Acid–Base Balance

Basics

Definitions

- **Acid-base balance:** Mechanisms maintaining blood/body fluid **pH** within a narrow optimal range
- **Acids: [H+] donor**
- **Alkalis (bases): [H+] acceptor**
- **Physiologic note:** Positively charged ions = "acids"; negatively charged ions = "bases"

Body Acids

- **Volatile acids: Carbonic acid (H_2CO_3)** (weak acid; partially dissociated)
  - **Equation: $CO_2 + H_2O \rightleftarrows H_2CO_3 \rightleftarrows H^+ + HCO_3^-$** (CA-mediated)
  - **Elimination: CO_2** via lungs
- **Non-volatile acids:** Strong acids (completely dissociate)
  - **Examples:** Sulfuric acid, phosphoric acid, other organic acids
  - **Daily load: ~150 mEq/day** (~1 mEq/kg/day)
  - **Elimination:** Kidneys (urine)

pH Regulation

- **Normal arterial pH range: 7.35–7.45** (goal ≈ 7.4)
- **pH definition:** Quantitative measure of acidity/basicity
- **Equation: $pH = -\log[H^+]$**
- **Clinical thresholds:**
  - **pH < 7.35:** Acidosis
  - **pH > 7.45:** Alkalosis
  - **pH < 7.2:** Cellular functions seriously impaired
  - **pH < 6.8:** Incompatible with life
  - **pH > 7.55:** Cellular functions seriously affected
  - **pH > 7.8:** Incompatible with life
- **Why [H+] matters:** Enzymes, ion movement, nerve impulses, muscle contraction

Lines of Defense Against pH Change

- **Buffer systems: 1st line**; fastest (seconds)
- **Respiratory system: 2nd line**; minutes
- **Renal system: 3rd line**; most powerful; hours–days
- **Response to acidosis:** Buffers absorb **H^+**; lungs ↑ ventilation (↓ **CO_2**); kidneys ↑ **H^+** excretion + ↑ **HCO_3^-** reabsorption/production
- **Response to alkalosis:** Buffers release **H^+**; lungs ↓ ventilation (↑ **CO_2**); kidneys ↓ **H^+** excretion + ↓ **HCO_3^-** reabsorption/production

Buffer systems

General concepts

- **Buffer components:** Weak acid + conjugate base pair
- **Buffer function:** Prevent major pH change when acid/base added/removed
- **Important limitation:** Buffers **do not eliminate or add H+** from body

Dominant buffers by compartment

- **ECF major buffer:** Bicarbonate buffer system
- **Blood major buffers:** Hemoglobin (**best**) + bicarbonate
- **ICF major buffer:** Proteins (**best**) + phosphate
- **Urine buffers:** Ammonia + phosphate

Specific buffer systems

- **Bicarbonate buffer:** Weak acid **H_2CO_3** / base **HCO_3^-**
  - **With base: $H_2CO_3 + NaOH \rightarrow NaHCO_3 + H_2O$**
  - **With acid: $NaHCO_3 + HCl \rightarrow H_2CO_3 + NaCl$**
- **Phosphate buffer: $H_2PO_4^-$ / HPO_4^{2-}**
  - **With base: $NaH_2PO_4 + NaOH \rightarrow Na_2HPO_4 + H_2O$**
  - **With acid: $Na_2HPO_4 + HCl \rightarrow NaH_2PO_4 + NaCl$**
- **Protein buffer:** Plasma & cells; amino groups (+) and carboxyl groups (–) bind **H+ / OH–**
- **Hemoglobin buffer:** In erythrocytes; key in **CO_2** transport (tissue → lungs)

Respiratory regulation

- **Stimuli:** Blood **[H+]** and **pCO_2**
- **Receptors:** Central chemoreceptors (medulla) + peripheral chemoreceptors (carotid bodies, aortic arch)
- **If ↓ pH (↑ H+):** ↑ ventilation → ↓ **pCO_2** → ↑ pH
- **If ↑ pH (↓ H+):** ↓ ventilation → ↑ **pCO_2** → ↓ pH

Acid-base disturbances

Classification

- **Metabolic disorders:** Kidney-related; abnormal intake/output
- **Respiratory disorders:** Respiratory system-related
- **Acidosis:** Systemic ↑ **H+** concentration
- **Alkalosis:** Systemic ↓ **H+** concentration

Metabolic acidosis

Definition

- **Metabolic acidosis:** Primary ↓ blood **HCO_3^-**

Etiology

- **High anion gap metabolic acidosis (HAGMA):** ↑ acids
  - **Exogenous acids:** Methanol, ethylene glycol, paraldehyde, **NH_4Cl**, salicylates
  - **Endogenous acids:** Lactic acidosis; ketoacidosis (DKA, starvation)
  - **↓ Renal acid excretion:** Uremia (CKD); **Type 1 (distal) RTA**; **Type 4 RTA**
- **Normal anion gap metabolic acidosis (NAGMA):** ↓ **HCO_3^-** (loss)
  - **Renal loss: Type 2 (proximal) RTA**
  - **GIT loss: Diarrhea**, tube drainage, ureteral diversion (e.g., ileal loop)

✧ Clinical Picture

- **Cause-specific clues:**
  - **DKA:** Fruity breath odor; polyuria; polydipsia
  - **Lactic acidosis:** Hypoxia/hypotension/shock history
  - **Renal failure:** Refer to CKD/AKI context
- **Acidosis symptoms:**
  - **Neurologic:** Headache; altered mental status
  - **Respiratory:** Kussmaul breathing (rapid, deep) for **CO_2** washout
  - **GIT:** Anorexia; nausea/vomiting; diarrhea; abdominal discomfort
  - **Cardiac:** Myocardial depression; hypotension; arrhythmias (e.g., ventricular fibrillation)
  - **Bone:** Decalcification in chronic cases; bone pain

✧ Treatment

- **Cause treatment:** Primary priority
- **Severe acidosis:** Consider **$NaHCO_3$**
- **Renal failure with acidosis:** May need dialysis

Metabolic Alkalosis

✧ Definition

- **Metabolic alkalosis:** Primary ↑ serum **HCO_3^-**

✧ Causes

- **Intracellular shift of H^+:** Hypokalemia
- **Hydrogen loss / HCO_3^- gain:**
  - **GI H^+ loss:** Vomiting; NG suction; congenital chloride diarrhea
  - **Renal H^+ loss:** Loop/thiazide diuretics; contraction alkalosis; mineralocorticoid excess; Bartter/Gitelman syndromes
  - **HCO_3^- gain:** Milk-alkali syndrome; ingestion of **$NaHCO_3^-$**
- **Common pattern:** Vomiting + NG suction cause alkalosis via H^+ loss + volume depletion → contraction alkalosis

✧ Clinical Picture

- **History focus:** Vomiting; NG suction; diuretic therapy
- **Neurologic:** Alkalosis → vasoconstriction → ↓ blood flow; confusion; ↓ seizure threshold
- **Respiratory:** Hypoventilation → hypercapnia + hypoxia
- **Cardiac:** ↓ cardiac output; ↓ coronary flow; arrhythmias
- **Metabolic:** Hypokalemia; ↓ ionized **Ca^{2+}**
- **Neuromuscular:** ↑ excitability; cramps/weakness; tetany

✧ Etiology Sorting (Volume Status Approach)

- **Step:** Assess volume status (low vs normal/high)
- **Low volume causes:** Contraction alkalosis; diuretics; vomiting; NG suction; Bartter/Gitelman
- **Normal/high volume causes:** Mineralocorticoid excess
- **Hyperaldosteronism patterns:**
  - **Primary:** Aldosterone ↑; renin ↓
  - **Secondary:** Aldosterone ↑; renin ↑
  - **Other:** Exogenous steroids; licorice ingestion; Liddle syndrome (aldosterone ↓; renin ↓)

✧ Treatment

- **Cause treatment:** Primary priority
- **Volume depletion: Normal saline**
- **Severe hypokalemia: KCl** (oral or IV)
- **If pH > 7.5: HCl infusion** or **NH4Cl**
- **Avoid:** Ringer's lactate (lactate → **HCO3–**; worsens alkalosis)

Respiratory Disorders

✧ Respiratory Acidosis

- **Definition:** ↑ arterial **PCO2** + ↓ pH
- **Mechanism:** Alveolar hypoventilation → CO2 retention → ↑ **PCO2**
- **Expected compensation:** Renal ↑ **HCO3–** reabsorption + ↑ **H+** excretion
- **Etiology:** Hypoventilation causes
  - **Obstructive:** COPD; asthma
  - **Restrictive:** Interstitial lung disease; massive effusion; marked obesity
  - **Neuromuscular:** CNS depression (opiates, barbiturates); head injury; ALS; Guillain-Barré; myasthenia gravis; myopathies

✧ Respiratory Alkalosis

- **Definition:** ↓ arterial **PCO2** + ↑ pH
- **Mechanism:** Alveolar hyperventilation → CO2 washout → ↓ **PCO2**
- **Expected compensation:** Renal ↓ **HCO3–** reabsorption + ↓ **H+** excretion
- **Etiology:** Hyperventilation causes
  - **Hypoxia-associated:** Pneumonia; pulmonary embolism; pulmonary edema; high altitude
  - **Other:** Anxiety/panic; pain; fever; salicylate toxicity; sepsis

ABG Interpretation

✧ Normal Values

- **pH: 7.35–7.45** (average **7.4**)
- **PaCO2: 35–45 mmHg** (average **40**)
- **HCO3–: 22–28 mEq/L** (average **24**)
- **PaO2: 75–100 mmHg**
- **SpO2: 95–100%**

✧ Step 1: Validity Check

- **Calculate [H+]: H+ = 24 × (PCO2 / HCO3–)**
- **pH conversion anchors:**
  - **pH 7.4 ↔ [H+] 40 nmol/L**
  - **Δ1 nmol/L in [H+] ↔ Δ0.01 in pH**
- **Validity rule:** Calculated pH ≈ measured pH = valid; large mismatch = possible error

Step 2: Sample type

- **Arterial:** O2 saturation **>70%**
- **Venous:** O2 saturation **<70%** with PO2 **<40 mmHg**

Step 3: Gas exchange

- **Oxygenation (pO2):** Severe **<40**; moderate **40–59**; mild **60–79**; normal **80–100 mmHg**
- **Ventilation:** Hypercapnia if PaCO2 **>45 mmHg**
- **Respiratory failure:** Type **1**: PO2 **<60**; Type **2**: PCO2 **>45** with PO2 **<80**

Step 4: Primary disorder

- **pH interpretation:** Acidemia **<7.35**; alkalemia **>7.45**; normal/compensated **7.35–7.45**
- **Direction rule:** Same-direction PaCO2 change vs pH → metabolic; opposite-direction → respiratory

Core patterns

Disorder	pH	PaCO2	HCO3−
Metabolic acidosis	↓	↓ (comp)	↓ (primary)
Metabolic alkalosis	↑	↑ (comp)	↑ (primary)
Respiratory acidosis	↓	↑ (primary)	↑ (comp)
Respiratory alkalosis	↑	↓ (primary)	↓ (comp)

Step 5: Compensation formulas

- **Metabolic acidosis (Winters): PaCO2 ≈ 1.5(HCO3−) + 8 ± 2**
- **Metabolic alkalosis: PaCO2 ≈ 0.7(HCO3− − 24) + 40 ± 2**
- **Respiratory acidosis:** Acute HCO3− ↑ **1** per **10** above **40**; chronic ↑ **3.5≈4** per **10** above **40**
- **Respiratory alkalosis:** Acute HCO3− ↓ **2** per **10** below **40**; chronic ↓ **5** per **10** below **40**

Anion gap

- **Formula: AG = Na+ − (Cl− + HCO3−)**
- **Normal AG: 8–12 mEq/L** (lab-specific)
- **If K+ included:** Normal ≈ **12–16 mEq/L**
- **Hypoalbuminemia correction: AGadjusted = AGmeasured + 2.5(4 − Alb)**

Delta ratio (AG elevated)

- **Formula: (AG − 12) / (24 − HCO3−)**
- **Interpretation: <1** = NAGMA + HAGMA; **1–2** = HAGMA only; **>2** = metabolic alkalosis + HAGMA