ABG'S AND VENTILATORS:
LET'S TALK ABOUT GAS!

Andrew Walker, PSM, MS, PA-C
Physician Assistant
Instructor of Medicine
Critical Care/Internal Medicine
Mayo Clinic Arizona

Amelia Lowell, RRT, RCP
Assistant Professor of Anesthesiology
Director of Respiratory Care
Mayo Clinic Arizona

DISCLOSURES

None.

OBJECTIVES

By the end of this workshop, the learner should be able to:

- Analyze ABGs to determine acid-base disorders, mixed disorders, and compensation.
- Understand and manage basic high flow, CPAP, BiPAP, and Ventilator settings.
- Apply ABGs to clinical scenarios and decision making.

HENDERSON-HASSELBALCH EQUATION

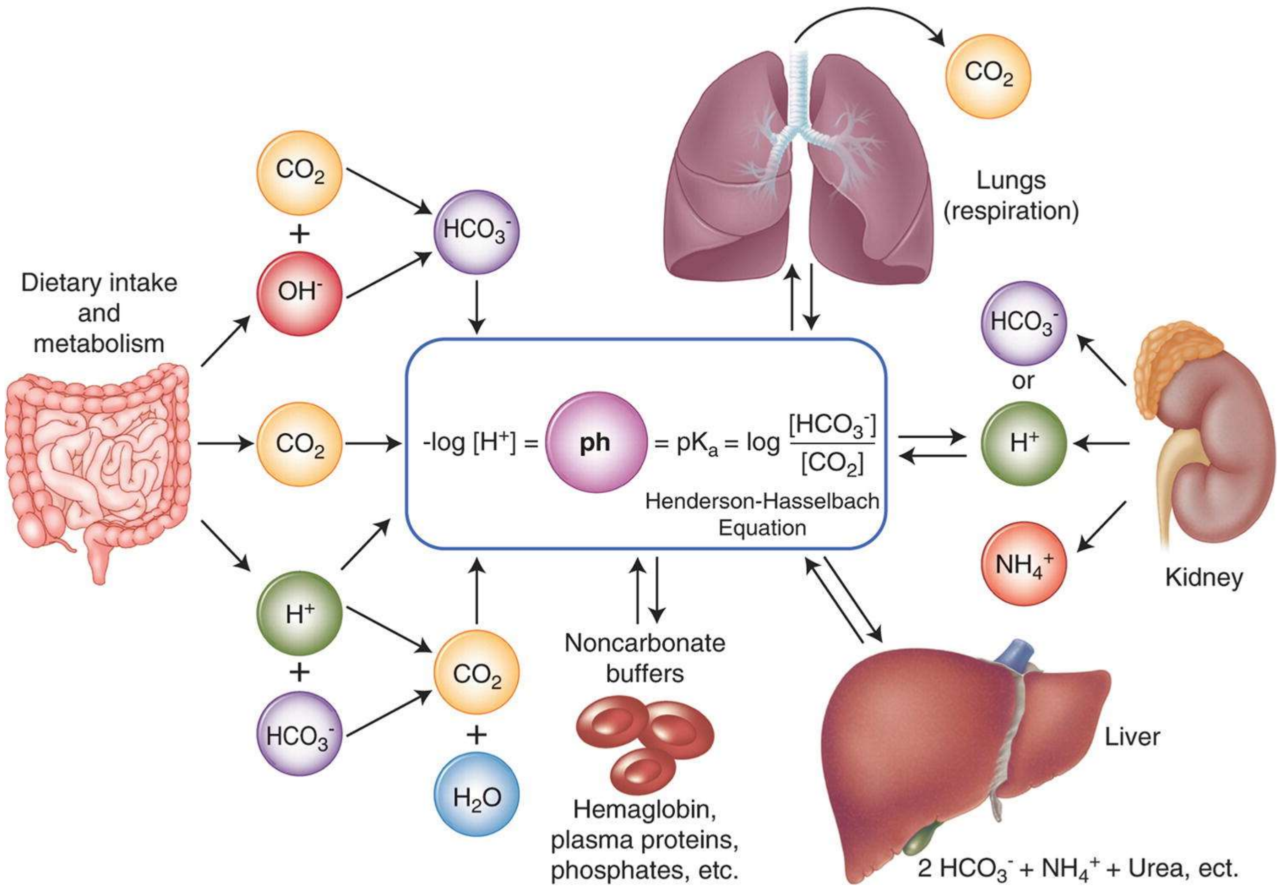
$$pH = pK_a + \log_{10} \frac{[A^-]}{[HA]}$$

[A−] → BASE

[HA] → ACID

- The ratio of base-acid must stay relatively constant for the pH to stay constant
  - Because this is a logarithmic equation, it takes a fairly large change in acid or base to change the pH

ACID-BASE PHYSIOLOGY



COMPONENTS OF THE ABG

Component	Measure
pH	Acid-base balance
PaO_2	Partial pressure of oxygen
$PaCO_2$	State of alveolar ventilation
HCO_3^-	Reflects metabolic component of blood
Alveolar-arterial (A-a) gradient	Gradient between alveolar and arterial oxygen
Base excess*	The amount of acid or base it would take to return the pH back to 7.4

INDICATIONS FOR ABG

- Identify respiratory, metabolic, and mixed acid-base disorders
- Monitoring acid-base status in disorders such as DKA
- Quantification of oxyhemoglobin and oxygen carrying capacity of the patient
- Quantification of levels of dyshemoglobins (methemoglobin, carboxyhemoglobin)

INDICATIONS FOR ABG

- Measuring partial pressures of respiratory gases involved in ventilation and perfusion, e.g….
  - COPD exacerbation
  - Asthma exacerbation
  - Pulmonary embolism
  - Pulmonary fibrosis
  - Pneumothorax
  - In these cases, can measure severity and progression of disease/exacerbation
- Assessment of response to mechanical ventilation

CLINICAL SCENARIOS WHERE ABG'S ARE USEFUL

- Respiratory distress
- Hypoxia
- Airway obstruction
- Sepsis or shock
- DKA
- Renal failure
- Drug overdose or intoxication
- AMS or obtundation
- Monitoring response to invasive and non-invasive ventilation
- Code blue

CONTRAINDICATIONS TO ABG

- Local infection
- Distorted anatomy
- Abnormal Allen test
- AV fistula
- Severe PVD
- Relative contraindications:
  - Anticoagulation, tPA, severe coagulopathy

- Consider a-line if repeat ABGs will be necessary!

BEFORE YOU GET AN ABG

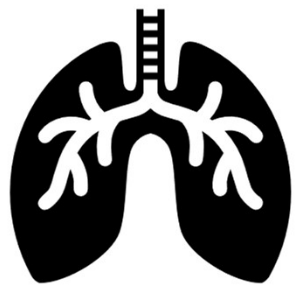
Ask yourself…

1. What am I looking for/expecting?
2. How will the results help guide or change my management?
3. Will comparison be helpful after treatment/intervention?

RESPIRATORY ACIDOSIS

"I can't catch my breath!"

- Rapid, shallow breaths OR bradypnea
- Dyspnea
- Headache
- Disorientation
- Dizziness
- Drowsiness



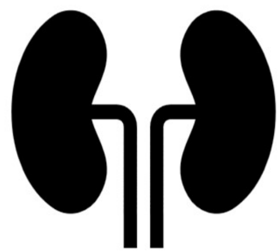
↓pH ↑pCO_2

- Hypoxia
- Hyperkalemia
- Dysrhythmias
- Hyperreflexia
- Muscle Weakness

<u>Retention of CO_2 by the lungs</u>

METABOLIC ACIDOSIS

- Confusion
- Drowsiness
- Headache
- Nausea, Vomiting
- Diarrhea



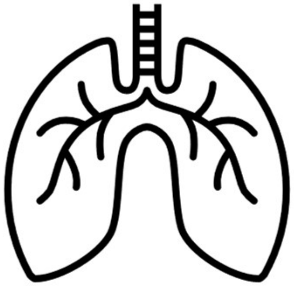
↓pH ↓ HCO_3^-

- Decreased BP
- Hyperkalemia
- Vasodilation
- Kussmaul respirations

Decreased ability of kidneys to excrete acid

RESPIRATORY ALKALOSIS

- Rapid, deep breathing
- Lethargy
- Confusion
- Nausea, vomiting
- Numbness and tingling



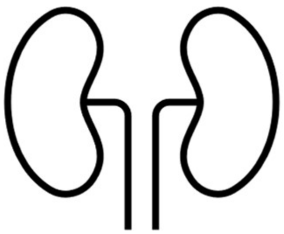
↑pH ↓pCO_2

- Light headedness
- Seizure
- Tachycardia
- Hyperventilation
- Hyperkalemia

Loss of CO_2 from the lungs

METABOLIC ALKALOSIS

- Restlessness → lethargy
- Confusion
- Dizziness
- Irritability
- Nausea, vomiting
- Diarrhea



↑pH ↑HCO_3^-

- Tremors
- Muscle cramping
- Tingling in fingers/toes
- Hypokalemia
- Tachycardia

<u>A decrease in acid or an increase in base</u>

ABG "NORMAL" VALUES

Component	Low Normal	Normal Range	Estimated Normal	High Normal
pH	Acidosis	7.35 – 7.45	7.4	Alkalosis
PaO_2	Hypoxemia	80 – 100 mmHg	100 – (0.3 x age)	Hyperoxia
PCO_2	Respiratory alkalosis	35 – 45 mmHg	40 mmHg	Respiratory acidosis
HCO_3	Metabolic acidosis	22 – 26 mEq/L	24 mEq/L	Metabolic alkalosis
A-a gradient		< 10 mmHg	< 10 mmHg	
Base excess		-3 to +3 mEq/L		

FUNDAMENTALS OF ABG INTERPRETATION

Assume your patient is acutely ill and may have more than one disorder!

1. Look at the pH to determine the primary disorder
2. Does the pCO_2 explain the first disorder?
3. Does the bicarb explain the disorder or is there a mixed disorder?

ABG PRACTICE: STEPS 1-2

- pH low (<7.4) = Acidosis, pH high (>7.4) = Alkalosis
- If pH and PCO2 move in opposite directions, respiratory disorder is primary
- If pH and PCO2 move in the same direction, metabolic disorder is primary

pH	PCO_2	HCO_3	Disorder
7.2	70	28	

pH	PCO_2	HCO_3	Disorder
7.2	30	16	

ABG PRACTICE: STEPS 1-3A

pH	PCO_2	HCO_3	Disorder
7.5	40	31	

pH	PCO_2	HCO_3	Disorder
7.5	30	16	

DIVIDE UP!

ABG VS. VBG

- Why get an ABG instead of a VBG?
- Venous blood gases (VBG) are widely used in the emergency setting
  - There is no data to confirm that this level of agreement is maintained in shock states or mixed acid-base disturbances
  - Quicker: performed by a phlebotomist with other labs
  - Less painful

HOW ABG VALUES COMPARE TO VBG

ABG	VBG
pH	pH + 0.035 units
pCO_2	pCO_2 + 5.7 mmHg *correlation dissociates in hypercapnia and shock
HCO_3	HCO_3 – 1.41 mmol/L
Base excess (BE)	BE + 0.089 mmol/L
Lactate	Does NOT correlate > 2mM
pO_2	Does NOT correlate (venous vs. arterial sample)

CLINICAL APPLICATIONS

- What do acidosis and alkalosis look like?
- What do they imply?
- How dangerous are they?
- What disturbances can they cause in the body?

CLINICAL CONSEQUENCES OF ACIDEMIA

Cardiovascular	• Impaired cardiac contractility • Decreased CO • Decreased systemic BP • Increased PVR • Decreased threshold for arrhythmia
Respiratory	• Hyperventilation with possible muscle fatigue
Neurologic	• Obtundation/coma
Metabolic	• Insulin resistance • Loss of bone and muscle • Protein degradation • Abnormalities in the release of many hormones • Hyperkalemia • Inhibition of anaerobic glycolysis • Reduction in ATP synthesis

CLINICAL CONSEQUENCES OF ALKALEMIA

Cardiovascular	• Reduced coronary blood flow • Reduced threshold for angina • Decreased threshold for arrhythmia
Respiratory	• Hypoventilation with hypercapnia and hypoxemia
Neurologic	• Seizure • Tetany • Lethargy/delirium/stupor
Metabolic	• Hypokalemia • Hypomagnesemia • Hypophosphatemia • Stimulation of anaerobic glycolysis • Decreased oxyhemoglobin dissociation

Acid-base Differentials

CAUSES OF RESPIRATORY ACIDOSIS

- ↓Respiratory stimuli
  - Drug overdose
  - Anesthesia
  - Intracranial issues (TBI, Stroke, SAH, etc.)
- Spinal or peripheral nerve issues (C-spine injury, myasthenia gravis, ALS, peripheral neuropathy, etc.)
- Pulmonary issues (ARDS, asthma, pneumonia, COPD, massive PE/Shock, atelectasis)
- Extrathoracic/abdominal distention (obesity, compartment syndrome)

CAUSES OF METABOLIC ACIDOSIS

MUDPILES

- Methanol
- Uremia
- DKA
- Propylene glycol (Ativan, Dilantin)
- Isoniazid/Iron
- Lactate
- Ethanol/Ethylene glycol
- Salicylates / Seizures / Starvation

USED CRAP

- Ureteroenterostomy
- Small bowel fistula
- Excess chloride*
- Diarrhea
- Carbonic Anhydrase Inhibitors
- Renal Tubular Acidosis (RTA)
- Addison's disease / Acetazolamide
- Pancreatoenterostomy

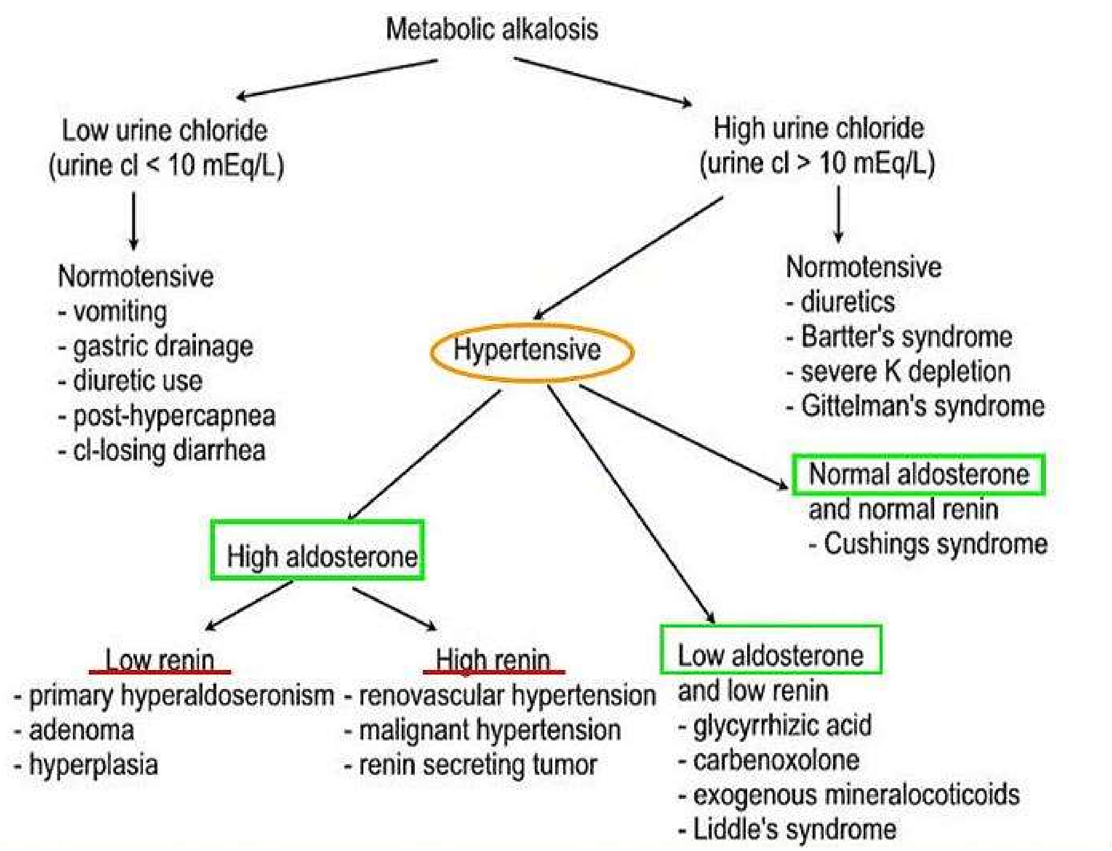
FLUID CHEMISTRY

Fluid	Na	Cl	K	Mg	Ca	HCO_3	Glucose	Osm	pH
Plasma	140	104	4.5	1.25	2.5	24	0.8	290	7.4
0.9% NaCl	154	154						308	5.5
0.45% NaCl	77	77						154	
LR	130	109	4		1.5	28 as lactate		273	6.5
P-lyte	140	98	5	1.5			23 as gluconate	294	7.4
5% Dex							50	252	

CAUSES OF RESPIRATORY ALKALOSIS

- Pain
- Trauma
- Sepsis
- Pulmonary embolism
- Shock
- Drugs
- Pregnancy
- Hyperventilation (think sick first!)
- Mechanical ventilation

CAUSES OF METABOLIC ALKALOSIS



ABG ANALYSIS: THE BIG PICTURE

1. Look at the pH to determine primary disorder

2. Look at PCO2, use in conjunction with pH to determine primary disorder
   - If pH and PCO2 move in opposite directions, respiratory disorder is primary
   - If pH and PCO2 move in the same direction, metabolic disorder is primary

ABG ANALYSIS: THE BIG PICTURE

3. Look for mixed disorder
   - If both pCO_2 and HCO_3 are ↑ ↑ = respiratory acidosis OR metabolic alkalosis
   - If both pCO_2 and HCO_3 are ↓ ↓ = respiratory alkalosis OR metabolic acidosis
   - If pCO_2 and HCO_3 move in opposite direction ↑ ↓ = mixed disorder is present
4. Apply Compensation rules
   - Boston rule
   - Winter's formula
5. Consider calculating Corrected Anion Gap and Delta Gap
6. Clinical Application

ABG PRACTICE: STEP 3

- If both pCO_2 and HCO_3 are ↑ ↑ = respiratory acidosis OR metabolic alkalosis
- If both pCO_2 and HCO_3 are ↓ ↓ = respiratory alkalosis OR metabolic acidosis
- If pCO_2 and HCO_3 move in opposite direction ↑ ↓ = mixed disorder is present

pH	PCO_2	HCO_3	Disorder
7.28	55	19	

ABG PRACTICE: STEP 3

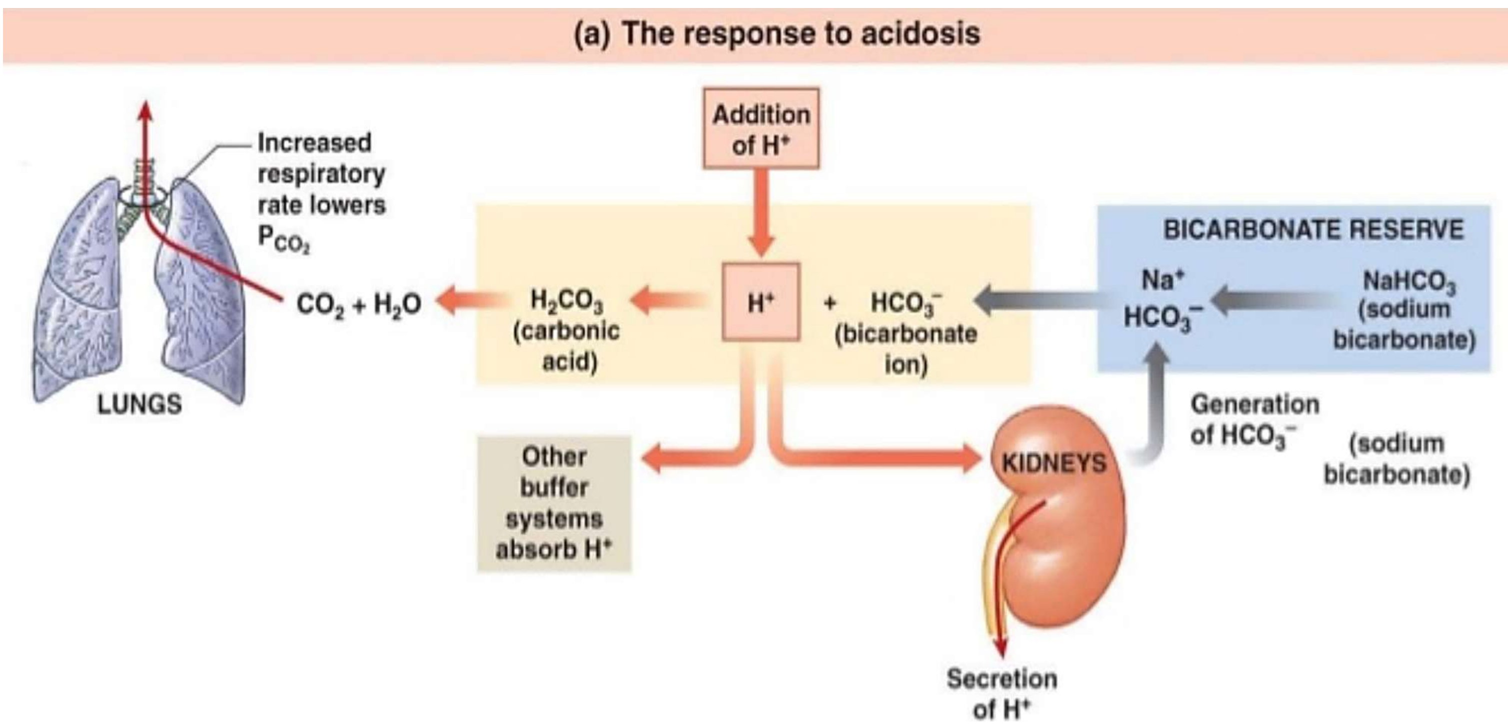
pH	PCO_2	HCO_3	Disorder
7.50	24	28	

COMPENSATION PHYSIOLOGY

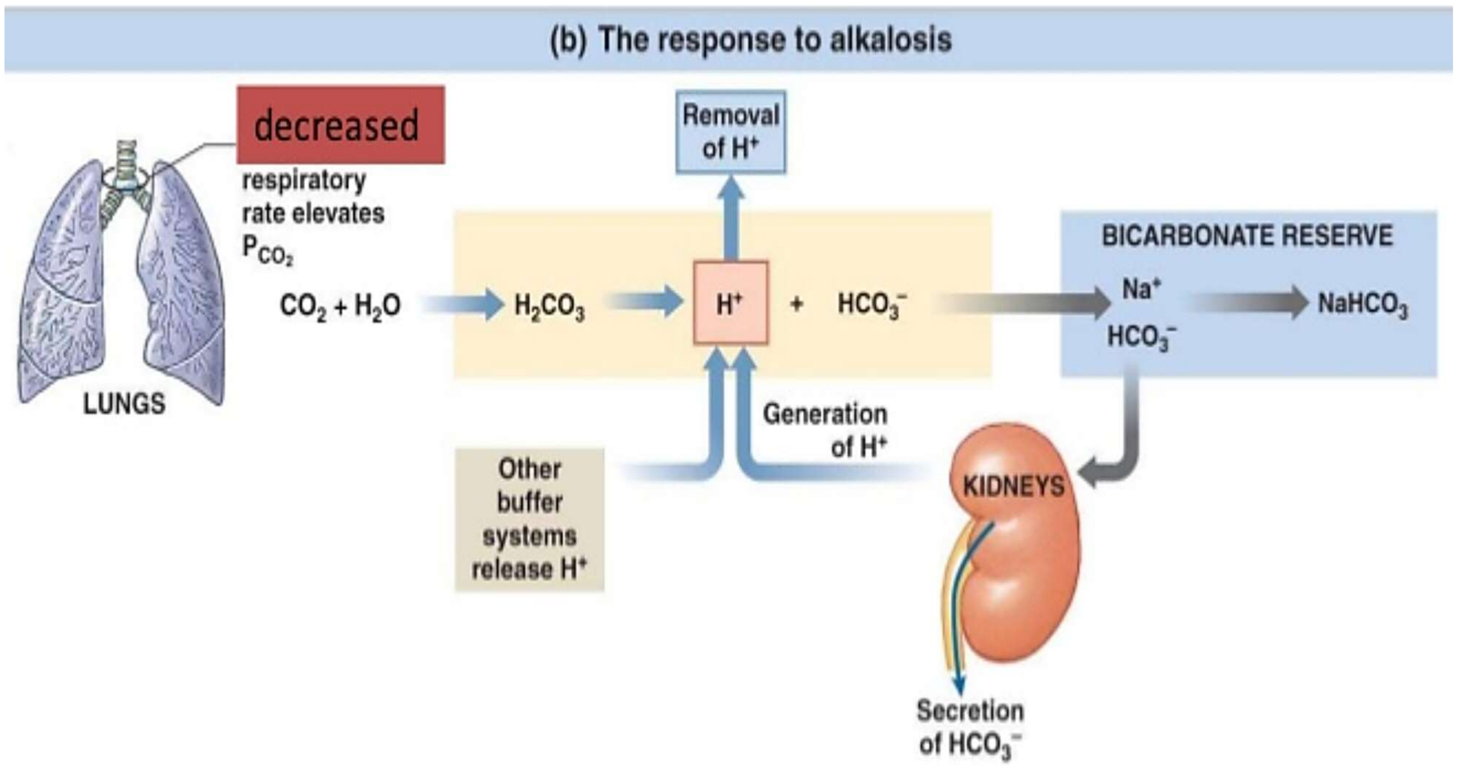
- Respiratory system: maintains pH by regulating CO_2
  - Can compensate quickly
- Renal (metabolic) system: regulates pH by excreting H^+ (acid) or reabsorbing HCO_3^- (base)
  - Several hours to days to compensate

- With the body's ACUTE compensation, the pH will NOT return to normal, but it may get close

BUFFERING SYSTEMS/COMPENSATION



BUFFERING SYSTEMS/COMPENSATION



COMPENSATION

Acid-Base Disorder	Primary Change	Compensatory Change
Respiratory acidosis	PCO_2 ↑	HCO_3 ↑
Respiratory alkalosis	PCO_2 ↓	HCO_3 ↓
Metabolic acidosis	HCO_3 ↓	PCO_2 ↓
Metabolic alkalosis	HCO_3 ↑	PCO_2 ↑

ABG PRACTICE: STEP 4

pH	PCO_2	HCO_3	Disorder
7.5	55	36	

CALCULATING FOR COMPENSATION

- Respiratory Rule #1: pH changes INVERSELY by 0.08 for 10 mm CO_2 in ACUTE cases
  - If CO_2= 50, pH will be 7.32 (0.08 below)
  - If CO_2=30, pH will be 7.48 (0.08 above)

- *DO NOT USE IN CHRONIC CASES…pH usually corrects/compensates to normal (7.4).

CALCULATING FOR COMPENSATION

Boston Rules (to predict changes in HCO_3^- from $PaCO_2$ – respiratory disorders):

Change in CO2	Change in HCO3	Condition	Example
10	1	Acute Resp Acidosis	If CO2=50, HCO3=25
10	2	Acute Resp Alkalosis	If CO2=30, HCO3=22
10	4	Chronic Resp Acidosis	If CO2=50, HCO3=28
10	5	Chronic Resp Alkalosis	If CO2=30, HCO3=19

CALCULATING FOR COMPENSATION

- Winter's Formula (metabolic acidosis):
  - Expected $pCO_2 = 1.5 \times HCO_3 + 8 +/- 2$

- Metabolic Alkalosis
  - Expected $pCO_2 = 0.7 \times [HCO_3^-] + 20$ (+/- 5)

CASE 1

A 26 YO M with asthma presents to the ED with difficulty breathing x 3 days. It is getting progressively worse. He has tried his regular and rescue inhalers; nothing seems to help. He looks pale and is taking rapid, shallow breaths. On exam, he has diffuse wheezing in all lung fields.

Vitals:

- HR – 120
- BP – 113/76
- RR – 28
- SpO_2 – 92%
- Temp – 37.8C

ABG:

- pH – 7.08
- pCO_2 – 80 mmHg
- HCO_3^- – 28 mEq/L

CMP:

- Na – 138 mEq/L (135-145)
- K – 4.0 mmol/L (3.6-5.2)
- Cl – 106 mEq/L (96-106)
- Albumin – 3.8 g/dL (3.5-5.5)
- Phos – 3.0 mg/dL (2.8 – 4.5)

CASE 1

ABG results:

- pH – 7.08
- pCO_2 – 80 mmHg
- HCO_3^- – 28 mEq/L

Respiratory rule #1

pH changes INVERSELY by 0.08 for 10 mm CO2 in ACUTE cases

CASE 2

A 35 YO M presents to the ED with gun shot wound (GSW) to the abdomen. He was found down by a civilian about 20 minutes after the shooting who called 911. Upon arrival, he appears pale, diaphoretic, and is experiencing severe abdominal pain. He is slightly altered and cannot tell you where he is. He has no past medical history.

Vitals:
- HR – 116
- BP – 86/68
- RR – 10
- SpO_2 – 96%
- Temp – 37.6C

ABG:
- pH – 7.18
- pCO_2 – 34 mmHg
- HCO_3^- – 12 mEq/L

CMP:
- Na – 132 mEq/L (135-145)
- K – 3.6 mmol/L (3.6-5.2)
- Cl – 92 mEq/L (96-106)
- Albumin – 3.2 g/dL (3.5-5.5)
- Phos – 2.1 mg/dL (2.8 – 4.5)

CASE 2

ABG:
- pH – 7.18
- pCO_2 – 34 mmHg
- HCO_3^- – 12 mEq/L

Winter's formula (metabolic acidosis)

- Expected PCO_2 in metabolic acidosis:

CASE 2 DDX

calcAG = 132 – [92+12] = 28

Respiratory Acidosis

- ↓respiratory stimulus
- Atelectasis
- Additional injuries?

HAGMA

- MUDPILES:
  - Methanol
  - Uremia
  - DKA
  - Propylene glycol (Ativan, Dilantin)
  - Isoniazid/Iron
  - Lactate
  - Ethanol/Ethylene glycol
  - Salicylates/Seizures/Starvation

ANION GAP (CALCULATED)

- **Anion Gap** = the difference between measured cations (Na^+, K^+) and measured anions (Cl^- and HCO_3^-)

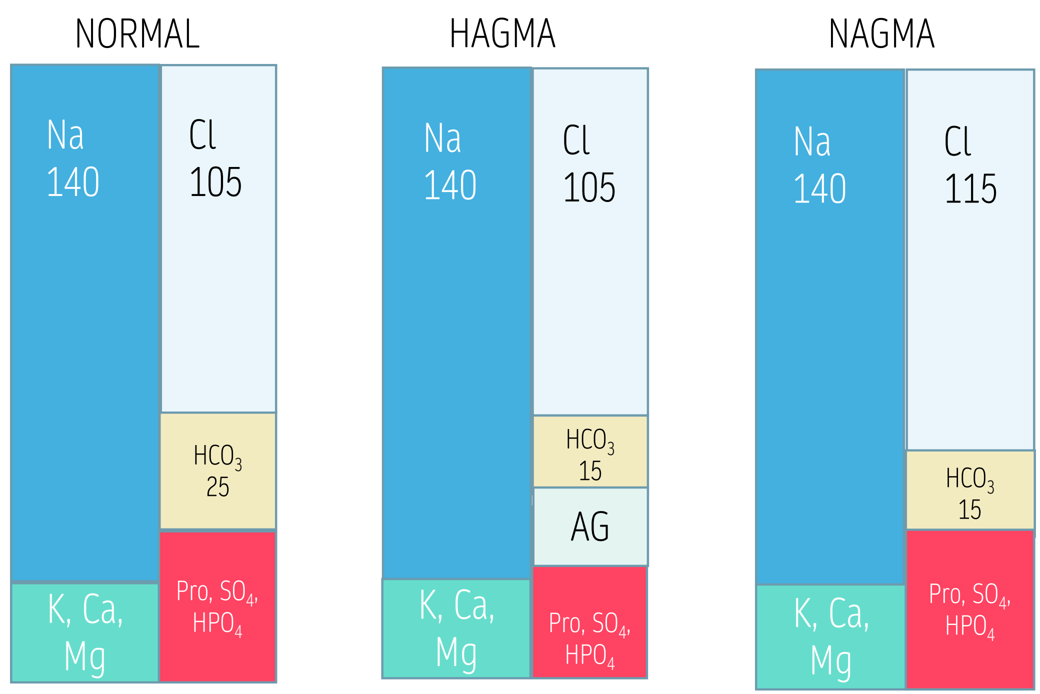
$$= Na - [Cl + HCO_3]$$

Normal range = 4 – 12 mmol/L

*We call this the calculated anion gap (cAG), because it is calculated from the BMP

- Significance?
  - The law of electrochemical neutrality
  - Provides foresight into managing acidosis

HIGH VS. NORMAL ANION GAP METABOLIC ACIDOSIS



HIGH ANION GAP METABOLIC ACIDOSIS (HAGMA)

- Accumulation of or impairment of excretion of acids
- MUDPILES:
  - Methanol
  - Uremia
  - DKA
  - Propylene glycol (Ativan, Dilantin)
  - Isoniazid/Iron
  - Lactate
  - Ethanol/Ethylene glycol
  - Salicylates/Seizures/Starvation

NORMAL ANION GAP METABOLIC ACIDOSIS (NAGMA)

- Mainly from losses of bicarb (HCO_3^-)
- USEDCRAP (earlier slide) OR
- ABCDE
  - Addison's
  - Bicarbonate loss (GI or renal – think v/d, fistula, ostomy)
  - Chloride excess*
  - Diuretics (acetazolamide)*
  - Extra – Renal tubular acidosis (RTA)*

CORRECTED ANION GAP (OPTIONAL)

- Corrected Anion Gap (corrAG) = takes into account the unmeasured anions (albumin, sulfate, phos), which may change with acute or chronic illness

= [2 x Albumin] + [0.5 Phosphate] (+/- 2) OR [3 x Albumin]

Normal range = 8 – 12 mmol/L

- Significance?
  - If calcAG > corrAG, there is high gap metabolic acidosis present

DELTA GAP (OPTIONAL)

- *Check in the presence of HAGMA to determine if pure HAGMA or additional disorder present*

- Delta Gap = [calcAG – corrAG] + HCO_3
  - Net sum = 24
    - HAGMA only
  - Net sum < 24
    - NAGMA (non-anion gap acidosis) is present
  - Net sum > 24
    - METABOLIC ALKALOSIS is also present

PRACTICE: MINDING THE GAPS

ABG:

pH	7.18
PCO_2	34 mmHg
HCO_3	12 mEq/L

BMP:

Na= 138, K=3.8,
Cl=115
Albumin=2.3,
Phos=1

calcAG = 138 – [115+12] = 11

corrAG = 2 x 2.3 + [0.5 x1] = 5.1 (+/- 2)

calcAG > corrAG → HAGMA present

Delta Gap = [calcAG- corrAG] + HCO_3 = 6 + 12 = 18

18 < 24…therefore, NAGMA present also

CASE 3

A 64 YO M with ESRD s/p kidney transplant, type 2 DM, and chronic HFrEF presents to the ED with 3 days of fatigue, abdominal pain, and shortness of breath. He is unsure, but he may have had a fever. On exam, he appears unwell and has crackles in the L lung base. He missed dialysis today. CXR shows a L basilar infiltrate.

Vitals:

- HR 100
- BP 92/78
- RR 20
- SpO_2 84%
- Temp 38.0

ABG:

- pH 7.29
- pCO_2 23.3
- HCO_3^- 11.1
- pO_2 52.9

labs:

- Na – 136
- K – 5.2
- Cl – 106
- AG – 18
- Glucose - 260
- Albumin – 2.8
- Phos – 3.0
- BUN – 89.1
- Cr – 4.3
- Lactate – 1.3
- Beta-hydroxybutyrate – 2.7

CASE 3

ABG results:
- pH 7.29
- pCO_2 23.3
- HCO_3^- 11.1
- pO_2 52.9

Winters formula

Expected pCO_2= 1.5 x 11 + 8 = 24.5 (+/- 2)

Actual pCO_2 = 23.3 ☑

CASE 3 DDX

calcAG = 136 – [106+11] = 19

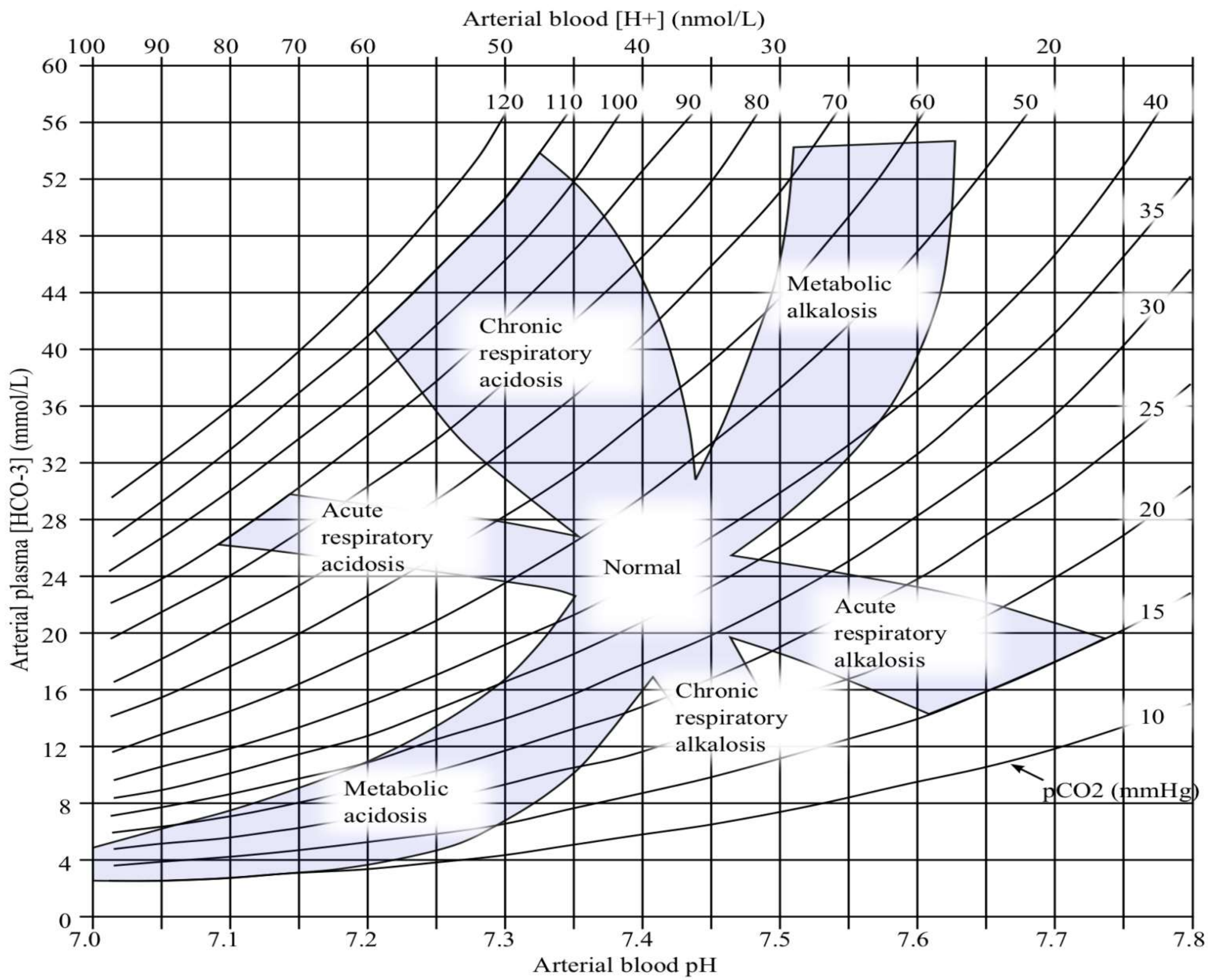
labs:
- Na – 136
- K – 5.2
- Cl – 106
- AG – 18
- Glucose - 260
- Albumin – 2.8
- Phos – 3.0
- BUN – 89.1
- Cr – 4.3
- Lactate – 1.3
- Beta-hydroxybutyrate – 2.7

CASE 3 MANAGEMENT

- How are we going to correct this patient's HAGMA and NAGMA ?

1. Treat DKA
2. Dialysis…add bicarb
3. Treat underlying cause of DKA…what's going on with this patient?

- Are you going to get another ABG? If so, when?



Arterial blood [H+] (nmol/L)
100 90 80 70 60 50 40 30 20
120 110 100 90 80 70 60 50 40
35
30
25
20
15
10
pCO2 (mmHg)
Arterial plasma [HCO-3] (mmol/L)
60 56 52 48 44 40 36 32 28 24 20 16 12 8 4 0
Chronic respiratory acidosis
Metabolic alkalosis
Acute respiratory acidosis
Normal
Acute respiratory alkalosis
Chronic respiratory alkalosis
Metabolic acidosis
7.0 7.1 7.2 7.3 7.4 7.5 7.6 7.7 7.8
Arterial blood pH

CASE 4

A 68 YO F presents to the ED with 3 days of progressively worsening cough and shortness of breath. She has been experiencing intermittent fevers. Her appetite is diminished, and she is fatigued. On exam, she has scattered crackles. CXR reveals multifocal pneumonia.

Vitals:
HR 96
BP 112/82
RR 26
SpO_2 84%
Temp 37.9 C

ABG:
- pH 7.55
- pCO_2 22 mmHg
- HCO_3^- 16 mEq/L

Labs:
Na – 134
K – 4.2
Cl – 100
BUN – 32
Cr – 1.2
Albumin – 3.8
Phos – 3.0
Lactate – 3.2

CASE 4

ABG Results:

- pH 7.55
- pCO_2 22 mmHg
- HCO_3^- 16 mEq/L

Compensation rules…Boston Approach for Resp Disorders

Change in CO2	Change in HCO3	Condition	Example
10	1	Acute Resp Acidosis	If CO2=50, HCO3=25
10	2	Acute Resp Alkalosis	If CO2=30, HCO3=22
10	4	Chronic Resp Acidosis	If CO2=50, HCO3=28
10	5	Chronic Resp Alkalosis	If CO2=30, HCO3=19

CASE 4 DDX

- Hypoxia 2/2 pneumonia leads to hyperventilation reducing systemic CO_2 →

calcAG = 134– [100+16] = 18

ABG:
- pH 7.55
- pCO_2 22 mmHg
- HCO_3^- 16 mEq/L

CASE 4 MANAGEMENT

- What is an appropriate management strategy to correct respiratory alkalosis?

- How are we going to correct the metabolic acidosis?

- How did the ABG help us here?
- Would you get a repeat ABG? If so, when?

IN SUMMARY…

- Look at the pH first then CO_2 and HCO_3
  - Is there a mixed disorder?
- Use all components/calculations of the ABG and labs
  - Challenge yourself with the calculations…it may change your management!
- Apply clinically to your patient; don't just treat the numbers
  - Use your differentials…MUDPILES, USEDCRAP, etc.
- Consider what will happen if you start treatment
  - Will treating help or hurt?

Questions? Walker.Andrew@mayo.edu; Lowell.Amelia@mayo.edu

REFERENCES

- Brandis K. Acid Base Book. https://www.anaesthesiamcq.com/AcidBaseBook/. Accessed August 1, 2021.
- Simple and mixed acid-base disorders. UpToDate.com. https://www.uptodate.com/contents/simple-and-mixed-acid-base-disorders?search=simple%20and%20mixed%20acid%20base%20disorders&source=search_result&selectedTitle=1~150&usage_type=default&display_rank=1. Updated September 9, 2020. Accessed August 1, 2021.
- Story DA. Stewart Acid-Base: A Simplified Bedside Approach. Anesthesia & Analgesia. 2016;123(2):511-515. doi: 10.1213/ANE.0000000000001261
- VBG versus ABG. litfl.com. https://litfl.com/vbg-versus-abg/. Published Nov 3, 2020. Accessed August 1, 2021.
- Reddi AS. Acid-Base Disorders: Clinical Evaluation and Management. Cham, Switzerland: Springer Nature Switzerland AG; 2020. https://link-springer-com.proxy2.cl.msu.edu/book/10.1007%2F978-3-030-28895-2#toc. Accessed August 1, 2021.