Chapter 11

Fluids and Electrolytes

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I. INTRODUCTION

Intravenous fluids (IVFs) should be thought of as a medication by those who prescribe them. Since the late 1950s, IVF choice has been largely guided by Holliday and Segar's estimations of sodium requirements. Using the electrolyte composition of human milk, they calculated that the average child requires 3 mEq sodium (Na) and 2 mEq potassium (K) per 100 to 120 mL water (H_2O).[1] According to their calculation, basic solute needs can be met by administering ¼ normal saline (NS), a hypotonic fluid. While this estimation led to a long-standing tradition in pediatric maintenance IVF (MIVF) therapy, evidence published over the past few decades culminated in new American Academy of Pediatrics (AAP) guidelines recommending isotonic fluids as the maintenance fluid of choice for the majority of hospitalized children.[2]

II. FLUID RESUSCITATION

A. Calculating Maintenance Fluid Volume

1. The Holliday-Segar method (Table 11.1 and Box 11.1) is the most widely used method to approximate maintenance fluid volume. This method estimates caloric expenditure in fixed-weight categories and assumes the average patient will require 100 mL of water for each 100 calories metabolized, with approximately 100 kcal burned per kg.[1]
2. NOTE: The Holliday-Segar method is not suitable for neonates <14 days old, because it generally overestimates fluid needs in neonates. (See Chapter 18 for neonatal fluid management.)

B. Calculating Fluid Loss

1. Total body water (TBW) is equal to **60% of a child's weight in kg (75% in infants).**[3]

EQUATION 11.1: TBW^a = weight (kg) × 0.6
[a]TBW uses preillness weight; 1 L water = 1 kg water

2. In a euvolemic child, 60% of TBW resides in the intracellular compartment [where potassium (K) concentration is 140 mEq/L and sodium (Na) is negligible], and 40% of TBW is in the extracellular compartment (where Na concentration is ~140 mEq/L and K is negligible).[4-6]
3. The most precise method of assessing fluid deficit uses weight loss:

EQUATION 11.2: Fluid deficit (L) = preillness weight (kg) – illness weight (kg)

TABLE 11.1

HOLLIDAY-SEGAR METHOD

Body Weight	Fluid Volume	
	mL/kg/day	mL/kg/hr
First 10 kg	100	≈4
Second 10 kg	50	≈2
Each additional kg	20	≈1

BOX 11.1

HOLLIDAY-SEGAR METHOD

Example: Determine the correct fluid rate for an 8-year-old child weighing 25 kg:

First 10 kg:	4 mL/kg/hr × 10 kg = 40 mL/hr	100 mL/kg/day × 10 kg = 1000 mL/day
Second 10 kg:	2 mL/kg/hr × 10 kg = 20 mL/hr	50 mL/kg/day × 10 kg = 500 mL/day
Each additional 1 kg:	1 mL/kg/hr × 5 kg = 5 mL/hr	20 mL/kg/day × 5 kg = 100 mL/day
	Answer: 65 mL/hr	Answer: 1600 mL/day

TABLE 11.2

CLINICAL OBSERVATIONS IN DEHYDRATION[7]

	Older Child		
	3% (30 mL/kg)	6% (60 mL/kg)	9% (90 mL/kg)
	Infant		
	5% (50 mL/kg)	10% (100 mL/kg)	15% (150 mL/kg)
Dehydration Classification	Mild	Moderate	Severe
Mental status	Alert		Lethargic/obtunded
Fontanelle	Flat	Soft	Sunken
Eyes	Normal	Deep set	Sunken
Tears	Present	Reduced	None
Buccal mucosa/lips	Dry	Dry	Parched/cracked
Pulse rate	Normal	Slightly increased	Increased
Skin (touch)	Normal	Dry	Clammy
Skin turgor	Normal	Tenting	None
Capillary refill	Normal	≈2–3 seconds	>3 seconds
Pulse quality	Normal	Weak	Feeble/impalpable
Urine output	Normal/mild oliguria	Mild oliguria	Severe oliguria

4. Clinical assessment: If weight loss is not known, clinical observation may be used to approximate the percentage of dehydration (Table 11.2).[7,8]

EQUATION 11.3: $\%\ \text{Dehydration} = \dfrac{\text{fluid deficit}^a}{\text{preillness weight}} \times 100\%$

[a]1 % dehydration = 10 mL/kg of fluid deficit;
[a]1 L of water = 1 kg of water

5. In a healthy child, insensible fluid volume loss is approximated as ⅓ of the Holliday-Segar MIVF per day. **NOTE**: This calculation is based on fluid requirements of healthy children. Many hospitalized children have increased insensible losses (e.g., secondary to fever or increased respiratory rate) that must be factored into fluid determinations.

C. Maintenance Fluid Choice in Hospitalized Children

1. Based on a growing body of evidence, the AAP recommends isotonic fluid as the most appropriate MIVF therapy for the vast majority of hospitalized children between the ages of 28 days and 18 years.[2] See Table 11.3 for isotonic fluid options.
2. Various disease states can lead to an increased secretion of antidiuretic hormone (ADH), which promotes the retention of free water, leading to hyponatremia.[9,10] See Box 11.2 for examples.
3. Exceptions exist in certain patient populations, such as children with neurosurgical disorders, congenital or acquired cardiac disease, hepatic disease, cancer, acute kidney injury, chronic kidney disease, nephrotic syndrome, diabetes insipidus, and voluminous watery diarrhea or severe burns.[2]
4. See Table 11.3 and Table 11.4 for electrolyte composition of various parenteral and enteral fluid replacement options.
5. Unless hyperkalemia is present or the child is in renal failure, maintenance potassium requirements (20 mEq/L of fluid) should be given.[11] Do not add potassium (K^+) to fluids until urine output has been established.[12,13]

D. Volume Replacement Strategy[7,12,13]

1. Volume resuscitation and deficit replacement should generally be completed over 24 hours.
2. See Table 11.5 for a three-phase approach to fluid replacement.
3. Children with isonatremic hypovolemia can be repleted with isotonic fluid per AAP recommendations.[2] See Box 11.3 for sample calculations in isonatremic hypovolemia.
4. If ongoing losses can be measured directly, they should be replaced 1:1 concurrently with maintenance fluid administration. If the losses cannot be measured, an estimate of 10 mL/kg body weight for each watery stool and 2 mL/kg body weight for each episode of emesis should be administered.[3] See Table 11.6 for electrolyte composition of certain bodily fluids.
5. Oral intake is the preferred method for repletion and maintenance, if possible.

III. ELECTROLYTE MANAGEMENT

See Chapter 28 for age specific normal values of electrolytes.

A. Serum Osmolality and Tonicity[2,7,14]

1. Fluids can be expressed in terms of their tonicity and their osmolality.

TABLE 11.3

COMPOSITION OF FREQUENTLY USED PARENTERAL REHYDRATION FLUIDS

	D% CHO (g/100 mL)	Protein[a] (g/100 mL)	Cal/L	Na (mEq/L)	K^+ (mEq/L)	Cl^- (mEq/L)	HCO_3^-[b] (mEq/L)	Mg^{2+}	Ca^{2+} (mEq/L)	mOsm/L
HYPOTONIC										
D_5W	5	—	170	—	—	—	—	—	—	252
$D_{10}W$	10	—	340	—	—	—	—	—	—	505
D_5 1/4 NS (0.225% NaCl)	5	—	170	38.5	—	34	—	—	—	329
1/2 NS (0.45% NaCl)	—	—	—	77	—	77	—	—	—	154
ISOTONIC										
Lactated Ringer	0–10	—	0–340	130	4	109	28	—	3	273
Plamalyte	—	—	—	140	5	98	27	3		294
Ringer solution	0–10	—	0–340	147	4	155.5	—	—	≈4	—
NS (0.9% NaCl)	—	—	—	154	—	154	—	—	—	308
HYPERTONIC										
2% NaCl	—	—	—	342	—	342	—	—	—	684
3% NaCl	—	—	—	513	—	513	—	—	—	1027
8.4% sodium bicarbonate (1 mEq/mL)	—	—	—	1000	—	—	1000	—	—	2000
COLLOID										
Plasmanate	—	5	200	110	2	50	29	—	—	—
Amino acid 8.5% (Travasol)	—	8.5	340	3	—	34	52	—	—	880
Albumin 25% (salt poor)	—	25	1000	100–160	—	<120	—	—	—	300
Intralipid[c]	2.25	—	1100	2.5	0.5	4.0	—	—	—	258–284

[a]Protein or amino acid equivalent.

[b]Bicarbonate or equivalent (citrate, acetate, lactate).

[c]Values are approximate; may vary from lot to lot. Also contains < 1.2% egg phosphatides.

CHO, Carbohydrate; *HCO_3^-*, bicarbonate; *NS*, normal saline.

BOX 11.2

CLINICAL SETTING OF INCREASED ADH RELEASE IN CHILDREN[7,26]

Hemodynamic Stimuli for ADH Release (Decreased Effective Volume)	Nonosmotic and Nonhemodynamic Stimuli for ADH Release
Hypovolemia	CNS disturbances (infection, brain tumors, head injury, thrombosis)
Nephrosis	Pulmonary disease (pneumonia, asthma, bronchiolitis, PPV)
Cirrhosis	Cancer
Congestive heart failure	Medications (MDMA, AEDs, cytoxan, vincristine, opiates, TCAs, SSRIs)
Hypoaldosteronism	GI disturbances (nausea and emesis)
Hypotension	Pain or stress
Hypoalbuminemia	Postoperative state

ADH, Antidiuretic hormone; *AED*, antiepileptic drugs; *CNS*, central nervous system; *GI*, gastrointestinal; *MDMA*, 3,4-methylenedioxymethamphetamine (ecstasy); *PPV*, positive pressure ventilation; *SSRI*, selective serotonin reuptake inhibitor; *TCA*, tricyclic antidepressant.

2. Serum osmolality (285 to 295 mOsm/kg) is a measure of both permeable and nonpermeable solutes and is calculated using the following equation:

EQUATION 11.4: $$\text{Osmolality} = 2\,\text{Na} + \frac{\text{glucose (mg/dL)}}{18} + \frac{\text{BUN (mg/dL)}}{2.8}$$

3. Osmolality is measured as osmoles per weight (kg) versus osmolarity, which is measured as osmoles per volume (L).
4. Tonicity is effective osmolality. It is the net force on water across a semipermeable membrane (e.g., the cell membrane) based on the osmotic pressures. It is relative and determined largely by sodium content. Substances that flow freely across membranes, such as urea, are ineffective osmoles and influence osmolality but not tonicity.

B. Sodium

The equations within this section are **theoretical** and are not validated. They offer a starting point for calculation of electrolyte abnormalities, but clinical context is **ALWAYS** of the utmost importance and frequent monitoring is necessary. **Children with neurosurgical disorders, cardiac disease, hepatic disease, cancer, kidney disease, diabetes insipidus, and severe burns may require consultation with subspecialists before fluid choice and volume is administered.** When correcting dysnatremias, frequent lab monitoring (~2 to 4 hours) is indicated with adjustment of fluid type and rate as needed.

1. **Hyponatremia**: Excess Na loss (Na <135 mEq/L)
   a. Clinical manifestations and differential diagnosis (Table 11.7)
   b. Pseudohyponatremia etiologies:
      (1) Increased serum osmolality: Hyperglycemia: Na artificially decreased 1.6 mEq/L for each 100-mg/dL rise in glucose
      (2) Normal serum osmolality:
         (a) Hyperlipidemia: Na artificially decreased by 0.002 × lipid (mg/dL)

TABLE 11.4

COMPOSITION OF ORAL REHYDRATION FLUIDS

	D% CHO (g/100 mL)	Na (mEq/L)	K^+ (mEq/L)	Cl^- (mEq/L)	HCO_3^-[b] (mEq/L)	Ca^{2+} (mEq/L)	mOsm/L
ORAL FLUIDS							
Pedialyte	2.5	45	20	35	30	—	250
WHO solution	2	90	20	80	30	—	310
Rehydralyte	2.5	75	20	65	30	—	310
COMMONLY CONSUMED FLUIDS (NOT RECOMMENDED FOR ORAL REHYDRATION)[a]							
Apple juice	11.9	0.4	26	—	—	—	700
Coca-Cola	10.9	4.3	0.1	—	13.4	—	656
Gatorade	5.9	21	2.5	17	—	—	377
G2	4.7	20	3.2	—	—	—	
Ginger ale	9	3.5	0.1	—	3.6	—	565
Milk	4.9	22	36	28	30	—	260
Orange juice	10.4	0.2	49	—	50	—	654
Powerade	5.8	18	2.7	—	—	—	264

[a]Electrolyte values are approximate

[b]Bicarbonate or equivalent (citrate, acetate, lactate).

CHO, Carbohydrate; *HCO_3^-*, bicarbonate; *NS*, normal saline; *WHO*, World Health Organization

TABLE 11.5

VOLUME REPLACEMENT STRATEGY

Phase I	Phase II	Phase III
Initial stabilization	**Deficit repletion, maintenance volume, and ongoing losses**	**Recovery and ongoing losses**
Rapid fluid resuscitation with isotonic fluid.[a] 20 mL/kg represents only a 2% volume replacement	Replace half of the remaining deficit over the first 8 hr (this includes any fluid given in the initial stabilization phase). Replace the second half of deficit over the following 16 hr, making sure to also include maintenance fluid volume replacement during this time.	Continue maintenance fluid replacement, taking ongoing losses into consideration.

[a]Should be used in patients in need of rapid volume expansion.
See Box 11.3 for sample calculation

BOX 11.3

SAMPLE CALCULATIONS: ISONATREMIC DEHYDRATION

Example: A 15-kg (preillness weight) child with 10% dehydration and normal serum sodium

Requirement	Formula	Sample Calculation
Maintenance fluid requirements	Holliday–Segar formula	(100 mL/kg/day × 10 kg) + (50 mL/kg/day × 5 kg) = 1250 mL/24 hr = 52 mL/hr
Fluid deficit	Equation 11.2 or Equation 11.3	10 mL × 15 kg × 10% = 1500 mL
	Fluid Replacement Rate Over 24 hrs	
½ fluid deficit replaced in first 8 hrs	750 mL/8 hr = 94 mL/hr + 52 mL/hr maintenance = 146 mL/hr	
½ fluid deficit replaced over 16 hrs	750 mL/16 hr = 47 mL/hr + 52 mL/hr maintenance = 99 mL/hr	

Note: If patient received an initial 20 mL/kg bolus (300 mL): 1500 mL – 300 mL = 1200 mL
½ fluid deficit in first 8 hrs: 600 cc/8 hr = 75 mL + 52 mL/hr maintenance = 127 mL/hr
½ fluid deficit over next 16 hrs: 600 cc/16 hr = 38 mL/hr + 52 mL/hr maintenance = 90 mL/hr

(b) Hyperproteinemia: Na artificially decreased by 0.25 × [protein (g/dL) – 8]

c. Management

(1) The traditional equation used to calculate the excess sodium deficit in hyponatremia is:

EQUATION 11.5[3]:

$$\text{Na deficit(mEq)}^{a} = [\text{Desired Na (mEq/L)} - \text{Serum Na (mEq/L)}] \times \text{TBW (L)}$$

[a]This represents the *excess* sodium deficit in hyponatremic dehydration. It must be added to the daily sodium requirement for hospitalized patients of **~14 mEq/100 mL fluid given**.

(2) Hyponatremia should be corrected **by no more than 10 to 12 mEq per 24 hr** to avoid rapid change of serum sodium, which can cause osmotic demyelination syndrome.[6,13,15]

TABLE 11.6

ELECTROLYTE COMPOSITION OF VARIOUS FLUIDS

Source of Fluid	Na^+ (mEq/L)	K^+ (mEq/L)	Cl^- (mEq/L)
Gastric	20–80	5–20	100–150
Pancreatic	120–140	5–15	90–120
Small bowel	100–140	5–15	90–130
Bile	120–140	5–15	80–120
Ileostomy	45–135	3–15	20–115
Diarrhea	10–90	10–80	10–110
Skin with burns[a]	140	5	110
Sweat			
Normal	10–30	3–10	10–35
Cystic fibrosis[b]	50–130	5–25	50–110

[a]3–5 g/dL of protein may be lost in fluid from burn wounds.

[b]Replacement fluid dependent on sodium content.

Modified from Kliegman RM, Stanton B, St. Gene J, et al. *Nelson Textbook of Pediatrics*. 19th ed. Philadelphia: Saunders; 2011.

TABLE 11.7

HYPONATREMIA[7,14]

CLINICAL MANIFESTATIONS			
Related to rate of change: Nausea, headache, muscle cramps, weakness, confusion, apnea, lethargy, seizure, coma, hypothermia, depressed DTRs			
ETIOLOGIES			
Hypovolemic		**Euvolemic**	**Hypervolemic**
Renal Losses	**Extrarenal Losses**		
Na-losing nephropathy Diuretics Juvenile nephronopthisis Hypoaldosteronism (CAH, pseudohypoaldosteronism, UTI/obstruction) Cerebral salt-wasting syndrome Postobstructive diuresis ATN (polyuric phase)	GI losses Skin losses Third spacing Cystic fibrosis	SIADH (see Chapter 10) Excess salt-free infusions Desmopressin acetate Water intoxication Hypothyroidism Sepsis Primary polydipsia[c] Malnutrition[c]	Nephrotic syndrome Hypoalbuminemia Heart failure Cirrhosis Renal failure Glucocorticoid deficiency
LABORATORY DATA			
↑ Urine Na (> 20 mEq/L) ↑ Urine volume ↓ Specific gravity ↓ Urine osmolality[a] (< 100 mOsm/L)	↓ Urine Na (< 20 mEq/L) ↓ Urine volume ↑ Specific gravity ↑ Urine osmolality (> 100 mOsm/L)	↓ Urine volume ↑ Specific gravity ↑ Urine osmolality (> 100 mOsm/L)	↓ Urine Na[b] (< 20 mEq/L) ↓ Urine volume
MANAGEMENT			
Replace losses (see hypovolemic hyponatremia)		Restrict fluids Address the underlying cause	

[a]Minimum possible urine osmolality = 50 mOsm/kg

[b]Urine Na may be appropriate for the level of Na intake in patients with SIADH and water intoxication.

[c]Urine osmolality is <100 mOsm/L

ATN, Acute tubular necrosis; *CAH*, congenital adrenal hyperplasia; *DTR*, deep tendon reflex; *GI*, gastrointestinal; *Na*, sodium; *SIADH*, syndrome of inappropriate antidiuretic hormone secretion; *UTI*, urinary tract infection.

(3) Witnessed onset of hyponatremia over the course of hours does not pose as great of a risk and can be corrected in a similar amount of time that it developed.[7]

(4) If central nervous system (CNS) symptoms are present, hypertonic saline (HTS) should be administered over 3 to 4 hours to correct the hyponatremia by ~5 mEq/L.[5,6,11] Use Equation 11.7 to determine rate of HTS.

(5) To determine the sodium content of the fluid necessary for repletion:

EQUATION 11.6:

$$\text{Na content (mEq/L)} = \frac{[\text{Na deficit} + (14\ \text{mEq}/100\ \text{mL} \times \text{maintenance fluid volume [mL]})}{\text{volume deficit}^a}$$

[a]Use daily maintenance volume requirements if euvolemic

(6) Once the fluid type is determined, the starting rate can be calculated using the following:

EQUATION 11.7:

$$\text{Fluid rate (mL/hour)} = \frac{\text{Na deficit (mEq)} \times 1000\ \text{mL}}{\text{infusate Na (mEq)} \times \text{hours IVF will run in a day}}$$

(7) See Box 11.4 and 11.5 for sample calculations in hyponatremic dehydration.

2. **Hypernatremia**: Excess free water loss (Na >145 mEq/L)
   a. Clinical manifestations and differential diagnosis (Table 11.8)
   b. Management
      (1) Hypernatremic hypovolemia occurs in scenarios in which free water is either unavailable/restricted or there is excessive loss of solute-free water (see Table 11.8).
      (2) Hypernatremia is dangerous because of complications from potential treatment sequelae, the most serious of which is cerebral edema.[4,7]
      (3) Plan to correct the serum Na by no more than 10 mEq/24 hours and correct the free water deficit over 48 hours to minimize the risk of cerebral edema.[4,10,11,16]
      (4) As with hyponatremia, witnessed onset of hypernatremia over the course of hours can be corrected rapidly; this is because the brain has not had time to produce idiogenic osmoles to adapt to the change in osmolality.[7,11]
      (5) Expert opinion recommends starting with D5 ½ NS.[16] However, the sodium and fluid needs can also be calculated.
      (6) The free water deficit is as follows:

EQUATION 11.8[4,6]:

$$\text{FWD (mL)} = \text{TBW (mL)} \times \left[1 - \frac{\text{Desired Na (mEq/L)}}{\text{Serum Na (mEq/L)}}\right]^a$$

[a]The difference in desired and serum Na should be no more than 10 mEq/L/day

BOX 11.4

SAMPLE CALCULATIONS: HYPONATREMIC DEHYDRATION

Example: A 15-kg (preillness weight) child with 10% dehydration and serum sodium 125 mEq/L without central nervous system symptoms

Requirement	Formula	Sample Calculation
Maintenance fluid requirements	Holliday-Segar formula	(100 mL/kg/d × 10 kg) + (50 mL/kg/d × 5 kg) = 1250 mL/24 hr = 52 mL/hr
Fluid deficit	Equation 11.2 or Equation 11.3	10 mL × 15 kg × 10% = 1500 mL
Fluid Replacement Rate Over 24 hrs		
1500 mL/24 hr = 63 mL/hr + 52 mL/hr maintenance = 115 mL/hr		
Calculations for Fluid Selection		
Maintenance sodium requirements	3 mEq per 100 mL of maintenance fluid	3 mEq × (1250 mL/100 mL) = 38 mEq Na^+
Isotonic sodium deficit	8–10 mEq Na^+ per each 100 mL of fluid deficit	10 mEq × (1500 mL/100 mL) = 150 mEq Na^+
Sodium deficit	Equation 11.5	(135 mEq − 125 mEq) × 9 = 90 mEq Na^+
Total sodium content	Equation 11.6	90 mEq + (14 mEq/100ml × 1250) = 265 mEq
Sodium required per L	Divide total sodium by fluid deficit in L	278 mEq/1.5 L = 185 mEq

BOX 11.5

SAMPLE CALCULATIONS: SEVERE SYMPTOMATIC HYPONATREMIC DEHYDRATION

Initial Fluid Replacement for Neurologic Stabilization

Example: A 15-kg (preillness weight) child with altered mental status and serum sodium 110 mEq/L

Fluid to be used: 3% hypertonic saline (HTS)

Requirement	Formula	Sample Calculation
Sodium deficit	Equation 11.5	5 mEq/L × 9 = 45 mEq Na^+
Rate of administration	Equation 11.7	[(45 mEq × 1000 mL) /513 mEq × 4 hrs] = 22 mL/hr of 3% HTS

(7) The FWD is used to calculate the solute fluid deficit (SFD) (i.e., the amount of fluid that contains electrolytes).

EQUATION 11.9: SFD = Fluid Deficit [a] − FWD

[a]See equation 11.2 for fluid deficit calculations

(8) Despite the hypernatremia, there is also a Na deficit that should be accounted for:

TABLE 11.8

HYPERNATREMIA[7,25]

CLINICAL MANIFESTATIONS		
With hypernatremic hypovolemia, there is better preservation of intravascular volume compared to hypovolemic hyponatremia. Lethargy, weakness, altered mental status, irritability, coma, and seizures. High-pitched cry, thrombosis, brain hemorrhage, muscle cramps, hyperpnea, and respiratory failure.		
ETIOLOGIES		
Low urine osmolality	**Elevated urine osmolality**[b]	
	↓ Urine Na (< 20 mEq/L)	**↑ Urine Na (> 20 mEq/L)**
Diabetes insipidus (central and nephrogenic) (see Chapters 10 and 19) Postobstructive diuresis CKD Diuretic use Polyuric phase of ATN	GI losses Skin losses Respiratory[a] Increased insensible losses Adipsia	Exogenous Na^+ (meds, infant formula) Mineralocorticoid excess (e.g., hyperaldosteronism)
MANAGEMENT		
Timeline of onset can mirror timeline for correction.		

[a]This cause of hypernatremia is usually secondary to free water loss; therefore the fractional excretion of sodium may be decreased or normal.
[b]>1000 mosm/kg
ATN, Acute tubular necrosis; *CKD*, chronic kidney disease; *GI*, gastrointestinal; *Na*, sodium.

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EQUATION 11.10:

$$\text{Na required (mEq)} = [\text{SFD (mL)} + \text{maintenance fluid volume (mL)}] \times \frac{14\ \text{mEq}}{100\text{mL}}$$

(9) The amount of sodium is then divided by the total fluid deficit in addition to the maintenance fluid volume. This will help approximate the fluid tonicity required.

EQUATION 11.11:

$$\text{Na content of fluid (mEq/L)} = \frac{\text{Na required (mEq)}}{\text{Fluid Deficit (L)} + \text{maintenance fluid volume (L)}}$$

(10) See Box 11.6 for sample calculations in hypernatremic dehydration.

(11) If the fluid necessary contains >154 mEq of Na, then the following equation can be used to make a 1-L bag at the desired tonicity:[16]

EQUATION 11.12:

$$\text{mL of 3\% saline} = 1000\ \text{mL} \times \frac{\text{desired Na (mEq/L)} - 154\ \text{(mEq/L)}}{513\ \text{(mEq/L)} - \text{desired Na (mEq/L)}}$$

(12) This equation can also be used to calculate rate to run HTS with NS bolus in a severely hypernatremic child. See Box 11.7.

BOX 11.6

SAMPLE CALCULATIONS: HYPERNATREMIC DEHYDRATION

Example: A 15-kg (preillness weight) child with 10% dehydration and serum sodium 155 mEq/L

Requirement	Formula	Sample Calculation
Maintenance fluid requirements	Holliday-Segar formula	(100 mL/kg/d × 10 kg) + (50 mL/kg/d × 5 kg) = 1250 mL/24 hr = 52 mL/hr
Total fluid deficit	Equation 11.2 or Equation 11.3	10 mL × 15 kg × 10% = 1500 mL
Fluid Replacement Rate Over 24 hrs		
1500 mL/24 hr = 63 mL/hr + 52 mL/hr maintenance = 115 mL/hr		
Calculations for Fluid Selection		
Free water deficit	Equation 11.8	4 mL/kg × 15 kg × (155 mEq/L − 145 mEq/L) = 600 mL
Solute fluid deficit	Equation 11.9	1500 mL − 600 mL = 900 mL
Total sodium required	Equation 11.10	(900 mL + 1250 mL) × 14 mEq/100 mL = 300 mEq Na^+
Na content of fluid	Equation 11.11	300 mEq / (1.25 + 1.5 L) = 110 mEq Na

BOX 11.7

SAMPLE CALCULATIONS: SEVERE HYPERNATREMIC DEHYDRATION

Initial Fluid Resuscitation Strategy to Avoid Rapid Sodium Correction when Serum Na^+ >175 mEq/L[16]

Example: A 3-kg (preillness-weight) breastfed neonate appearing severely dehydrated with serum sodium 185 mEq/L and hemodynamic instability

Resuscitation with normal saline (NS) may drop the serum Na^+ too quickly. Plan to simultaneously run NS and 3% hypertonic saline (HTS), given rapidly together (i.e., over 5 minutes), to effectively give resuscitation fluid with a concentration no more than 15 mEq/L below the child's serum Na^+. Repeat the boluses as needed to achieve hemodynamic stability.

Requirement	Formula	Sample Calculation
Ideal bolus fluid concentration	Serum sodium (in mEq/L) − 15 mEq/L	185 mEq/L − 15 mEq/L = 170 mEq/L
mL of HTS required per L of NS	Equation 11.12	1000 mL × (170 mEq/L − 154 mEq/L) / (513 mEq/L − 170 mEq/L) = 47 mL
Bolus NS amount in mL	20 mL/kg × wt (in kg)	20 mL/kg × 3 kg = 60 mL
Bolus amount HTS in mL	mL HTS required per L of NS × NS bolus amount (in mL) / 1000 mL	47 mL × 60 mL / 1000 mL = 2.8 mL

Note: In clinical practice, one will often not have laboratory data available quickly enough to employ this strategy. However, severe hypernatremia should be suspected in the clinical scenario of a solely breastfed neonate who appears severely dehydrated.[16] STAT labs should be sent, and this strategy may be employed as soon as laboratory values are available.

3. Calculations pertaining to dysnatremias can be double-checked using the following equation:

EQUATION 11.13:[4-6]

$$\frac{\text{Change in Serum Na}}{\text{1L of parenteral fluid administration}} = \frac{(\text{Infusate Na} + \text{Infusate K}) - \text{Serum Na}}{\text{TBW} + 1}$$

C. Potassium

1. **Hypokalemia**
   a. Clinical manifestations and differential diagnosis (Table 11.9)
   b. The transtubular potassium gradient (TTKG) can help differentiate between etiologies of hypokalemia, as noted in Table 11.9:

EQUATION 11.14:[7]

$$^{7}\text{TTKG}^{a} = \frac{[K]_{urine}}{[K]_{plasma}} \times \left(\frac{\text{plasma osmolality}}{\text{urine osmolality}}\right)$$

[a]The urine osmolality must be greater than the serum osmolality for the calculation to be valid

   c. Management: Potassium infusion rates generally should not exceed 1 mEq/kg/hr.[3]
2. **Hyperkalemia**
   a. Clinical manifestations and differential diagnosis (Table 11.10)
   b. Management (Fig. 11.1)

D. Calcium

1. **Hypocalcemia**
   a. Clinical manifestations and differential diagnosis (Table 11.11)
   b. Special considerations:
      i. Albumin readily binds serum calcium. Correction for albumin: Δ of 1 g/dL changes the total serum calcium in the same direction by 0.8 mg/dL.
      ii. pH: Acidosis increases ionized calcium.
      iii. Symptoms of hypocalcemia refractory to calcium supplementation may be caused by hypomagnesemia.
      iv. Significant hyperphosphatemia should be corrected before the correction of hypocalcemia because renal calculi or soft-tissue calcification may occur if total $\mathbf{[Ca^{2+}] \times [PO_4^{3-}] \geq 70}$.[7]
2. **Hypercalcemia:** Table 11.11

E. Magnesium

1. Hypomagnesemia: Table 11.12
2. Hypermagnesemia: Table 11.12

F. Phosphate

1. Hypophosphatemia: Table 11.13
2. Hyperphosphatemia: Table 11.13

TABLE 11.9

HYPOKALEMIA[7,25]

CLINICAL MANIFESTATIONS

Manifest at levels <2.5 mEq/L. Skeletal muscle weakness or ascending paralysis, muscle cramps, ileus, urinary retention, and cardiac arrhythmias.
Electrocardiogram (ECG) changes:
Delayed depolarization, flat T waves, depressed ST segment, and U waves.

ETIOLOGIES

Decreased Stores					
Metabolic Alkalosis					
Hypertensive	**Normotensive**	**Metabolic Acidosis**	**No Change in Serum pH**	**Extrarenal**	**Normal Stores[a]**
Renovascular disease Excess renin Cushing syndrome CAH Adrenal adenoma Licorice ingestion Liddle syndrome	Gitleman syndrome Bartter syndrome Hypoparathyrodism Cystic fibrosis EAST syndrome Loop and thiazide diuretics Emesis	RTA (type I and II) DKA Uretosigmoidoscopy Fanconi Syndrome	Meds (amphotericin, cis-platin, aminoglycosides, penicillin or penicillin derivatives, diuretics) Interstitial nephritis	Skin losses GI losses/laxative abuse/enema abuse Clay ingestion Kayexalate Malnutrition/Anorexia nervosa	Acute metabolic alkalosis Hyperinsulinemia Leukocytosis (if sample sits at room temperature) Meds (adrenergic agonists, theophylline, toluene, cesium chloride, hydroxy-chloroquine, barium) Familial hypokalemic periodic paralysis Familial

LABORATORY DATA

TTKG > 4				TTKG ≤ 4	~ Urine K^+

MANAGEMENT

Acute	Calculate deficit and replace with potassium acetate or potassium chloride. Enteral replacement is safer when feasible. Follow K^+ closely. IV replacement generally should not exceed 1 mEq/kg given over 1 hr.
Chronic	Determine daily requirement and replace with potassium chloride or potassium gluconate.

[a]Blood pressure may vary.

CAH, Congenial adrenal hyperplasia; *DKA*, diabetic ketoacidosis; *GI*, gastrointestinal; *K^+*, potassium; *RTA*, renal tubular acidosis; *EAST*, epilepsy, ataxia, sensorineural hearing loss, and tubulopathy; *TTKG*, transtubular potassium gradient.

TABLE 11.10

HYPERKALEMIA[7]

CLINICAL MANIFESTATIONS

Skeletal muscle weakness, fasciculations, paresthesias, and ascending paralysis.

The typical ECG progression with increasing serum K^+ values:

1. Peaked T waves
2. Prolonged PR and widening of QRS
3. Loss of P waves
4. ST segment depression with further widening of QRS
5. Bradycardia, atrioventricular (AV) block, ventricular arrhythmias, torsades de pointes, and cardiac arrest

ETIOLOGIES

Increased total body K^+		Intracellular shifts (no change in total body K^+)
Increased urine K^+	**Decreased urine K^+**	
Transfusion with aged blood	Renal failure	Tumor lysis syndrome
Exogenous K^+	Hypoaldosteronism	Leukocytosis (>200 x 10^3/μL)
Spitzer syndrome	Aldosterone insensitivity	Thrombocytosis (>750 x 10^3/μL)[b]
	↓ Insulin causing hyperglycemia and/or DKA	Metabolic acidosis[a]
	K^+-sparing diuretics	Blood drawing (hemolyzed sample)
	Congenital adrenal hyperplasia	Rhabdomyolysis/crush injury
	Type IV RTA	Malignant hyperthermia
	Meds: ACE inhibitors, angiotensin II blockers, K sparing diuretics, calcineurin inhibitors, NSAIDs, heparin, TMX, drospirenone	Theophylline intoxication

MANAGEMENT

See Fig. 11.1.

[a]For every 0.1-unit reduction in arterial pH, there is approximately a 0.2–0.4 mEq/L increase in plasma K^+.

[b]For every platelet increase of 100,000/μL, there is a 0.15 mEq/L increase in serum K^+.

ACE, Angiotensin converting enzyme; *DKA*, diabetic ketoacidosis; *ECG*, electrocardiogram; *K^+*, potassium; *NSAIDS*, nonsteroidal antiinflammatory drugs; *RTA*, renal tubular acidosis; *TMX*, trimethoprim.

IV. ALGORITHM FOR EVALUATING ACID-BASE DISTURBANCES[7,17,18]

A. Determine the pH

The body does not fully compensate for primary acid-base disorders; therefore the primary disturbance will shift the pH away from 7.40.

1. **Acidemia (pH < 7.35):**
   a. Respiratory acidosis: PCO_2 > 45 mm Hg
   b. Metabolic acidosis: Arterial bicarbonate < 20 mmol/L
2. **Alkalemia (pH > 7.45):**
   a. Respiratory alkalosis: PCO_2 < 35 mm Hg
   b. Metabolic alkalosis: Arterial bicarbonate > 28 mmol/L

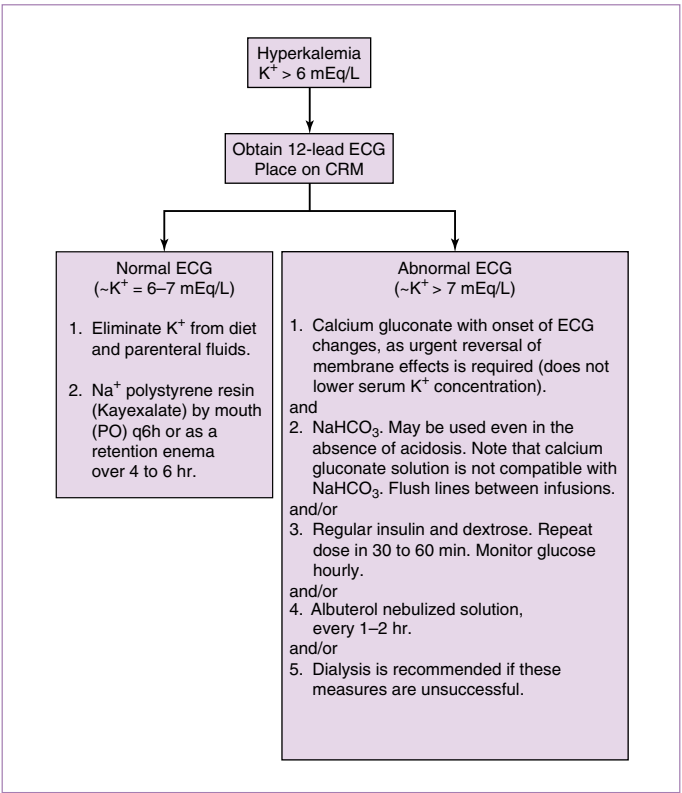

FIGURE 11.1

Algorithm for hyperkalemia. *CRM*, Cardiorespiratory monitor; *D25W*, 25% dextrose in water; *ECG*, electrocardiogram; *INH*, inhaled; *IV*, intravenous.

TABLE 11.11

HYPOCALCEMIA AND HYPERCALCEMIA

Hypocalcemia	Hypercalcemia
CLINICAL MANIFESTATIONS	
Tetany, neuromuscular irritability with weakness, paresthesias, fatigue, cramping, altered mental status, seizures, laryngospasm, and cardiac arrhythmias[18,19]: • ECG changes (prolonged QT interval) • Trousseau's sign (carpopedal spasm after arterial occlusion of an extremity for 3 minutes) • Chvostek sign (muscle twitching on percussion of the facial nerve)	Weakness, irritability, lethargy, seizures, coma, abdominal cramping, anorexia, nausea, vomiting, polyuria, polydipsia, renal calculi, pancreatitis, and ECG changes (shortened QT interval)
ETIOLOGIES	
Hypoparathyroidism Vitamin D deficiency Hyperphosphatemia Pancreatitis Malabsorption (malnutrition) Drugs (anticonvulsants, cimetidine, aminoglycosides, calcium channel blockers) Hypomagnesemia/hypermagnesemia Maternal hyperparathyroidism (in neonates) Ethylene glycol ingestion Calcitriol (activated vitamin D) insufficiency Tumor lysis syndrome	Hyperparathyroidism Vitamin D intoxication Excessive exogenous calcium administration Malignancy Prolonged immobilization Thiazide diuretics Subcutaneous fat necrosis Williams syndrome Granulomatous disease (e.g., sarcoidosis) Hyperthyroidism Milk-alkali syndrome
MANAGEMENT	
Acute: Consider IV replacement (calcium gluconate, calcium gluceptate, or calcium chloride [cardiac arrest dose]) Chronic: Consider use of oral supplements of calcium carbonate, calcium gluconate, calcium glubionate, or calcium lactate	Increase UOP and Ca^{2+} excretion: 1. If the glomerular filtration rate and blood pressure are stable, give NS with maintenance K^+ at 2-3 times the maintenance rate 2. Diuresis with furosemide Consider hemodialysis for severe or refractory cases Consider steroids in malignancy, granulomatous disease, and vitamin D toxicity to decrease vitamin D and Ca^{2+} absorption Severe or persistently elevated Ca^{2+}: Consider calcitonin or bisphosphonate

Ca^{2+}, Calcium; *ECG*, electrocardiogram; *UOP*, urine output.

B. Calculate the anion gap (AG)

1. **AG:** Represents anions other than bicarbonate and chloride required to balance the positive charge of Na. Normal: 12 mEq/L ± 2 mEq/L.

EQUATION 11.15: $AG = Na^+ - (Cl^- + HCO_3^-)$

TABLE 11.12

HYPOMAGNESEMIA AND HYPERMAGNESEMIA[7]

Hypomagnesemia				Hypermagnesemia
CLINICAL MANIFESTATIONS				
Typically, dominant manifestations are caused by concurrent hypocalcemia (Table 11.11) Typically occur at levels <0.7 mg/dL: Anorexia, nausea, weakness, malaise, depression, nonspecific psychiatric symptoms, hyperreflexia, ECG changes: flattening of T wave and lengthening of ST segment				Typically occur at levels >4.5 mg/dL: Hypotonia, hyporeflexia, paralysis, lethargy, confusion, hypotension, and prolonged QT, QRS, and PR intervals. Respiratory failure and cardiac arrest at >15 mg/dL
ETIOLOGIES				
GI Disorders	**Genetic**	**Medications**	**Miscellaneous**	**Renal Failure and Excessive Administration**
Diarrhea	Gitelman syndrome	Amphotericin	Decreased intake	Status asthmaticus eclampsia/preeclampsia, cathartics, enemas, phosphate binders, laxatives, lithium ingestions, milk-alkali syndrome
Malabsorption diseases	Bartter syndrome	Cisplatin	Hungry bone syndrome	
Short bowel	EAST syndrome	Cyclosporine	Exchange transfusion	
Malnutrition	AD hypoparathyroidism	Loop and thiazide diuretics	Diabetes mellitus	
Pancreatitis	Mitochondrial disorders	Mannitol	Steatorrhea	
	Miscellaneous disorders	Pentamidine	Hyperaldosteronism	
MANAGEMENT				
Acute			IV Magnesium sulfate	Stop supplemental Mg^{2+} Diuresis Ca^{2+} supplements, such as calcium chloride (cardiac arrest doses) or calcium gluconate
Chronic			PO Magnesium oxide or magnesium sulfate	

AD, Autosomal dominant; *Ca^{2+}*, calcium; *EAST*, epilepsy, ataxia, sensorineural hearing loss, and tubulopathy; *ECG*, electrocardiogram; *GI*, gastrointestinal; *IV*, intravenous; *Mg^{2+}*, magnesium ; *PO*, by mouth.

2. The majority of unmeasured anions contributing to the AG in normal individuals are albumin and phosphate. Correcting the AG for albumin concentration increases the utility of the traditional method.[19]

EQUATION 11.16: Corrected AG =
Observed AG + 2.5 × (Normal albumin − measured albumin)

AG > 15 : Anion gap metabolic acidosis (AGMA)

AG < 12 : Nonelevated anion gap metabolic acidosis (NAGMA)

AG > 20 mEq / L : Primary AGMA regardless of the pH or serum HCO_3^- concentration

TABLE 11.13

HYPOPHOSPHATEMIA AND HYPERPHOSPHATEMIA[7]

Hypophosphatemia		Hyperphosphatemia
CLINICAL MANIFESTATIONS		
Symptomatic only at very low levels (<1 mg/dL). Acute: rhabdomyolysis, tremor, paresthesias, irritability, confusion, hemolysis, delirium, seizure, myocardial depression, and coma. Chronic: Rickets, proximal muscle weakness		Symptoms of resulting hypocalcemia and systemic calcification (i.e., deposition of phosphorus calcium salts in tissues).
ETIOLOGIES		
Refeeding syndrome Insulin BMT Hungry bone Decreased intake Antacids Glucocorticoids Rickets Hyperparathyroidism Increased renal losses (e.g., renal tubular defects, diuretic use) McCune-Albright syndrome Epidermal nevus syndrome Fanconi syndrome Metabolic acidosis/respiratory alkalosis Glycosuria Volume expansion Sepsis		Tumor lysis syndrome Rhabdomyolysis DKA/lactic acidosis Hemolysis Renal failure Hypoparathyroidism Hyperthyroidism Excessive intake (enemas/laxatives and cow's milk) Vitamin D intoxication Familial tumoral calcinosis Acromegaly
MANAGEMENT		
Acute	IV potassium phosphate or sodium phosphate	Restrict dietary phosphate. Phosphate binders (calcium carbonate, aluminum hydroxide)
Chronic	PO potassium phosphate or sodium phosphate	

BMT, Bone marrow transplant; *DKA*, diabetic ketoacidosis. *IV*, intravenous; *PO*, by mouth.

C. Calculate the delta gap (DG)[20]:

If there is an AGMA, calculating the DG will help to determine if there is another, concurrent metabolic abnormality:

EQUATION 11.17: $DG = (AG - 12) - (24 - HCO_3^-)$

$DG > 6$: combined AGMA and metabolic alkalosis.

$DG < -6$: combined AGMA and NAGMA.

D. Calculate the osmolal gap

EQUATION 11.18: Serum osmolal gap = calculated serum osmolality – laboratory measured osmolality

TABLE 11.14

CALCULATION OF EXPECTED COMPENSATORY RESPONSE[7,20]

Disturbance	Primary Change	Expected Compensatory Response
Acute respiratory acidosis	↑$PaCO_2$	↑HCO_3^- by 1 mEq/L for each 10 mmHg rise in $Paco_2$
Acute respiratory alkalosis	↓$PaCO_2$	↓HCO_3^- by 2 mEq/L for each 10 mmHg fall in $PaCO_2$
Chronic respiratory acidosis	↑$PaCO_2$	↑HCO_3^- by 4 mEq/L for each 10 mmHg rise in $PaCO_2$
Chronic respiratory alkalosis	↓$PaCO_2$	↓HCO_3^- by 4 mEq/L for each 10 mmHg fall in $PaCO_2$
Metabolic acidosis	↓HCO_3^-	$PaCO_2 = 1.5 \times [HCO_3^-] + 8 \pm 2$
Metabolic alkalosis	↑HCO_3^-	↑$PaCO_2$ by 7 mmHg for each 10 mEq/L rise in HCO_3^-

1. There is always a difference (<6) between calculated osmolality and measured osmolality.[21]
2. A markedly elevated osmolar gap (>10) in the setting of an AG acidosis is highly suggestive of acute methanol or ethylene glycol intoxication.[22–24]

E. Calculate expected compensatory response: (Table 11.14)

1. Pure **respiratory** acidosis (or alkalosis): 10 mmHg rise (fall) in $PaCO_2$ results in an average 0.08 fall (rise) in pH.
2. Pure **metabolic** acidosis (or alkalosis): 10 mEq/L fall (rise) in HCO_3^- results in an average 0.15 fall (rise) in pH.

F. Determine the likely etiology

Check for appropriate compensation

G. If there is not appropriate compensation, consider an additional acid-base derangement (Fig. 11.2)

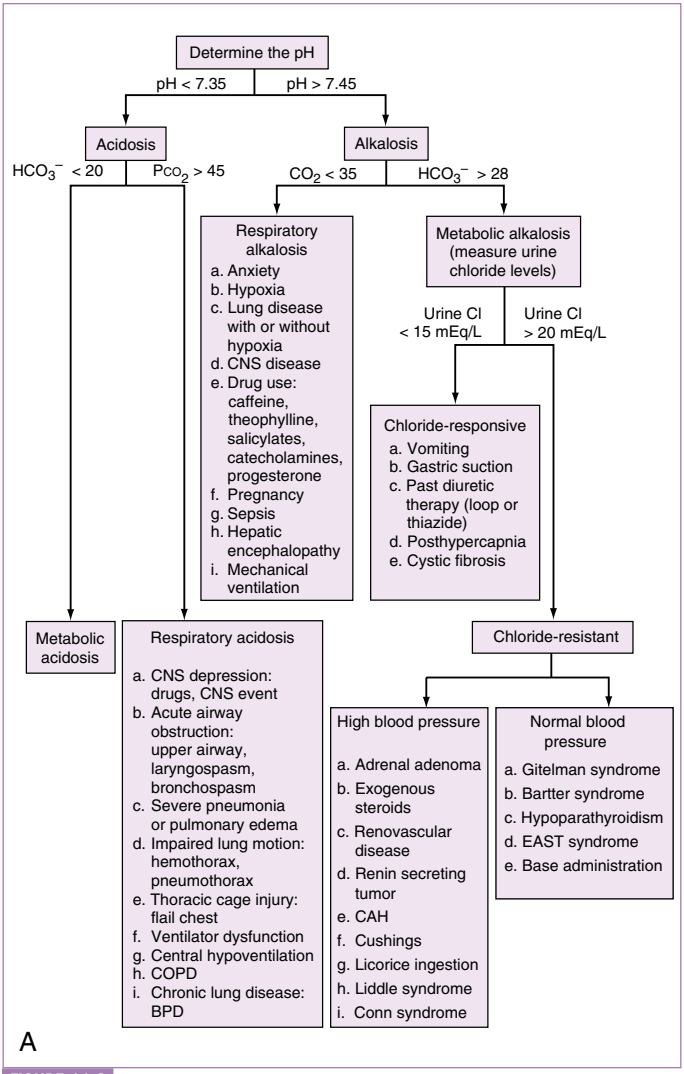

FIGURE 11.2

(A and B) Etiology of acid-base disturbances. *BPD*, bronchopulmonary dysplasia; *CAH,* congenital adrenal hyperplasia; *CNS*, central nervous system; *COPD*, chronic obstructive pulmonary disease; *EAST,* epilepsy, ataxia, sensorineural hearing loss, and tubulopathy; *NSAID*, nonsteroidal antiinflammatory drug.

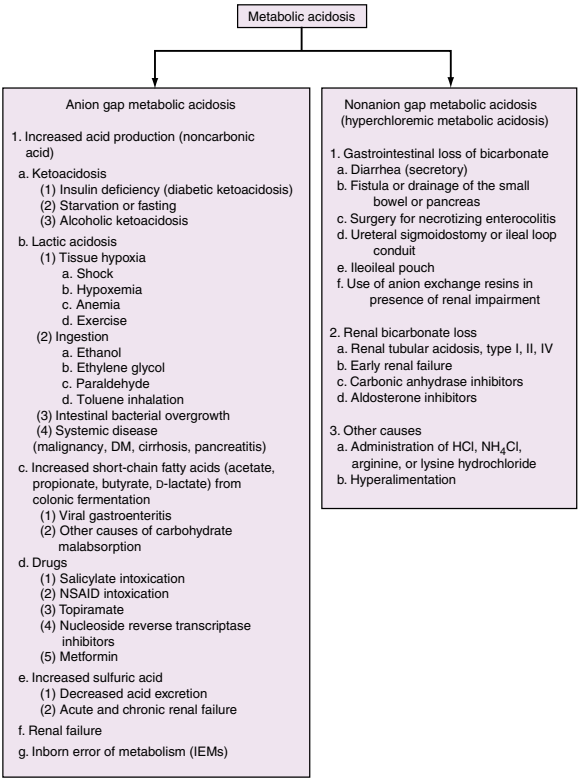

FIGURE 11.2, cont'd

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