 mL	—	—
Total Requirements		1640 mL		88 mEq
Previous Replacement		0		0
Balance of Requirements		1640 mL		88 mEq
Concentration of Saline Solution	88 mEq ÷ 1640 L	54 mEq/L		

Note: numbers that are highlighted in blue are specific for the patient data provided in the example.

Maintenance:
For this 7-kg boy, his maintenance water needs are 10 mL/kg for each of his 7 kg of body weight, or 700 mL each day. His maintenance sodium needs for this time period are 3 mEq for each 100 mL of water, or 27 mEq/day.

Total Fluid Deficit:
The difference between his pre-illness weight (7.0 kg) and his weight at the time of presentation (6.2 kg) indicates the total fluid deficit, which is 0.8 kg, or equivalent to 800 mL.

ECF Sodium Deficit:
Despite the fact that this child is hypernatremic, he still has a sodium deficit due to fluid losses from the ECF, which makes up 60% of the total fluid deficit. The sodium content of this total fluid deficit is calculated by multiplying the ECF proportion of the total fluid deficit (0.6 × 800 mL) by the sodium concentration of the ECF (approximately 140 mEq/L), which yields 67 mEq/L.

Correction for Sodium Derangement:
However, this boy's hypernatremia is caused by an additional loss of free water, which needs to be replaced. The amount of free water is calculated based on the difference between the current serum sodium level and the desired serum sodium (155 − 145), which is multiplied by a factor of 4 mL/kg and the patient's weight. Since corrections of hypernatremia should proceed more slowly, only half of the estimated free water deficit is replaced in the first 24 hours, which yields a result of 140 mL.

Total Requirements:
The water and sodium requirements are totaled, which indicated that this patient should receive 1640 mL of water and 88 mEq of sodium in the first 24 hours.

Previous Replacement/Balance of Requirements:
In this example, the patient did not receive a normal saline bolus or any other replacement therapy, so the balance of water and sodium requirements are the same as for the total requirements.

Concentration of Saline Solution:
If the sodium requirements were mixed in the amount of water required, it would yield a saline solution containing 54 mEq/L, which is equivalent to ⅓ normal saline solution. To avoid the risk of correcting the serum sodium level too quickly, i.e., more than 0.5 mEq/L per hour, most clinicians would select a stock solution of ½ normal saline for this patient.

As previously calculated, the potassium needs are estimated by multiplying the daily maintenance potassium needs (2 mEq/100 mL each day) by the maintenance fluid requirements (700 mL), which yields 14 mEq/day. This amount should be added to the total fluids that this boy will receive in the first 24 hours (1640 mL), which is equivalent to 9 mEq/L (14 mEq ÷ 1640 mL = 8.5 mEq/L). A standard solution that contains 10 mEq/L of KCl can be used. Potassium should not be added routinely to intravenous solutions if renal failure is suspected.

To provide some caloric support and to deliver a more isotonic fluid through the vein, the saline solution is provided with 5% dextrose solution. The total volume should be delivered over 24 hours, so one would divide 1640 mL by 24 hours to provide a rate of 68 mL/hour.

Answer: D5/½ NS + 10 mEq/L KCl to run at 68 mL/hour.

Subsequent Therapy: The entire deficit of ECF, along with half of the additional free water deficit, is replaced during the first 24 hours. The remaining free water deficit is then replaced over the next 24 hours. For this period, the maintenance needs remain the same: 700 mL of water, 21 mEq of sodium, and 14 mEq of potassium per day. Adding the 140 mL of free water yields a total of 840 mL of water with 21 mEq of sodium, or 25 mEq/L, which is equivalent to ⅙ normal saline with 17 mEq/L of potassium. A stock solution of D5¼ normal saline with 10 or 20 mEq/L of KCl may be used at a rate of 35 mL/hr (840 mL ÷ 24 hours).

Table 58-6 Causes of Hyperkalemia
Decrease in K^+ Excretion
Acute or chronic kidney disease
Aldosterone deficiency: Addison's disease or congenital adrenal hyperplasia
Drugs
Potassium-sparing agents
Angiotensin-converting enzyme inhibitors
Nonsteroidal anti-inflammatory drugs
Miscellaneous (trimethoprim-sulfamethoxazole, heparin, pentamidine, alpha- and beta-blockers)
Increase in K^+ Load: Cellular Destruction
Ingestion of a K^+-rich diet
Tumor lysis syndrome
Rhabdomyolysis
Trauma
Intravascular hemolysis
Transfusion of stored red blood cells
Catabolic states
Redistribution of K^+
Metabolic acidosis
Infusion of hypertonic solution
Hyperkalemic periodic paralysis
Nonselective beta-blockers
Tubular Unresponsiveness to Aldosterone
Sickle cell anemia
Systemic lupus erythematosus
Amyloidosis
Renal transplantation

of tubular dysfunction, or because of impairment of aldosterone production by the adrenal gland, as in some forms of congenital adrenal hyperplasia (21-hydroxylase deficiency). Drugs that decrease glomerular filtration rates (such as angiotensin-converting enzyme inhibitors and nonsteroidal anti-inflammatory agents) or inhibit the action of aldosterone (potassium-sparing diuretics) can increase serum and total body potassium. Shifts in potassium from the intracellular to the extracellular space, as in metabolic acidosis or with nonselective beta-blockers, can lead to an increase in serum potassium, although total body potassium is normal. Extreme and rapid cellular destruction can overwhelm the kidney's ability to excrete the increased potassium load. This can occur as a result of tumor lysis, intravascular hemolysis such as with a transfusion reaction, rhabdomyolysis or tissue destruction secondary to a crush injury or burn, and extreme catabolic states. Tubular unresponsiveness to aldosterone is unusual but may occur as an isolated defect or in association with systemic lupus erythematosus, sickle cell disease, amyloidosis, and renal transplantation.

Treatment of Hyperkalemia

If the patient has none of the aforementioned causes of hyperkalemia and the serum potassium level is reported as high, it is often prudent to recheck the potassium from a venous, easy-flowing blood draw and minimize the use of a tourniquet to avoid pseudohyperkalemia from a hemolyzed blood specimen. In metabolic acidosis from bicarbonate losses in diarrhea or from diabetic ketoacidosis, buffering occurs at the cellular level as potassium shifts from the intracellular to the extracellular space while hydrogen ion shifts to the intracellular space. Correction of the acidosis will usually correct the hyperkalemia.

If true hyperkalemia exists, check an electrocardiogram for prolongation of the PR or QRS intervals and for peaked T waves. If any of these changes exist, urgent action must be taken to lower the potassium level before a life-threatening arrhythmia develops. The patient should be placed on a cardiorespiratory monitor and transferred to an ICU setting. Immediately discontinue any potassium intake.

To block the effects of hyperkalemia on the cardiac conduction system, the following infusion is administered:

- 10% calcium gluconate, 0.5 to 1 mL/kg intravenously (50 to 100 mg/kg per dose) peripherally, or 27% calcium chloride, 0.2 mL/kg (20 mg/kg per dose) through a central venous line, not to exceed 100 mg/min.

Potassium can be shifted from the extracellular to the intracellular space by

- Infusing $NaHCO_3$, 1 to 2 mEq/kg per dose intravenously; this works best in the presence of metabolic acidosis.
- Infusing dextrose, 0.5 to 1 g/kg (e.g., 2 to 4 mL/kg of 25% dextrose) with 0.1 U/kg of insulin.

Potassium can be removed from the body by

- Sodium polystyrene sulfonate (Kayexalate) with sorbitol (1 g/kg per dose) orally or per rectum.
- Diuresis if the patient has normal renal function by a combination of an NS bolus, 10 to 20 mL/kg per dose, and furosemide, 0.5 to 1 mg/kg per dose intravenously.
- Hemodialysis or peritoneal dialysis, which can also be used in patients with renal failure or severe poisoning.[27-29]

Hypokalemia

Hypokalemia is defined as a serum potassium concentration less than 3.5 mEq/L. Moderate to severe hypokalemia exists when serum K^+ is less than 2.5 to 3.0 mEq/L.

Clinical Presentation

The most common clinical signs and symptoms are caused by disordered electrical conduction in cardiac, skeletal, and smooth muscle that results in electrocardiographic changes such as the presence of U waves and arrhythmias, generalized muscle weakness, paralytic ileus, and impaired respiration. In addition, hypokalemia impairs the ability of the kidneys to reabsorb hydrogen ion, thereby promoting metabolic alkalosis and renal medullary dysfunction with an inability to dilute or concentrate the urine.

Causes of Hypokalemia

Causes of hypokalemia can be divided into increased potassium losses or shift of potassium into the intracellular space. Stool losses occur as a result of diarrhea or laxative abuse. Increases in renal potassium excretion can be seen with metabolic alkalosis, metabolic acidosis, or administration of drugs such as diuretics and high doses of penicillin. If the cause of the hypokalemia is not clear, a urine potassium level higher than 10 indicates excess urine loss. In the face of

Table 58-7 Causes of Hypokalemia
Increase in Renal K^+ Excretion
Metabolic alkalosis
Chloride responsive
Volume contraction
Chloride unresponsive
Primary hyperaldosteronism
Hypertension
Liddle syndrome
11β-Hydroxysteroid dehydrogenase deficiency
No hypertension
Bartter syndrome
Gitelman syndrome
Metabolic acidosis
Type I and II renal tubular acidosis
Drugs
Diuretics
Fluorinated steroids
Penicillins
Transcellular K^+ Shift
β-Adrenergic agonists
Insulin administration
Theophylline and caffeine
Verapamil and chloroquine ingestion
Hyperthyroidism
Familial hypokalemic paralysis
Excessive K^+ Loss in Stool
Laxative abuse
Diarrheal illness
Miscellaneous
Mg^{2+} depletion

volume contraction, as seen in chloride-responsive metabolic alkalosis, urine Cl^- is less than 25 mEq/L and the renin-angiotensin system is activated by the low circulating blood volume, which leads to increased aldosterone secretion to retain sodium and chloride and results in continued potassium excretion by the kidney. Chloride-unresponsive metabolic alkalosis (urine Cl^- >40 mEq/L) can occur with primary mineralocorticoid excess, either associated with hypertension (Liddle syndrome or 11β-hydroxysteroid dehydrogenase deficiency) or with renal tubular dysfunction and normal blood pressure as in Bartter or Gitelman syndrome. Renal tubular acidosis can also be associated with hypokalemia inasmuch as potassium is excreted with unabsorbed bicarbonate or instead of hydrogen ion in the distal tubule. Potassium is wasted with furosemide or thiazide diuretics.

Potassium can also shift into the intracellular space in association with diseases such as hyperthyroidism and familial hypokalemic paralysis, as well as a variety of drugs such as β-adrenergic agonists, insulin, theophylline, caffeine, verapamil, and chloroquine (Table 58-7).

Treatment of hypokalemia is potassium repletion. Up to 40 mEq of KCl/L intravenously can be safely given on the floor. If infusions of 40 to 80 mEq/L are needed, patients should be monitored in an ICU setting and a central line should be used for administration. For severe hypokalemia, a potassium bolus may be given intravenously during close cardiac monitoring (dose of 0.25 to 0.5 mEq/kg with a maximum dose of 40 mEq over a 2-hour period; the concentration should not exceed 0.1 mEq/mL in a peripheral line and 0.2 mEq/mL in a central line). In the non-ICU setting, KCl infusion should not exceed 0.25 mEq/kg/hour. Enteral replacement (oral or via nasogastric tube) can supplement repletion efforts or, in less severe setting, can be used instead. For hypokalemia in the face of metabolic acidosis, potassium may be given as phosphate or acetate, whereas with metabolic alkalosis it is given as KCl.[1,2,5-7]

CONSULTATION

Given the myriad of disease states that can lead to electrolyte disturbances, the hospitalist may consult any number of specialists, including renal, endocrine, and critical care colleagues, to assist in the management of these patients, especially if the electrolyte derangements are severe.

ADMISSION CRITERIA

- Any patient with a significant fluid or electrolyte disturbance should be admitted, especially if the cause of the abnormality is unclear.

DISCHARGE CRITERIA

- Correction of abnormal electrolyte status
- Presence of a treatment plan to maintain normal electrolyte status

IN A NUTSHELL

- An understanding of pediatric fluid and electrolyte therapy is one of the most important aspects of pediatric hospital medicine. In general, the approach to patients with various electrolyte disturbances is based on the underlying physiology of how the body handles water and the specific electrolyte itself. The further from normal at the time of presentation, the greater the care and need for monitoring during the correction process.

ON THE HORIZON

- As stated earlier, there is a growing literature suggesting that administration of isotonic fluid may help prevent many cases of iatrogenic hyponatremia and that many centers are reducing their use of hypotonic intravenous fluids.
- Recently, the Food and Drug Administration approved the first human recombinant hyaluronidase, which degrades hyaluronic acid into smaller tetrasaccharide blocks, thus opening up the interstitial space and allowing coinjected fluid or drugs, or both, to be more readily absorbed into the bloodstream. This may allow subcutaneous delivery of drugs and fluids and be a potential solution for patients with poor venous access.