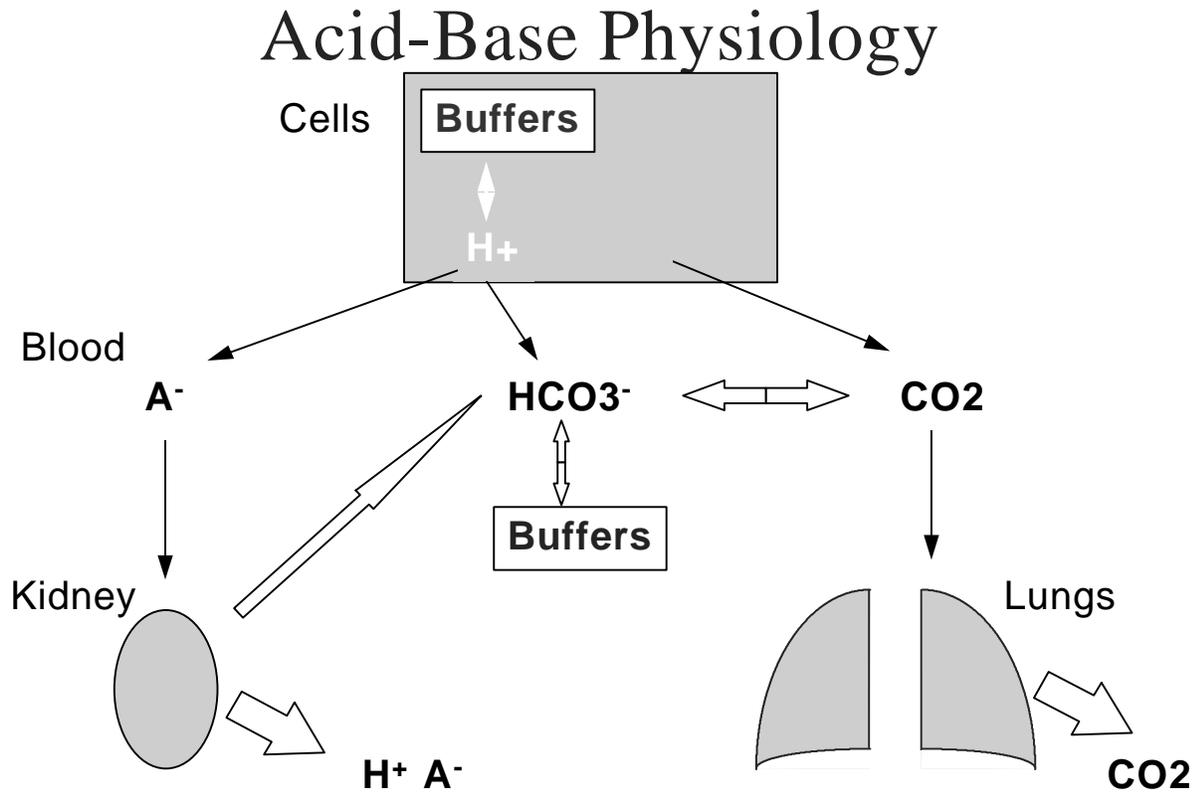


Fluids, Electrolytes, and Acid-Base Status in Critical Illness

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Blood Gas Analysis--Insight into the Acid-Base status of the Patient

The blood gas consists of

pH-negative log of the Hydrogen ion concentration: $-\log[H^+]$.

(also, $pH = pK + \log [HCO_3^-] / 0.03 \times pCO_2$). The pH is always a product of two components, respiratory and metabolic, and the metabolic component is judged, calculated, or computed

by allowing for the effect of the pCO₂, ie, any change in the pH unexplained by the pCO₂ indicates a metabolic abnormality.



CO₂ and water form carbonic acid or H₂CO₃, which is in equilibrium with bicarbonate (HCO₃⁻) and hydrogen ions (H⁺). A change in the concentration of the reactants on either side of the equation affects the subsequent direction of the reaction. For example, an increase in CO₂ will result in increased carbonic acid formation (H₂CO₃) which leads to an increase in both HCO₃⁻ and H⁺ (ΔpH). Normally, at pH 7.4, a ratio of one part carbonic acid to twenty parts bicarbonate is present in the extracellular fluid [HCO₃⁻/H₂CO₃]=20. A change in the **ratio** will affect the pH of the fluid. If both components change (ie, with chronic compensation), the pH may be normal, but the other components will not.

pCO₂-partial pressure of carbon dioxide. Hypoventilation or hyperventilation (ie, minute ventilation--tidal volume x respiratory rate--imperfectly matched to physiologic demands) will lead to elevation or depression, respectively, in the pCO₂. V/Q (ventilation/perfusion) mismatch does not usually lead to abnormalities in PCO₂ because of the linear nature of the CO₂ elimination curve (ie, good lung units can make up for bad lung units). Diffusion abnormalities almost never are severe enough to effect CO₂ elimination. Any change in pCO₂ will effect the equilibrium reaction of CO₂ and H₂O and will effect pH.

pO₂-partial pressure of oxygen.

HCO₃⁻-concentration of bicarbonate ion

TCO₂-total CO₂=dissolved CO₂ + HCO₃⁻

SaO₂-oxygen saturation, calculated

pH, pCO₂, and pO₂ are the primary measurements of the blood gas machine.

Other terms that are used when discussing blood gas analysis

Base deficit or excess--the difference between a patients measured serum bicarbonate level and the normal value of 27 (bicarbonate plus carbonic acid). A way of characterizing the acidosis or alkalosis. It is a nonrespiratory reflection of acid-base status.

Anion gap--Cations (sodium plus potassium) minus anions (bicarbonate plus chloride). If hydrogen ions accumulate, the hydrogen ion is not accounted for on the cation side, but the decrease in bicarbonate buffer compensation would appear as a bicarb deficit, and the anion gap would increase.

Respiratory acid and respiratory acidosis--Carbon dioxide is "respiratory acid" and is the only acid which can be controlled by respiration. When the pCO₂ is high, there is a respiratory acidosis.

Metabolic acid and metabolic acidosis--Metabolic acids are all the body's acids except carbon dioxide--they are not controlled by respiration, hence they have to be neutralized,

metabolized, or excreted by the kidney. Metabolic acidosis is a pH which is more acid than appropriate for the pCO₂.

Possible interpretations of a blood gas

Normal (pH, pCO₂, pO₂ and HCO₃)

Respiratory acidosis

Respiratory acidosis, metabolic compensation (partial or complete)

Metabolic acidosis

Metabolic acidosis, respiratory compensation (partial or complete)

Hyoxemia (with or without an acid-base abnormality)

Respiratory alkalosis

Respiratory alkalosis, metabolic compensation (partial or complete)

Metabolic alkalosis

Metabolic alkalosis, respiratory compensation (partial or complete)

Guidelines for interpretation of acid-base status)--ie, STEPS TO TAKE

1. What is the pH--normal, acidotic, or alkalotic?
2. What is the pCO₂--high, normal, or low?
3. What is the bicarbonate--high, normal, or low?
4. Is the primary problem **respiratory or metabolic**?
5. Is the problem **acute, partially compensated, or compensated**?

A Couple “rules”

1. **For an acute change in pCO₂ of 10, the pH will change by 0.08.** If all changes in pH can be accounted for by the change in pCO₂, then the problem is an acute respiratory acidosis or alkalosis. If not, there is a metabolic component.
2. A pH change of 0.15 corresponds to a base change of 10 meq/L. This only applies to the base changes that are not due to pCO₂ changes. First apply rule 1. If there is “unaccounted for” pH change, apply rule 2 to that and determine the degree of metabolic abnormality.

Example--Blood gas 7.26/50. According to rule 1 the pH should be 7.32. The difference between the predicted and actual pH is -0.06 (base deficit). Apply rule 2-- $0.15/10=0.06/x$. Solving for x, $x=4$ meq/l, which is the base deficit. Thus, there is a combined respiratory and metabolic acidosis.

3. An immediate increment in plasma HCO₃ will occur due to titration of non-bicarb buffers in response to acute hypercapnia. This is approximately 0.1 meq/L for each mmHg increase in pCO₂.
4. The only way to have a normal blood gas is to have a normal pH, pCO₂, and HCO₃. If the pH is normal but the pCO₂ and or HCO₃ are not, there is a **compensated** abnormality, or a mixed abnormality (ie respiratory alkalosis and metabolic acidosis). This is still abnormal and requires attention!!!

| | | pH | pCO ₂ | HCO ₃ | Base excess |
|------------------|-------------------|------|------------------|------------------|-------------|
| Acidosis | acute respiratory | low | high | N | N |
| | acute metabolic | low | N | low | low |
| Alkalosis | acute respiratory | high | low | N | N |
| | acute metabolic | high | N | high | high |

| | | pH | pCO ₂ | HCO ₃ | Base excess |
|------------------|---------------------|----|------------------|------------------|-------------|
| Acidosis | chronic respiratory | N | high | high | high |
| | chronic metabolic | N | low | low | low |
| Alkalosis | chronic respiratory | N | low | low | low |
| | chronic metabolic | N | high | high | high |

Why be impressed?

[H⁺] is maintained between 36-43 nanoequivalents/L (10⁻⁹ eq/L)

Normal CO₂ production is 15,000meq/day (or 15 equivalents). (adult)

Nonvolatile acid load (not excreted by lungs) 1 meq/day. This acid load increases in critical illness-burns, starvation, sepsis

Buffering--How are acute changes in pH buffered by the body??

1. pCO₂/HCO₃--pK=6.1, but pCO₂ and HCO₃ can be independently regulated by lungs and kidneys.
2. Hemoglobin--histidine residues. When in deoxy form, Hg can buffer more acid--CO₂ is transported to the lungs as HCO₃.
3. Cellular and plasma proteins, intracellular organic phosphates, bone (carbonates and phosphates).

Derangements of Acid-Base Homeostasis

Respiratory acidosis--

How?--Rise in CO₂ production (fever, sepsis), or failure of ventilation (CNS causes, muscle weakness, increased dead space)

For each 10 mmHg pCO₂, pH falls by 0.08 units

Renal compensation-hydrogen ion secretion and ammonium secretion increase

predicted $[HCO_3] = (pCO_2 - 40) \times 0.3 + 24$

Respiratory alkalosis

How?--result of *hyperventilation* or *decreased CO₂ production*

Causes of hyperventilation in the ICU: iatrogenic, sepsis, pain, acidemia, CNS, liver, pulmonary disease

Causes of decreased CO₂ production: sedation/paralysis, hypothermia, low carbohydrate diet, brain death

$\Delta[H^+] = 0.008 \times \Delta PCO_2$, or for fall PCO₂ of 10mmHg, pH rises by 0.08 units.

Compensation: renal excretion bicarbonate ion, titratable acid excretion decreases

Predicted $[HCO_3] = (40 - PCO_2) \times 0.17 + 40$

Metabolic Acidosis

Renal (non anion-gap)

Renal Tubular Acidosis (RTA)

proximal (type II)-- HCO_3^- , difficult to treat

distal (type I)--less severe, can be more easily treated.

Renal Failure:

Complete renal failure: cant regenerate bicarb, cant excrete unmeasured anions.

Bone buffers to $[HCO_3] = 14$

Acute increase in acid during critical illness can be life-threatening (previously compensated acidosis can become clinically important in the face of acute illness)

GI Bicarbonate losses (non anion-gap)

Pancreatic, bile, small intestinal fluid high in HCO_3^- .

Usually renal compensation occurs, except in the case of severe dehydration, very excessive loss (ie, cholera), or renal failure

Other (anion gap)

Lactic acidosis

ketoacidosis

congenital metabolic defects: organic acidemias, CHO metabolism defects (MCAD)

Exogenous: ethylene glycol, methanol, TPN amino acids

Compensation for metabolic acidosis: Central chemoreceptors cause increased

V_A (alveolar minute ventilation)--increased ventilation, hence decreased pCO₂.

Predicted $pCO_2 = 1.5 \times [HCO_3] + 8 \pm 2$

Metabolic Alkalosis:

Initiation phase--excessive HCO₃ production (net gain of HCO₃ or net loss of H⁺)

excess renal production: mineralocorticoid excess, steroids stimulate distal nephron acidification (H⁺ ions excreted, HCO₃⁻ produced)

vomiting/NG suction--loss of Cl⁻ and volume--secondary hyperaldosteronism and renal acidification, plus attempt to retain volume and Na leads to Na/H⁺ exchange and increased HCO₃ resorption. (H⁺, Cl loss, mineralocorticoids, volume contraction all contribute)

Bicarbonate, acetate, lactate, citrate administration

Maintenance phase

Normal kidneys in a normal host can excrete all filtered bicarbonate

Factors which maintain alkalosis: volume depletion, hypochloremia, mineralocorticoid excess, decreased GFR

Check urinary chloride--low in volume depletion ("chloride responsive"), high in mineralocorticoid excess ("chloride resistant")

Potassium depletion almost always accompanies alkalosis (metabolic or respiratory), and may in itself contribute to metabolic alkalosis (as K moves out of cells, H⁺ moves into cells).

Compensation

There is some evidence that patients will hypoventilate in an "attempt" to compensate for a metabolic alkalosis. The degree to which a given patient or disease process is likely to compensate not well defined.

Electrolytes: Interactions with Acid Base and Volume Abnormalities

It is important to realize that acid-base status, electrolytes status, and volume status interact and inter-relate, both on a purely chemical means and through the bodies "homeostatic" mechanisms.

Magnesium: Renal loss increased with Na and Ca flux through nephron. Hyperaldosteronism, via increase Na delivery, increased Mg wasting.

Calcium: acidosis increases IONIZED Ca, alkalosis decreases ionized Ca. (Hydrogen ions compete for calcium binding sites). As the pH changes, the ionized calcium (the part that is *important* will change changes). Raising the pH (more alkalotic) causes decreased ionized Ca, lowering the pH (more acidotic) causes increased ionized Ca. This can be important acutely during resuscitation when bicarb is used, or during attempts to induce alkalosis in order to effect pulmonary hypertension.

Phosphate: phosphate is taken into cells when glycolysis is stimulated (eg, glucose administration after starvation, hyperal, anorexia, etc.)

Potassium: acidosis causes extracellular K to increase, alkalosis K to decrease. *Respiratory or metabolic alkalosis* leads to renal K excretion. Hyperaldosteronism increases renal K excretion.

Sodium: Na homeostasis closely linked with volume homeostasis, except in cases of

abnormalities of free water.

Volume Homeostasis

Regulation reflects arterial filling- Q_T and SVR

Homeostatic response: sympathetic nerves, renin-angiotensin-aldosterone system, ADH

In disease, arterial filling can be dissociated from venous filling (cardiac failure, tamponade, hepatic failure)

Free Water (there is no free water)

Adequate renal function is necessary for free water regulation

ADH controls water homeostasis; release is triggered by hyperosmolality and volume depletion (circulating blood volume)

Osmosensors detect change of 1-2%

“Volusensors” less sensitive, respond to change of 10%, but with much larger response. Volume will be maintained at the expense of osmolarity if necessary.

Non-osmotic or non-hemodynamic events can change the relationship (slope) between osms and ADH release--pain, drugs, etc.

SIADH-Syndrome of Inappropriate Anti-Diuretic Hormone

“Semantic” arguments--is non-osmotic release of ADH “inappropriate” (?)

Disorders associated with SIADH--any CNS disturbance (infection, trauma, surgery, etc), increased intrathoracic pressure (ie, as with mechanical ventilation), drugs. It is not uncommon to see hyponatremia in settings of pulmonary disease (ie, RSV).

Dx--decreased urine output, along with inappropriately high urinary osmolarity in the face of low serum osmolarity. Euvolemia is prerequisite. Urine sodium will be greater than 20 (indicates adequate or high circulating blood volume).

Rx--Fluid restriction (min 0.75L/M²/d)

3% NaCl (0.513 meq/ml) if symptomatic (ie, seizures)--

0.6 x Kg x (125-Na)meq. (generally 2-3 cc/kg 3% NS)

Cerebral Salt Wasting

Occurs after head trauma or cranial surgery

Dx--Hyponatremia, high urine Na, high urine volume

ADH high in response to volume depletion

Rx--salt supplementation--measure urine sodium to estimate needs.

Diabetes Insipidus

Absence of ADH release (brain injury) or effect on renal function (nephrogenic DI). May occur post-surgically (pituitary tumors), as a complication of serious brain injury (failure of the pituitary as part of the progression of brain injury). Nephrogenic DI may be congenital or may be a complication of sickle cell disease, pyelonephritis, drug toxicity (lithium, amphotericin), and others.

Dx--High urine output of low specific gravity, rising serum sodium

Rx--You need to replace either the free water or the ADH.

- a. H₂O replacement--D5 + 0.2 NS (initially 1:1) to replace urine output. Follow serum sodium and glucose closely.
- b. ADH replacement--Vasopressin infusion titrated to decrease urine output. Start at 0.5 milli-units/kg/min, and double infusion until desired urine output is achieved. Monitor serum Na closely, monitor fluid intake closely. Make sure the serum sodium does not fall (most common complication). This is not effective in treating nephrogenic DI.
- c. DDAVP should not be used in the acute setting, but is appropriate for chronic DI.

Dopamine

Low doses dilate renal vasculature

High doses constrict renal vasculature

Low doses can increase cardiac output, thus increase urine output

Dopamine has a direct tubular natriuretic effect-increased Na delivery to the mTAL and macula densa affects JG apparatus and vascular flow.

Acute Renal Failure

Cessation of kidney function *with or without* changes in urine volume

Non-oliguric-70%, oliguric 30%. Non-oliguric more common with nephrotoxic injury, oliguric more common with ischemic injury.

Pathophysiology involves renal perfusion and tubular dysfunction.

“Conversion” or oliguric to non-oliguric renal failure may merely reflect lesser degree of insult, nevertheless, does make management easier.

Diagnostic Studies

$FENa = \frac{U_{Na}}{P_{Na}} \times \frac{P_{Cr}}{U_{Cr}} \times 100$

FENa useless in the presence of diuretics (12 hours)

$RFI = \frac{U_{Na} \times 100}{U_{Cr} / P_{Cr}}$

Prerenal vs Intrinsic Renal Failure

“Classic Abnormalities”

1. Bronchiolitis--hyponatremia
2. Severe asthma--respiratory alkalosis, metabolic acidosis
3. Diarrhea--metabolic acidosis (bicarb loss)
4. Pyloric stenosis--hypochloremic metabolic alkalosis
5. Mineralocorticoid deficiency--young male infant with hyperkalemia, hyponatremia, shock
6. Diabetic--metabolic acidosis, respiratory alkalosis, hyper or hypokalemia

Questions

Match the following blood gas values to the clinical condition most likely associated with it.
pH/pCO₂/pO₂/HCO₃

| | |
|-------------------|---|
| 1. 7.35/44/52/24 | a. Bronchopulmonary dysplasia |
| 2. 7.40/28/63/16 | b. Acute respiratory distress syndrome |
| 3. 7.40/40/150/22 | c. Pyloric stenosis |
| 4. 7.16/70/88/24 | d. Asthma, acute exacerbation |
| 5. 7.50/66/92/45 | e. Mechanically ventilated patient s/p fusion |
| 6. 7.44/68/65/34 | f. Acute respiratory failure due to narcotic overdose |

Case Studies

1. 3 month old former term infant no significant past medical history presents with fever to 103, not feeding well for a few days, “breathing funny”, some history of emesis. In ED, infant is poorly perfused and tachycardic. SaO₂ is 100 % on blow-by O₂. IV access is difficult, so an IO line is started, and blood tests obtained. Transport to CHMCA is arranged

ABG-7.44/70/154

Na-133, K 3.0 Cl 56, HCO₃ 58, BUN 32, Cr 1.8

CBC normal, CXR unremarkable.

- a. Describe the acid base abnormality
- b. What is the differential diagnosis
- c. How would you work it up?

2. An 8 year old boy was involved in a pedestrian vs motor vehicle accident. He suffered a significant liver laceration as well as a femur fracture. He is quite tachycardic and hypotensive in the ED and receives several liters of normal saline during his resuscitation. Labs on admission to the ICU reveal a hyperchloremic metabolic acidosis.

- a. If he is adequately volume resuscitated, why does he have an acidosis?
- b. How could you avoid the problem?
- c. What other clinical situations cause a similar problem?

3. A 4 year old with DIC and liver failure requires massive blood product replacement. After several units of FFP and platelets, her bleeding has stopped but her blood pressure starts to fall.

- a. Why might her BP fall??
- b. How, ideally, would you test your hypothesis??

- c. What could you do about it.
4. You are responsible for the ventilator management of a 3 year old who has had tracheal reconstruction. The patient has been kept sedated, but the surgeon decides he want the patient paralysed due to the nature of the surgery. You havent changed the ventilator settings because the patient wasn't breathing over the ventilator set rate prior to paralysis.
 - a. What might you find on the next blood gas?
 - b. What might you find on the next electrolytes if you dont alter your ventilation?
 5. A patient with chronic respiratory insufficiency due to CF is admitted and a blood gas reveals a compensated hypercapnia, with pH 7.38, pCO₂ 68, pO₂ 59. The intern gets nervous and treats the patient with supplemental oxygen. The next gas has a pO₂ of 154 and a pCO₂ of 98.
 - a. Why did this happen??
 - b. Can anything be done about it??
 6. 12 year old with closed head injury (subdural hematoma and diffuse shearing injury) after MVA. Associated injuries include femur and pelvic fractures. In ED, HR=140, RR=36, BP=88/46.
 - a. What are your first 3 concerns?
 - b. What will you do about them?
 - c. After stabilization, the patient is admitted to the ICU. What electrolyte/water balance abnormalities will you anticipate?
 - d. How would you make the diagnosis?
 7. The previous patient has not done well neurologically, and you fear he may be brain dead. The nurse informs you that his urine output has just increased to 300 cc/hour for the last 3 hours.
 - a. What do you suspect?
 - b. How will you confirm it?
 - c. How will you treat it (2 ways)?