ELECTROLYTE DISORDERS

Physiology • Pathology • Deficiency • Excess

A Detailed Expert Guide with Clinical Cases,
Diagnostic Algorithms & High-Yield Pearls

Sinoe Medical Association

Danil Hammoudi, MD

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1. Introduction to Electrolyte Homeostasis

Electrolytes are ionized solutes that maintain membrane potential, osmotic balance, acid-base homeostasis, and enzymatic function. The major extracellular cations are sodium and calcium; the major intracellular cation is potassium. Chloride and bicarbonate are the primary anions. Disturbances are among the most common and most dangerous laboratory abnormalities encountered in clinical practice.

Serum concentrations reflect the interplay of intake, gastrointestinal absorption, transcellular shifts, renal excretion, and hormonal regulation. Because total body stores of potassium, magnesium, and phosphate are predominantly intracellular, serum values often under- or overestimate true deficits or excesses.

Normal Serum Ranges & Primary Roles

Electrolyte	Normal Range	Primary Roles	Key Regulators
Sodium (Na■)	135–145 mEq/L	ECF volume, osmolality, neuroexcitability	ADH, RAAS, ANP/BNP
Potassium (K■)	3.5–5.0 mEq/L	Resting membrane potential, cardiac conduction	Aldosterone, insulin, pH, β-adrenergic
Calcium (Ca²■)	8.5–10.5 mg/dL (total)	Muscle contraction, coagulation, bone, signaling	PTH, 1,25-(OH)■D, calcitonin
Magnesium (Mg²■)	1.7–2.2 mg/dL	Enzyme cofactor (>300 reactions), NMJ, cardiac	GI absorption, renal handling
Phosphate (PO■)	2.5–4.5 mg/dL	ATP, 2,3-DPG, bone mineral, buffers	PTH, FGF23, vitamin D
Chloride (Cl■)	96–106 mEq/L	Acid-base balance, osmotic partner of Na■	Renal tubular handling, HCO■ exchange

Core Principle: Always interpret electrolyte values in the context of volume status, acid-base balance, renal function, medications, and clinical symptoms. Isolated numbers without context lead to diagnostic error.

2. Sodium (Na■)

Physiology & Homeostasis

Total body sodium content determines extracellular fluid volume. Plasma sodium concentration, however, primarily reflects the relative balance of free water to sodium. The kidneys regulate both sodium excretion (via the RAAS and ANP) and free water excretion (via ADH/vasopressin acting on aquaporin-2 in the collecting duct).

Approximate renal handling: proximal tubule reabsorbs ~65% isosmotically; thick ascending limb ~25% (site of loop diuretics); distal convoluted tubule ~5–8% (thiazide-sensitive NCC); collecting duct 3–5% (aldosterone-regulated ENaC and ADH-regulated water channels).

Calculated serum osmolality ≈ 2 × [Na■] + glucose/18 + BUN/2.8. Effective osmoles (sodium and glucose) drive water movement across cell membranes; urea is an ineffective osmole because it freely permeates cells.

Hyponatremia (Na■ < 135 mEq/L)

Classification by extracellular volume status is the essential first step:

Hypovolemic hyponatremia — true sodium and water loss with relatively greater sodium loss or subsequent free-water replacement. Renal causes: diuretics (especially thiazides), cerebral salt wasting, mineralocorticoid deficiency. Extrarenal: gastrointestinal losses, burns, third-spacing. Urine Na■ > 20 mEq/L suggests renal losses; < 20 suggests extrarenal. Treat with isotonic saline to restore volume; once euvolemic, the stimulus for ADH dissipates.

Euvolemic hyponatremia — most commonly SIADH (ectopic ADH from small-cell lung cancer, CNS disorders, drugs, pneumonia). Also hypothyroidism and glucocorticoid deficiency. Diagnostic criteria: low plasma osmolality, urine osmolality > 100 mOsm/kg (inappropriately concentrated), urine Na■ usually > 40 mEq/L, clinical euvolemia, and exclusion of thyroid/adrenal disease. Treatment: fluid restriction (800–1000 mL/day); hypertonic saline for severe symptoms; vaptans or demeclocycline for refractory cases.

Hypervolemic hyponatremia — CHF, cirrhosis, nephrotic syndrome. Effective arterial underfilling stimulates ADH and RAAS despite total body volume overload. Urine Na■ typically low. Treat the underlying disease and restrict free water; loop diuretics may help.

Critical Correction Rule: In chronic hyponatremia, do not raise serum Na■ more than 8–10 mEq/L in 24 hours (many experts now target 4–6 mEq/L). Overly rapid correction risks osmotic demyelination syndrome (central pontine myelinolysis). In acute symptomatic hyponatremia with seizures or deep coma, a rapid 4–6 mEq/L rise with 100–150 mL 3% saline boluses is appropriate to stop seizures, after which slower correction continues.

Hypernatremia (Na■ > 145 mEq/L)

Almost always indicates a relative free-water deficit. Causes are classified by volume status: hypovolemic (renal or extrarenal pure water or hypotonic fluid losses), euvolemic (diabetes insipidus—central or nephrogenic), and rare hypervolemic (iatrogenic sodium load).

Free-water deficit ≈ TBW × ([Na■]/140 – 1), where TBW is approximately 0.6 × body weight in men and 0.5 × in women. Correct slowly (≤ 0.5 mEq/L per hour or 10–12 mEq/L per day) to avoid cerebral edema. Use hypotonic fluids (D5W or 0.45% saline) after initial volume resuscitation if hypovolemic. Central DI responds to desmopressin; nephrogenic DI may respond to thiazides plus amiloride.

3. Potassium (K■)

Physiology

Approximately 98% of total body potassium resides inside cells. Serum potassium therefore reflects both total body stores and the distribution between intracellular and extracellular compartments. Daily intake is 50–100 mEq; the kidney excretes the bulk via principal cells of the cortical collecting duct (ROMK channel), driven by aldosterone, distal sodium delivery, and tubular flow rate.

Transcellular shifts are clinically critical: insulin, β■-agonists, and alkalosis drive K■ into cells; acidosis, hyperosmolarity, β-blockers, digoxin toxicity, and cell lysis drive K■ out of cells. A change in pH of 0.1 units roughly corresponds to a reciprocal change in serum K■ of ~0.5 mEq/L.

Hypokalemia (K■ < 3.5 mEq/L)

Causes include gastrointestinal losses (diarrhea, vomiting, laxatives), renal losses (diuretics, mineralocorticoid excess, Bartter and Gitelman syndromes, magnesium deficiency, RTA), and transcellular shifts (insulin, catecholamines, alkalosis, thyrotoxic periodic paralysis). Clinical features range from muscle weakness and constipation to respiratory failure and rhabdomyolysis. ECG shows flattened T waves, prominent U waves, ST depression, and prolonged QT; arrhythmias are common.

Treatment: oral potassium chloride for mild-moderate cases (20–40 mEq doses). Intravenous replacement for severe or symptomatic patients at ≤ 10 mEq/h via peripheral line (up to 20 mEq/h centrally with continuous monitoring). Always replete magnesium concurrently—hypomagnesemia renders potassium repletion refractory.

Hyperkalemia (K■ > 5.0 mEq/L)

Most often caused by impaired renal excretion (AKI, CKD, ACE inhibitors/ARBs, potassium-sparing diuretics, NSAIDs, hypoaldosteronism) or transcellular shifts (acidosis, cell lysis, succinylcholine). Pseudohyperkalemia from hemolyzed samples must be excluded.

ECG progression (not strictly sequential): peaked T waves → flattened P waves → prolonged PR → widened QRS → sine-wave pattern → ventricular fibrillation or asystole. Any ECG change constitutes a medical emergency.

Emergency sequence: (1) Calcium gluconate 1–2 g IV (membrane stabilization—onset minutes, does not lower K■); (2) Insulin 10 units + dextrose (shift); (3) Nebulized albuterol; (4) Sodium bicarbonate if acidotic; (5) Remove potassium (loop diuretics, binders such as patiromer or sodium zirconium cyclosilicate, or dialysis).

4. Calcium (Ca^{2}■)

Regulation Axis

Ionized calcium is tightly regulated by parathyroid hormone (PTH), 1,25-dihydroxyvitamin D, and to a lesser extent calcitonin. Falling ionized Ca^{2}■ stimulates PTH, which increases bone resorption, renal calcium reabsorption in the distal tubule, and activation of 1α-hydroxylase in the kidney (producing active vitamin D that enhances intestinal absorption of calcium and phosphate). FGF23 provides an additional phosphate- and vitamin D–related feedback loop.

Approximately 40% of total serum calcium is bound to albumin. Corrected calcium ≈ measured calcium + 0.8 × (4 – albumin). In critically ill patients, ionized calcium measurement is preferred. Acidosis increases the ionized fraction; alkalosis decreases it.

Hypocalcemia

Common causes: post-surgical hypoparathyroidism, vitamin D deficiency, chronic kidney disease, severe hypomagnesemia, acute pancreatitis, massive transfusion (citrate binding), and alkalosis. Clinical hallmarks are neuromuscular irritability (Chvostek and Trousseau signs), perioral and acral paresthesias, tetany, seizures, laryngospasm, and prolongation of the QT interval.

Acute symptomatic hypocalcemia is treated with intravenous calcium gluconate (1–2 g over 10–20 minutes) followed by continuous infusion. Magnesium must be repleted simultaneously. Chronic management uses oral calcium plus active vitamin D (calcitriol).

Hypercalcemia

More than 90% of cases are due to primary hyperparathyroidism (outpatient setting) or malignancy (inpatient setting—PTHrP, osteolytic metastases, or extrarenal 1,25-OH vitamin D production). Other causes include granulomatous disease, vitamin D toxicity, thiazides, lithium, thyrotoxicosis, and immobilization.

Classic mnemonic: “bones, stones, abdominal groans, and psychiatric overtones.” Additional findings include polyuria (nephrogenic DI), short QT interval, and constipation. Severe hypercalcemia (>14 mg/dL) or symptomatic patients require aggressive intravenous saline, calcitonin (rapid onset), and a bisphosphonate or denosumab. Steroids are useful in granulomatous disease or lymphoma. Dialysis is reserved for refractory cases or renal failure.

5. Magnesium (Mg^{2+})

Magnesium is an essential cofactor for hundreds of enzymatic reactions, including those involved in ATP metabolism and nucleic acid synthesis. It stabilizes the neuromuscular junction and cardiac conduction system. Serum levels poorly reflect total body stores because most magnesium is intracellular or in bone.

Hypomagnesemia

Frequent causes: gastrointestinal losses, alcoholism, loop and thiazide diuretics, proton-pump inhibitors, malnutrition, cisplatin, amphotericin B, and the “hungry bone” syndrome after parathyroidectomy. Clinically it produces neuromuscular irritability, tremors, tetany, seizures, and arrhythmias—most notably torsades de pointes. It also causes refractory hypokalemia and hypocalcemia because magnesium is required for PTH secretion and potassium channel function.

Treatment of severe or symptomatic hypomagnesemia is intravenous magnesium sulfate 1–2 g over 15–60 minutes with cardiac monitoring. Oral supplementation (magnesium oxide or citrate) is used for milder deficits. Dose cautiously in renal failure.

Hypermagnesemia

Rare outside the setting of renal failure plus exogenous magnesium (antacids, laxatives, or therapeutic infusions). Clinical progression: nausea and flushing (3–5 mg/dL) $\rightarrow$ loss of deep tendon reflexes and hypotension (5–7 mg/dL) $\rightarrow$ respiratory depression, heart block, and cardiac arrest (>7–12 mg/dL). Treatment consists of stopping the source, intravenous calcium as a physiologic antagonist, loop diuretics with saline, and dialysis when necessary.

6. Phosphate (PO■)

Phosphate is critical for high-energy phosphate compounds (ATP, creatine phosphate), red-cell 2,3-DPG, bone mineralization, and buffering systems. Regulation is closely linked to calcium via PTH, FGF23, and vitamin D.

Hypophosphatemia

Major causes: refeeding syndrome, insulin therapy (especially in DKA), respiratory alkalosis, hungry-bone syndrome, vitamin D deficiency, and phosphate-binding antacids. Severe hypophosphatemia (<1.0 mg/dL) can produce profound muscle weakness, rhabdomyolysis, hemolysis, respiratory failure, seizures, and cardiomyopathy. Treatment is oral phosphate for mild cases; careful intravenous sodium or potassium phosphate for severe deficiency, watching closely for hypocalcemia and arrhythmias.

Hyperphosphatemia

Most common in acute or chronic kidney disease. Other causes include tumor lysis syndrome, rhabdomyolysis, hypoparathyroidism, and excessive intake or vitamin D toxicity. Consequences include secondary hyperparathyroidism, metastatic calcification, and symptomatic hypocalcemia. Management focuses on dietary restriction, phosphate binders (sevelamer, calcium-based, lanthanum), treatment of the underlying cause, and dialysis when indicated.

7. Integrated Clinical Cases

Case 1 — Euvolemic Hyponatremia

A 68-year-old man with known small-cell lung cancer is brought in for progressive confusion and lethargy. Serum Na■ is 118 mEq/L, measured serum osmolality 250 mOsm/kg, urine osmolality 520 mOsm/kg, and urine Na■ 65 mEq/L. He appears clinically euvolemic. Glucose and lipid panel are normal; TSH and cortisol are within normal limits.

Diagnosis: SIADH secondary to small-cell lung cancer. The combination of hyponatremia, low plasma osmolality, inappropriately concentrated urine, high urine sodium, and euvolemia with normal thyroid and adrenal function fulfills classic SIADH criteria.

Management: Free-water restriction is first-line for mild symptoms. For severe neurologic symptoms, administer 100–150 mL boluses of 3% saline to raise Na■ by 4–6 mEq/L acutely, then slow further correction. Tolvaptan or demeclocycline may be considered for refractory chronic SIADH once the acute phase has passed. Monitor Na■ every 2–4 hours during active correction.

Case 2 — Life-Threatening Hyperkalemia

A 72-year-old woman with stage 4 CKD, diabetes, and HFrEF on lisinopril and spironolactone presents with progressive weakness. Serum K■ is 7.1 mEq/L. ECG demonstrates peaked T waves and QRS widening. Blood pressure is 105/60 mmHg with mild volume overload.

Immediate actions (in order): (1) Calcium gluconate 1–2 g IV over 2–5 minutes to stabilize the cardiac membrane; (2) Regular insulin 10 units IV plus 1–2 amps of D50; (3) Nebulized albuterol 10–20 mg; (4) Hold ACE inhibitor and spironolactone; (5) Consider loop diuretic if volume status permits; (6) Urgent nephrology consultation for possible dialysis given advanced CKD and ECG changes. Continuous cardiac monitoring is mandatory.

Case 3 — Post-Thyroidectomy Hypocalcemia

A 45-year-old woman undergoes total thyroidectomy for Graves disease. Eighteen hours postoperatively she develops perioral numbness, finger paresthesias, and carpopedal spasm. Chvostek sign is positive. Total calcium is 6.8 mg/dL, albumin 3.9 g/dL, magnesium 1.4 mg/dL, and PTH is low.

Diagnosis: Acute hypoparathyroidism with concurrent mild hypomagnesemia. Accidental removal or ischemia of the parathyroid glands is the most common cause of post-thyroidectomy hypocalcemia; symptoms typically peak at 24–48 hours.

Management: Administer intravenous calcium gluconate until neuromuscular symptoms resolve, then continue a calcium infusion. Replete magnesium aggressively (magnesium is required both for PTH secretion and for end-organ responsiveness to PTH). Transition to oral calcium carbonate or citrate plus calcitriol. Monitor ionized calcium frequently. If permanent hypoparathyroidism develops, lifelong calcium and active vitamin D replacement will be required.

8. ECG Correlations & Comparison Tables

Classic ECG Findings by Electrolyte Disorder

Disorder	Classic ECG Findings	Principal Risk
Hyperkalemia	Peaked T → flat P → wide QRS → sine wave	VT / VF / asystole
Hypokalemia	Flattened T, prominent U waves, ST depression, long QT	VT / torsades
Hypercalcemia	Shortened QT interval, bradycardia	AV block
Hypocalcemia	Prolonged QT (mainly ST segment)	Torsades de pointes
Hypomagnesemia	Prolonged QT, U waves, polymorphic VT	Torsades (classic trigger)
Hypermagnesemia	Prolonged PR & QRS, complete heart block	Asystole

Hypo- versus Hyper- State Quick Comparison

Ion	Hypo — Key Features	Hyper — Key Features
Na■	Confusion, seizures; classify by volume status first	Thirst, lethargy, seizures if acute; free-water deficit
K■	Weakness, U waves, ileus; always replete Mg concurrently	Peaked T, wide QRS; calcium first, then shift, then remove
Ca²■	Tetany, long QT, Chvostek/Trousseau signs	Bones, stones, groans; short QT; hydrate + calcitonin + bisphosphonate
Mg²■	Refractory hypoK & hypoCa, torsades de pointes	Loss of DTRs → respiratory arrest → heart block
PO■	Refeeding, weakness, hemolysis, respiratory failure	CKD, metastatic calcification, secondary hyperparathyroidism

9. Practical Framework & Must-Know Numbers

Six-Step Approach to Any Electrolyte Disorder

1. Confirm the laboratory value (rule out hemolysis, lab error, improper timing or sample handling).

2. Assess clinical severity and obtain an ECG immediately for potassium, calcium, and magnesium abnormalities.

3. Determine volume status by physical examination and, when relevant, urine electrolytes and osmolality.

4. Identify the dominant mechanism (renal versus extrarenal losses, transcellular shifts versus total-body deficit/excess).

5. Treat life-threatening manifestations first (membrane stabilization, seizures, arrhythmias), then correct the underlying cause.

6. Monitor the response closely and avoid overcorrection—especially of sodium.

Must-Know Thresholds & Doses

Sodium correction ceiling (chronic): ≤ 8–10 mEq/L in 24 h (many target 4–6)

Hyperkalemia membrane stabilization: Calcium gluconate 1–2 g IV over 2–5 min

Severe hypokalemia IV rate: ≤ 10 mEq/h peripheral (20 mEq/h central + monitor)

Symptomatic hypocalcemia: Calcium gluconate 1–2 g IV over 10–20 min

Torsades de pointes magnesium: 1–2 g IV over 1–2 min (or 15 min if stable)

Severe hypercalcemia sequence: IV NS → calcitonin → bisphosphonate/denosumab

Free-water deficit formula: TBW × ([Na■]/140 – 1)

Corrected calcium formula: Measured Ca + 0.8 × (4 – albumin)

10. Key Clinical Pearls & Summary

- Always correct magnesium before or together with potassium; otherwise hypokalemia will be refractory.
- In hyponatremia, the first decision is volume status; laboratory tests (urine Na, Uosm) confirm the clinical impression.
- Hyperkalemia with any ECG change is a true emergency—calcium first, then shift, then remove.
- Post-thyroidectomy hypocalcemia typically peaks at 24–48 hours; monitor ionized calcium and PTH.
- Refeeding syndrome produces precipitous drops in phosphate, potassium, and magnesium; anticipate and replete early.
- Never administer intravenous potassium faster than 10 mEq/h through a peripheral line without continuous cardiac monitoring.
- SIADH requires euvolemia + low plasma osmolality + inappropriately high urine osmolality + high urine sodium + normal thyroid and adrenal function.
- Serum potassium is a poor surrogate for total body stores; large deficits can exist with near-normal serum values, and vice versa.
- Osmotic demyelination is largely preventable by disciplined, slow correction of chronic hyponatremia.
- Ionized calcium is preferred over corrected total calcium in critically ill patients with abnormal albumin or acid-base status.

This guide is intended for educational purposes for clinicians, residents, medical students, and advanced practice providers. Always integrate laboratory data with the full clinical picture and institutional protocols. For the accompanying high-yield PowerPoint presentation, see the Sinoe Medical Association educational materials series.

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