Acid-Base Disorders: A Practical Approach for Residents

Diagnosis, Compensation, and Clinical Pearls

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Learning Objectives

By the end of this session, residents will be able to:

1. Explain how the body maintains acid-base balance.
2. Confidently interpret an ABG—starting with pH, then $PaCO_2$ and HCO_3^-.
3. Distinguish between the four primary disorders and spot **mixed patterns**.
4. Use the anion gap to narrow causes of metabolic acidosis.
5. Recognize when to treat the disorder vs. the underlying cause.

What is pH?

- pH = -log[H^+], where [H^+] represents the hydrogen ion concentration of a solution.

$$H_2O + CO_2 \rightleftharpoons H^+ + HCO_3^-$$

- More H^+ ions means pH will go down

- Normal pH in blood is 7.35 – 7.45

Physiology Recap

$$H_2O + CO_2 \rightleftharpoons H^+ + HCO_3^-$$

1. **Chemical buffers** (e.g., bicarbonate) act instantly.
2. **Lungs** adjust $PaCO_2$ within minutes.
3. **Kidneys** regulate HCO_3^- reabsorption/excretion over hours to days.

Disorders arise when these systems fail or are overwhelmed.

The ABG Essentials

pH: Acidemia (< 7.35) vs Alkalemia (> 7.45)

$$H_2O + CO_2 \rightleftharpoons H^+ + HCO_3^-$$

$PaCO_2$: Respiratory component. (Changes opposite direction to pH)

HCO_3^-: Metabolic component. (Changes same direction as pH)

Normal ranges: $PaCO_2$ (35 – 45 mmHg), HCO_3^- (22 – 26 mmol/L)

Traditional Steps for Interpreting Acid-Base Disorders

- Step 1 – Identify Primary Disorder
- Step 2 – Assess compensation
- Step 3 – Calculate anion gap
- Step 4 – Calculate Delta-delta (If gap is present, is it the only process?)
- Step 5 – Determine the osmolar gap

Step 1 – Identify Primary Disorder

$$H_2O + CO_2 \rightleftharpoons H^+ + HCO_3^-$$

- **Low pH + High $PaCO_2$** → Respiratory acidosis (e.g., COPD)
- **High pH + Low $PaCO_2$** → Respiratory alkalosis (e.g., anxiety, PE)
- **Low pH + Low HCO_3^-** → Metabolic acidosis (e.g., DKA)
- **Low pH + High HCO_3^-** → Metabolic alkalosis (e.g., vomiting)

Case Example

- **What is this primary acid-base disorder?**
- pH = 7.3 (normal range 7.35 – 7.45)
- $PaCO_2$ = 50 mmHg (normal range 35 – 45)
- HCO_3 = 24 mmol/L (normal range 22 – 26)

Primary Acid-Base Disorders – Quick Reference Table

Disorder	pH	$PaCO_2$ (mmHg)	HCO_3^- (mmol/L)	Key Causes
Respiratory Acidosis	↓ (< 7.35)	↑ (> 45)	Normal (22-26)	COPD, opioid OD, airway obstruction
Respiratory Alkalosis	↑ (>7.45)	↓ (< 35)	Normal (22-26)	Anxiety, PE, sepsis, pain
Metabolic Acidosis	↓ (< 7.35)	Normal (35-45)	↓ (<22)	DKA, lactic acidosis, renal failure
Metabolic Alkalosis	↑ (> 7.45)	Normal (35-45)	↑ (>26)	Vomiting, diuretics, hypokalemia

Normal ranges: $PaCO_2$ (35– 45 mmHg), HCO_3^- (22 – 26 mmol/L)

Step 1 – What is the primary acid-base disorder?

- What is the primary acid-base disorder?
- Patient has pH 7.3, $PaCO_2$ 50 mmHg, HCO_3^- 24 mmol/L

- Answer: Respiratory acidosis

Step 2 – Assess Compensation

- Patient has pH 7.3, $PaCO_2$ 50 mmHg, HCO_3^- 24 mmol/L

- There is a primary respiratory acidosis

- Why is HCO_3^- normal?
- Shouldn't HCO_3 increase to compensate?

$$\mathbf{H_2O + CO_2 \rightleftharpoons H^+ + HCO_3^-}$$

Compensation Rules for Acute Disorders

Primary Disorder	Expected Compensation
Metabolic Acidosis	PCO_2 ↓ = (1.5 x HCO_3^-) + 8 (±2) mmHg
Metabolic Alkalosis	PaCO2 ↑ = (0.7 x HCO_3^-) + 20 mmHg
Respiratory Acidosis	Acute: HCO_3^- ↑ 1 mmol/L per 10 mmHg $PaCO_2$ ↑
Respiratory Alkalosis	Acute: HCO_3^- ↓ 2 mmol/L per 10 mmHg $PaCO_2$ ↓

Normal ranges: $PaCO_2$ (35– 45 mmHg), HCO_3^- (22 – 26 mmol/L)

Step 2 – Assess Compensation

- Patient has pH 7.3, $PaCO_2$ 50 mmHg, HCO_3^- 24 mmol/L
- Why is HCO_3^- normal?
- Compensation for acute respiratory acidosis:
  - HCO_3^- ↑ 1 mmol/L per 10 mmHg ↑ $PaCO_2$
- $PaCO_2$ increased 10 from normal; so HCO_3^- should increase by 1
- Answer: It’s acute – No time for renal compensation.

Step 2 – Assess Compensation (Another Example)

- Patient with chronic COPD brought to hospital for an unrelated issue.
- pH 7.34, $PaCO_2$ 60 mmHg, HCO_3^- 32 mmol/L

- Why is HCO_3 abnormal?

Compensation Rule for Chronic Respiratory Disorders

Disorder	Time frame	Compensation Mechanism	Expected HCO_3^- Change
Chronic Respiratory Acidosis (e.g., COPD)	3-5 days	Kidneys retain HCO_3^-	↑ 4 mmol/L per 10 mmHg ↑ in $PaCO_2$
Chronic Respiratory Alkalosis (e.g., chronic hypoxia at altitude)	> 48 hours	Kidneys excrete HCO_3^-	↓ 5 mmol/L per 10 mmHg ↓ in $PaCO_2$

Normal ranges: $PaCO_2$ (35– 45 mmHg), HCO_3^- (22 – 26 mmol/L)

Chronic vs Acute

- **Chronic COPD patient:** PaCO2 60 mmHg (↑20 from normal)
- Expected HCO_3^- = 24 + [0.4 x (60 – 40)] = 32
- If HCO_3^- is <32, suspect acute-on-chronic (ex. new infection)

- COPD patients: Always check if compensation matches chronicity.

Step 2 – Assess Compensation

- **Metabolic acidosis:** Expect $PaCO_2 = (1.5 \times HCO_3^-) + 8\ (\pm 2)$
- **Metabolic alkalosis:** Expect $PaCO_2 = (0.7 \times HCO_3^-) + 20$
- **Respiratory disorders:** Acute vs chronic compensation.

What if pH is normal?

Scenario: A 65-year-old COPD patient on long-term diuretics (furosemide) presents with worsening shortness of breath and nausea.

Labs: **pH 7.38**, **HCO_3^- 32**, **$PaCO_2$ 55, Na^+ 138, Cl^- 88, K^+ 2.9, Albumin 40**

Chronic respiratory acidosis

HCO_3^- = 24 + 0.4 (55 – 40) = **30 mmol/L**

Actual HCO_3^- = 32 → **Diuretics explains the extra alkalosis.**

So just hold diuretics?

Step 3 – Calculating the Anion Gap (AG)

- **What is an anion gap?**
  The anion gap (AG) is a calculated value that helps identify the cause of metabolic acidosis.

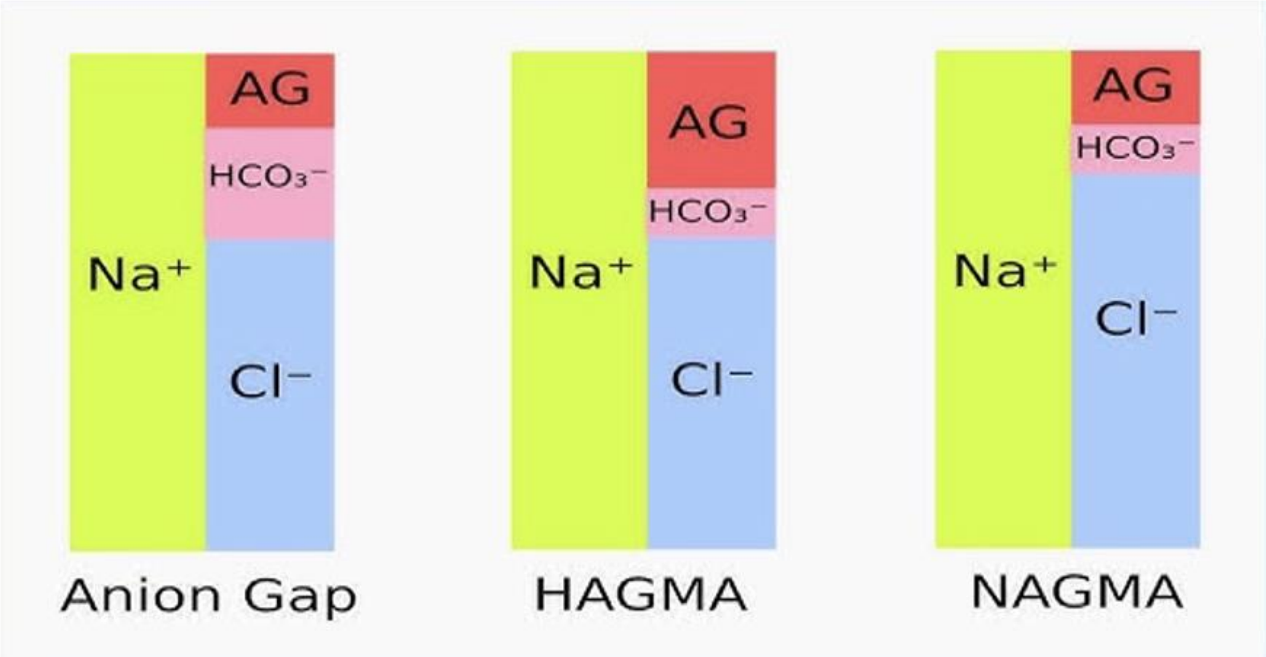
$$\textbf{Anion Gap (AG)} = Na^{+} - (Cl^{-} + HCO_3^{-})$$

The anion gap tells us whether there are "unmeasured" acids in the blood, which can point to serious underlying conditions.

Anion gap

The anion gap is composed of anions that aren’t typically measured in the blood.

One of the main anions is albumin which is a negatively charged protein.



Step 3 – Calculating the Anion Gap (AG)

- **Anion Gap (AG) = Na^+ – (Cl^- + HCO_3^-)**
- (Normal: 8 – 12 mmol/L)
- **Adjust for albumin** (every ↓ in albumin by 10, add 2.5 to the AG)

- **High AG causes (MUDPILES):**
- Methanol, Uremia, DKA, Paraldehyde, Isoniazid (INH), Lactic acidosis, Ethylene glycol, Salicylates.

- **Normal AG (hyperchloremic):** Diarrhea, Renal Tubular Acidosis, Saline infusion.

Calculate Anion Gap

Scenario: A 65-year-old COPD patient on long-term diuretics (furosemide) presents with worsening shortness of breath and nausea.

Labs: **pH 7.38, HCO_3^- 32, $PaCO_2$ 55, Na^+ 138, Cl^- 88, K^+ 2.9, Albumin 40**

If you calculated an anion gap first:

Anion Gap (AG) = Na^+ – (Cl^- + HCO_3^-)

Anion Gap = 138 – (88 + 32)

Anion Gap = 18 mmol/L (normal: 8-12 mmol/L)

If you didn't calculate an anion gap first, you wouldn't have known there was an anion gap.

My Steps for Interpreting Acid-Base Disorders

- Step 1 – Calculate anion gap
- Step 2 - Identify the Primary Disorder
- Step 3 – Assess compensation
- Step 4 – Delta-delta (If gap is present is it the only process?)
- Step 5 – Determine the osmolar gap

Step 4 - Delta-Delta (ΔΔ Ratio) – Mixed Metabolic Disorder

When to Use:

To identify **hidden metabolic disorders** in patients with high anion gap metabolic acidosis (AG > 12 mmol/L) to uncover:

1. **Mixed AGMA + metabolic alkalosis** (e.g., vomiting + DKA)
2. **Mixed AGMA + NAGMA** (e.g., diarrhea + lactic acidosis).

Formula:

- $\Delta\Delta = \Delta AG/\Delta HCO_3^- = (\textit{Patient's AG} - 12)/(24 - \textit{Patient's } HCO_3^-)$

Delta-Delta (ΔΔ Ratio)

ΔΔ Ratio	Interpretation	Clinical Example
~1.0	Pure high-AG acidosis	DKA or lactic acidosis alone.
<1.0	+Non-AG acidosis	DKA + diarrhea (HCO_3^- ↓↓ AG ↑ modestly)
>1.0	+Metabolic alkalosis	Lactic acidosis + vomiting (AG ↑↑, HCO_3^- ↓ less).

Step 4 - Delta-Delta (ΔΔ Ratio) – Mixed Metabolic Disorder

Scenario: A 65-year-old COPD patient on long-term diuretics (furosemide) presents with worsening shortness of breath and nausea.

Labs: **pH 7.38**, **HCO_3^- 32**, **$PaCO_2$ 55, Na^+ 138, Cl^- 88, K^+ 2.9, Albumin 40**

- $\Delta\Delta = \Delta AG/\Delta HCO_3^- = (\textit{Patient's AG} - 12)/(24 - \textit{Patient's } HCO_3^-)$
- $\Delta\Delta = (18-12)/(24-32) = -0.75$

- Doesn't that mean there is a concurrent metabolic acidosis based on the previous slide?

Step 4 - Delta-Delta (ΔΔ Ratio) – Mixed Metabolic Disorder

Scenario: A 65-year-old COPD patient on long-term diuretics (furosemide) presents with worsening shortness of breath and nausea.

Labs: **pH 7.38**, **HCO_3^- 32**, **$PaCO_2$ 55, Na^+ 138, Cl^- 88, K^+ 2.9, Albumin 40**

- ΔΔ = ΔAG/ΔHCO_3^- = (*Patient's AG* – 12)/(24 – *Patient's HCO_3^-*)
- ΔΔ = (18-12)/(24-32) = -0.75

- Doesn't that mean there is a concurrent metabolic acidosis based on the previous slide?
  - No, you can't use delta-delta if bicarbonate is going up.
  - If bicarbonate is going up, you already know there is a concurrent metabolic alkalosis.

Next steps

- Being an astute resident, you appropriately recognized the anion gap metabolic acidosis and sent off the appropriate workup.

- What was the workup again?
- Think of causes of anion gap metabolic acidosis (MUDPILES)

What was the workup again? (MUDPILES)

- M – Methanol
- U – Uremia
- D – DKA
- P – Paraldehyde
- I – Iron, isoniazid
- L – Lactic acidosis
- E – Ethanol , Ethylene glycol
- S – Salicylate/ASA Aspirin

What was the workup again? (MUDPILES)

- M – Methanol – Serum osmolality (or send directly if high suspicion)
- U – Uremia – Renal function (creatinine, urea, phosphate)
- D – DKA – β-hydroxybutyrate, glucose
- P – Paraldehyde – Acetaminophen level
- I – Iron, isoniazid – Only send if high suspicion of iron overdose
- L – Lactic acidosis - Lactate
- E – Ethanol , Ethylene glycol – Send ethanol level (helps with calculating osmol gap)
- S – Salicylate/ASA Aspirin – Send salicylate level

- Repeat VBG or ABG to confirm
- Repeat lytes to monitor anion gap

Your workup returns

- Measured serum osmolality 330 mOsm/kg
- Creatinine 70, Urea 5 mmol/L, Phos 1.0 mmol/L
- β-hydroxybutyrate 0.1 mmol/L, Glucose 5 mmol/L
- Acetaminophen level – not detected
- Lactate 1.2 mmol/L
- Ethanol 0 mmol/L
- Salicylate level – not detected

Repeat VBG: pH 7.32, $PaCO_2$ 45 mmHg, HCO_3 22
Repeat lytes: Na 138, Cl 88, K 2.9, albumin 40

Next step?

Next Step

- Repeat the steps with the new blood gas:

Repeat VBG: pH 7.32, PaCO2 45 mmHg, HCO3 22
Repeat lytes: Na 138, Cl 88, K 2.9, albumin 40

Step 1 – Calculate anion gap

- Anion gap = 138 – 88 – 22 = 28 (increased from 18)

→ Primary anion gap metabolic acidosis (that appears to be widening)

- Step 2 – Determine primary disturbance

- Anion gap metabolic acidosis

Next Step

Repeat VBG: pH 7.32, PaCO2 45 mmHg, HCO3 22
Repeat lytes: Na 138, Cl 88, K 2.9, albumin 40

- Step 3 – Assessing compensation

- Metabolic acidosis: Expect $PaCO_2 = (1.5 \times HCO_3^-) + 8\ (\pm 2)$
- Expected PaCO2 = (1.5 x 22) + 8 (±2)
- Expected PaCO2 = 41 (±2)

- Incomplete respiratory compensation (likely limited by underlying COPD)

Next Step

Repeat VBG: pH 7.32, $PaCO2$ 45 mmHg, $HCO3$ 22
Repeat lytes: Na 138, Cl 88, K 2.9, albumin 40

- Step 4 – Calculate delta-delta
- $\Delta\Delta = \Delta AG/\Delta HCO_3^- = (\textit{Patient's AG} - 12)/(24 - \textit{Patient's } HCO_3^-)$
- $\Delta\Delta = (28 - 12)/(24 - 22)$
- $\Delta\Delta = 8$

$\Delta\Delta > 2$ suggests concurrent metabolic alkalosis (likely from diuretics and intravascular volume depletion)

What next?

Step 5 – Calculate osmol gap – Detecting the Invisible Toxins

What is Osmolar Gap?

- The difference between measured and calculated serum osmolality, revealing unmeasured osmoles (e.g. toxins).

When to Calculate?

- Suspected toxic alcohol ingestion – methanol, ethylene glycol, isopropanol.
- **Unexplained AGMA** (normal lactate/ketones)
- Ex. "Drunk" patient with undetectable ethanol.

Osmolar Gap – Detecting Invisible Toxins

Formula:

Osmolar Gap = Measured Osmolality – Calculated Osmolality

(*Normal gap: < 10 mOsm/kg)*

Calculated Osmolality:

Osmolality = 2 x Na^+ + Glucose + Urea + Ethanol (*if present*)

Step 5 – Calculate osmol gap

- **Measured serum osmolality** 330 mOsm/kg
- Na 138, Urea 5 mmol/L, Glucose 5 mmol/L, Ethanol 0 mmol/L

Calculated Osmolality = 2 x Na^+ + Glucose + Urea + Ethanol
Calculated Osmolality = 2 x 138 + 5 + 5 + 0
Calculated Osmolality = 286 mOsm/kg

Osmol gap = Measured serum osmolality – Calculated serum osmolality
Osmol gap = 330 – 286
Osmol gap = 44 mOsm/kg (normal Osmol gap is <10 mOsm/kg)

There is a large Osmol gap present → think of toxic alcohol ingestion

Interpretation of Osmolar Gap

Osmolar Gap	Suspected Toxin	Clinical Clues
>10 mmol/kg	Methanol	Visual disturbances, abdominal pain
>10 mmol/kg	Ethylene glycol	Renal failure, calcium oxalate crystals
↑↑ (No high AG)	Isopropanol	Ketosis without acidosis

Next steps

- Start IV fomepizole 15mg/kg right away
- Call nephrology to arrange dialysis right away
- Send off a methanol and ethylene glycol level (do not delay treatment to do this)

- Monitor patient's respiratory status (had incomplete compensation) make sure not tiring out. Consider BiPAP.
- Consider intubation if LOC worsens.

Congratulations

- You saved the patient’s life!