Advanced Chemistry For Dialysis Technicians

John Sweeny

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Chemistry Topics

CO_2 in Dialysate – The mystery ingredient

Harness – What's "as $CaCO_3$ mean?
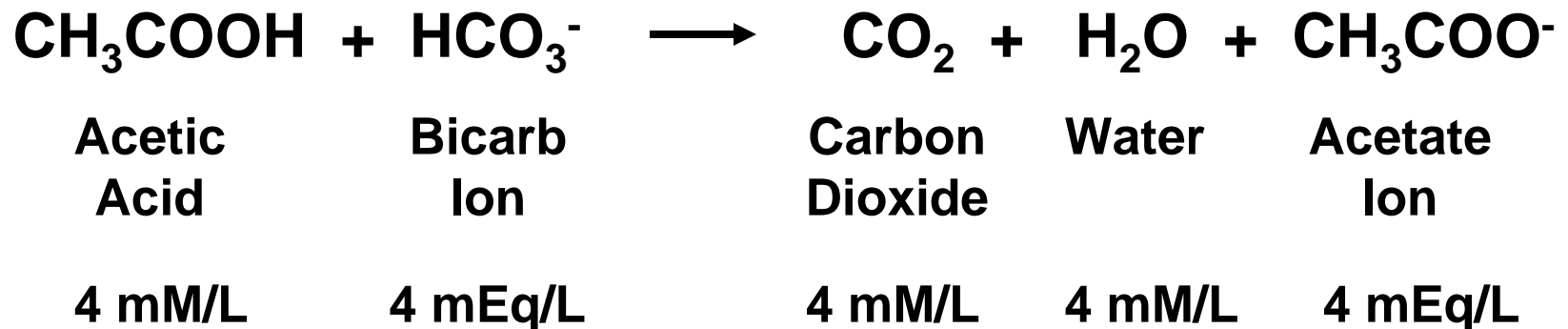
Urea vs. BUN – They aren't the same

Amino Acids – The Lego set for proteins

The 1st Membrane – An explosive story

Carbonate Precipitation – Why it happens

The Acid/Bicarbonate Reaction

When the Acetic Acid in the Acid concentrate mixes with the Bicarbonate ion in the Bicarb concentrate the following reaction occurs:

$$CH_3COOH + HCO_3^- \longrightarrow CO_2 + H_2O + CH_3COO^-$$

Acetic Acid	Bicarb Ion	Carbon Dioxide	Water	Acetate Ion
4 mM/L	4 mEq/L	4 mM/L	4 mM/L	4 mEq/L

For 45X concentrates the 37 mEq/L concentrate becomes 33 mEq/L in the final dialysate solution.

How much CO_2 pressure will be in the dialysate?

The reaction with the acetic acid produced 4 mmol of carbon dioxide.

That's 1/250th (4/1000) of a mole/liter.

From Avogadro's law, one mole of a gas occupies 22.4 liters at one atmosphere of pressure (760 mmHg)

Boyle's Law: P_1 x V_1 = P_2 x V_2 hence:

22.4 liters x 760 mmHg = 1 liter x 17,024 mmHg

17,024 mmHg / 250 = 68 mmHg

Normal blood CO_2 pressure is 40 mmHg hence:

CO_2 will go from the dialysate to the blood

This is a good thing because CO_2 levels promote breathing and as a result, good Oxygen levels.

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Blood pH and the Bicarbonate Ion

Blood pH is directly related to the concentrations of bicarbonate and carbon dioxide in the blood.

The relationship is defined by the Henderson-Hasselbalch Equation:

$$pH = pK + \log \frac{\left[HCO_3^- \right]}{0.03 \times pCO_2}$$

- Where: pK = the blood pH due to other acids

    HCO_3^- = bicarb concentration (mEq/L)

    pCO_2 = carbon dioxide pressure (mmHg)

Solving the equation

Blood normal values for pK, HCO_3^- , and pCO_2 are:

pK = 6.1, HCO_3^- = 24 mEq/L, and pCO_2 = 40 mmHg

Placing these values in the equation yields:

$$Blood\,pH = 6.1 + log\left(\frac{24\,mEq/L}{0.03 \times 40\,mmHg}\right)$$

$$Blood\,pH = 6.1 + log\left(\frac{24}{1.2}\right)$$

$$Blood\,pH = 6.1 + log(20) = 6.1 + 1.3 = 7.4$$

What is hardness?

Hardness is defined by the various minerals of Calcium and Magnesium dissolved in water.

There are 8 specific compounds:

- Calcium Carbonate - $CaCO_3$ – chalk, limestone, marble
- Calcium Bicarbonate – $Ca(HCO_3)_2$
- Calcium Sulfate – $CaSO_4$ - gypsum
- Calcium Chloride – $CaCl_2$
- Magnesium Carbonate - $MgCO_3$ – chalk, limestone, marble
- Magnesium Bicarbonate - $Mg(HCO_3)_2$
- Magnesium Sulfate - $MgSO_4$ – Epsom salts
- Magnesium Chloride - $MgCl_2$

Other elements such as Iron and Manganese also add to total hardness when in high concentrations which is rare.

The hardness unit: Grain per gallon (gpg)

A grain is 1/7000 of a pound = 0.0648 of a gram. (453.6 gm = 1 lb)

There's about 25,000 grains of rice to a pound.

A gallon of water weights 8.34 pounds.

1 grain/gallon = 0.000143/8.34 = 1.71×10^{-5}

To convert this ratio to parts per million (ppm) multiply by 1 million:

$(1.71 \times 10^{-5}) \times 10^{6} = 1.71 \times 10^{1} = 17.1$ ppm.

1 ppm = 1 mg/L

Grains per gallon as CaCO$_3$

Rather than list each mineral in water for its individual contribution to hardness, the minerals are converted to the equivalent amount of Calcium Carbonate and then added together.

This conversion is done using the gram equivalent weights of the minerals.

For Calcium and Magnesium compounds the equivalent weight of each compound is half it's gram molecular weight because both Calcium (Ca^{++}) and Magnesium (Mg^{++}) have double charges.

Molecular and Equivalent Weights

	Molecular Weight	Equivalent Weight
Calcium carbonate	**100.090**	**50.045**
Calcium bicarbonate	**162.114**	**81.057**
Calcium sulfate	**136.142**	**68.071**
Calcium chloride	**110.986**	**55.493**
Magnesium carbonate	**84.322**	**42.161**
Magnesium bicarbonate	**146.346**	**73.173**
Magnesium sulfate	**120.374**	**60.187**
Magnesium chloride	**95.218**	**47.609**

Equivalent Conversion Example

The formula:

$$\text{Amt. of Mineral} \times \frac{\text{Eqv. Wt.}\left(CaCO_3\right)}{\text{Eqv. Wt.}\left(\text{Mineral}\right)} = \text{Amt. Of Mineral as } CaCO_3$$

Convert 10.0 gpg of Magnesium sulfate to gpg as Calcium carbonate.

$$10 \text{ gpg } MgSO_4 \times \left(\frac{50.045}{60.187}\right) = 8.31 \text{ gpg as } CaCO_3$$

Urea vs. BUN

A compound formed in the liver by the process known as the urea cycle. It's gram molecular weight is:

$$CO(NH_2)_2$$

$12.01 + 16.00 + (14.008 + (1.008 \times 2)) \times 2 = 60.058$ daltons

BUN = Blood Urea Nitrogen = Amount of nitrogen from the urea in the blood.

Ratio: Urea/Urea Nitrogen =

$60.058/2 \times 14.008 = 60.058/28.016 = 2.14$

Dorland's Illustrated Medical Dictionary, Editor: Elizabeth J. Taylor, 27th Edition,1988, W. B. Saunders Company, pp 59, 1789.

Other Nitrogen Compounds

Ammonia – NH_3

      Subtract a Hydrogen and add a Chlorine and you get:

Mono-Chloramine – NH_2Cl

      Subtract a Hydrogen and add a Chlorine and you get:

Di-Chloramine – $NHCl_2$

      Subtract a Hydrogen and add a Chlorine and you get:

Nitrogen Trichloride – NCl_3

Organic Chemistry - $\alpha-$Amino Acids

All amino acids must have an amino group and an carboxyl group

AMINO	CARBOXYL
(NH_2^-)	$(COOH^+)$

There are 20 amino acids used to build all human proteins.

- 9 are essential (You must eat them.)

- 11 are nonessential (You can make them.)

Dorland's Illustrated Medical Dictionary, Editor: Elizabeth J. Taylor, 27th Edition,1988, W. B. Saunders Company, pp 59, 1370.

The α−Amino Acids

Essential

- Histidine
- Isoleucine
- Leucine
- Lysine
- Methionine
- Phenylalanine
- Threonine
- Tryptophan
- Valine

Non-essential

- Alanine
- Arginine
- Asparagine
- Aspartic Acid
- Cystine
- Glutamic Acid
- Glutamine
- Glycine
- Proline
- Serine
- Tyrosine

Proteins are…

Complex organic compounds containing carbon, hydrogen, oxygen, nitrogen and sulfur.

The main ingredient in the protoplasm of all living cells.

High molecular weight molecules consisting of $\alpha -$ amino acids in peptide linkages.

Each has a genetically defined sequence of amino acids which determine its shape and function.
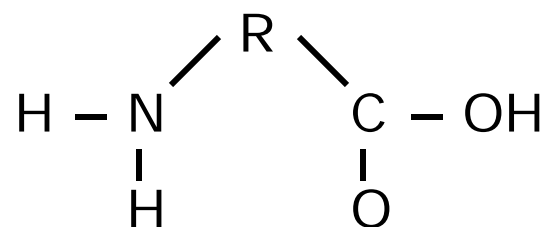
Water/salt solution soluble types:
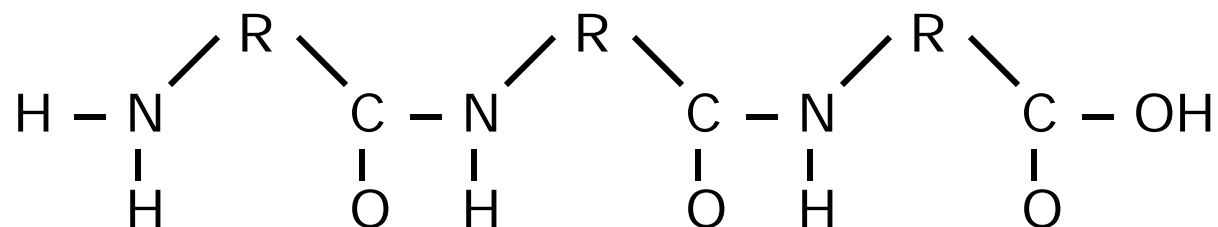
- Albumins, globulins, histones, protamines

Water insoluble types:

- Collagens, elastins, keratins, actins, myosin

Amino Acid Structure/Bonding

$$H - N \overset{\displaystyle R}{\diagup\diagdown} C - OH$$

with H below N and O below C (double bond to O)

For the smallest amino acid, Glycine, R = CH - H

Peptide chain structure:

$$H - N \overset{R}{\diagup\diagdown} C - N \overset{R}{\diagup\diagdown} C - N \overset{R}{\diagup\diagdown} C - OH$$

with H, O, H, O, H, O below respectively

Formation of a peptide (miniature protein) is called peptide linking. Note that each middle amino acid in the chain has lost a water molecule (H_2O)

Organic Chemistry, M. A. Fox and J. K. Whitesell, Copyright 1994, Jones and Bartlett, pp 619-621

Amino Acid Possibilities

Amino Acid Chain	Combinations
2	400
3	8,000
4	160,000
10	10,240,000,000,000
100	1.2675×10^{130}

The development of Collodion
The first practical membrane

1845 – Friedrich Schoenbeim spills a combination of nitric and hydrochloric acids and wipes it up with his wife's cotton apron.

The reaction synthesizes cellulose trinitrate (gun cotton).

He patents the process and forms his own company making the product which proved to be a fairly safe explosive for construction and mining.

Adapted by Alfred Nobel of Sweden into a controlled explosive called dynamite.

Nobel uses his wealth to create the Nobel Prizes.

Schoenbeim also discovered cellulose dinitrate which could be dissolved in ether and then dried to make thin films of the material.

The development of Collodion
The first practical membrane

Sheets of cellulose dinitrate were used as surgical dressings and the basis for photographic film until 1935.

The material was called "collodion" from the Greek word "*Kolla*" for glue like substance.

In the laboratory it became known as a good semipermeable membrane and was used by Fick to study diffusion.

1913 - Used by Able, Roundtree, and Turner to perform the first in vivo studies of blood. They made the collodion into tubes by dipping glass rods into the collodion solution.

1924 - Haas dialyzed patients using collodion for two years but none of the patients lived.

1929 - Collodion was replaces by cellulose acetate when the Visking company in Chicago started making tubes of cellulose acetate for sausage casing.

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Cellulose – $(C_6H_{10}O_5)_N$

$$CH_2OH$$
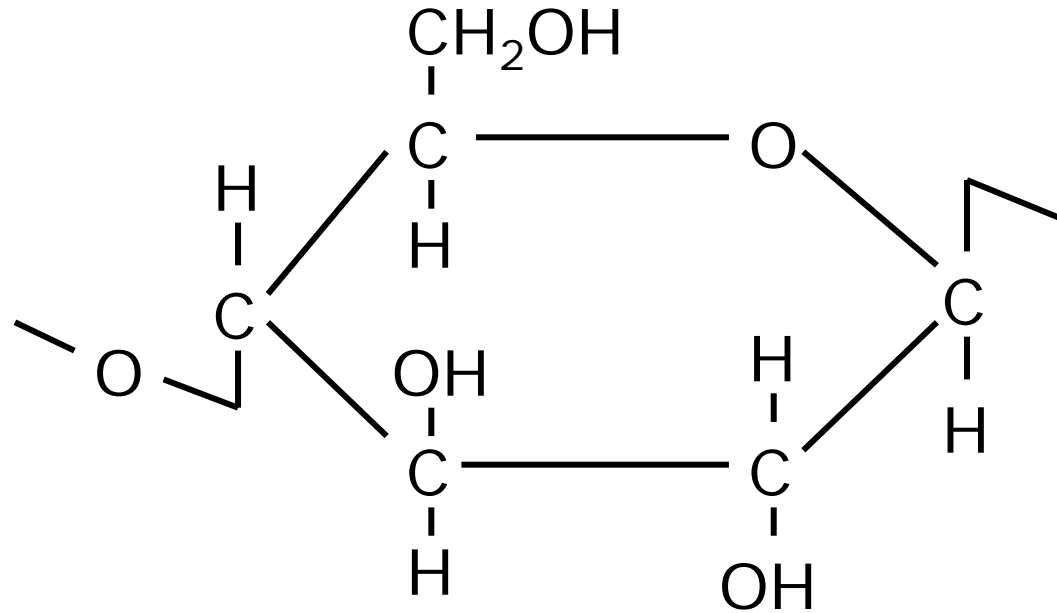
The main polysaccharide of plant cell walls. It's a polymer of β–D-glucose with a water molecule removed to form links between units resulting in chains of between 2000 and 4000 units long.

McGraw Hill page 263

Why is precipitation a problem in dialysis machines?

The problem is Calcium Carbonate's ($CaCO_3$) high degree of insolubility in water.

Calcium ions (Ca^{++}) and Carbonate ions (CO_3^{--}) just love to get together.

This "Togetherness" effect is well know in Chemistry.

The term that defines the degree to which two ions will form a compound is called Solubility Product Constant and is abbreviated K_{SP}.

The formula for K_{SP} is:

$$K_{SP} = [\ Ion^+\ ]\ x\ [\ Ion^-\ ]\ where:$$

$$[\ ] = Ion\ concentration\ in\ moles\ per\ liter$$

Anytime the concentration of the positive ion multiplied by the concentration of the negative ion exceeds the K_{SP} value for a compound, there will be precipitation.

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K_{SP} - Calcium Carbonate

K_{SP} of $CaCO_3$ = 8.7 x 10^{-9}

$[Ca^{++}]$ x $[CO_3^{--}]$ = 8.7 x 10^{-9}

[X] x [X] = 8.7 x 10^{-9}

[X^2] = 8.7 x 10^{-9}

[X] = square root of 8.7 x 10^{-9}

[X] = 9.3 x 10^{-5} moles/liter
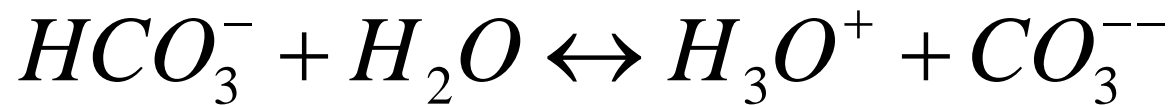
1 mole of $CaCO_3$ weighs = 100.09 grams

100.09 grams x 9.3 x 10^{-5} = 9.3 milligrams/L
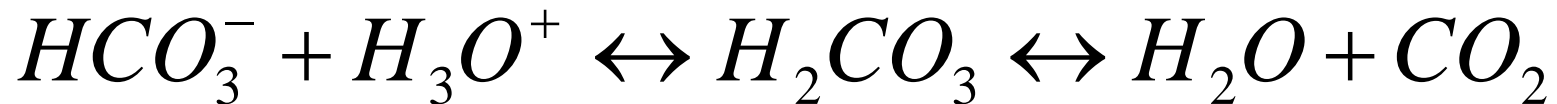
Where does the Carbonate in dialysate come from?

The answer is from the Bicarbonate ion

Bicarbonate + Water yields Hydronium + Carbonate

$$HCO_3^- + H_2O \leftrightarrow H_3O^+ + CO_3^{--}$$

Bicarbonate can also become Carbolic Acid

Bicarbonate + Hydronium yields Carbolic Acid

$$HCO_3^- + H_3O^+ \leftrightarrow H_2CO_3 \leftrightarrow H_2O + CO_2$$

Ionization Constants of Carbolic Acid

Since Carbolic Acid can loose two electrons, there are two equations:

$$K_{a1} = \frac{[H^+][HCO_3^-]}{[H_2CO_3]} = 4.3 \; x \; 10^{-7}$$

$$K_{a2} = \frac{[H^+][CO_3^{--}]}{[HCO_3^{--}]} = 5.6 \; x \; 10^{-11}$$

From the first equation, the pH of the dialysate can be calculated

Calculating Dialysate pH

The pH of dialysate can be determined from the concentrations of Carbolic Acid and the Bicarbonate ion. For typical dialysate:

Carbolic Acid = 4 mmol = [4 x 10^{-3}]

Bicarbonate ion = 35 mmol/L = [35 x 10^{-3}]

$$K_{a1} = \frac{[H^+][HCO_3^-]}{[H_2CO_3]} = 4.3 \ x \ 10^{-7}$$

$$\frac{[H^+][35 \ x \ 10^{-3}]}{[4 \ x \ 10^{-3}]} = 4.3 \ x \ 10^{-7}$$

Solve: [H$^+$] = 4.9 x 10^{-8} mol/L

The log(4.9 x 10^{-8}) = -7.31 therefore the PH = 7.31

Once the [H$^+$] is known, the concentration of the carbonate ion can be determined.

Baxter

$$K_{a2} = \frac{[H^+][CO_3^{--}]}{[HCO_3^{--}]} = 5.6 \; x \; 10^{-11}$$

$$\frac{[4.9 \; x \; 10^{-8}][CO_3^{--}]}{[35 \; x \; 10^{-3}]} = 5.6 \; x \; 10^{-11}$$

$$1.4 \; x \; 10^{-6} \; x \; [CO_3^{--}] = 5.6 \; x \; 10^{-11}$$

$$[CO_3^{--}] = 4.0 \; x \; 10^{-5} \; mol \, / \, L$$

Once the concentration of the carbonate ion is known, the solubility of $CaCO_3$ be determined.

CaCO$_3$ in dialysate

For dialysate, the Calcium and Carbonate concentrations are:

- Calcium ion = 3.25 mEq/L = 1.63×10^{-3} mol/L
- Carbonate ion = 4×10^{-5} mol/L

$[Ca^{++}] \times [CO_3^{--}] =$

$[1.63 \times 10^{-3}] \times [4.0 \times 10^{-5}] = 6.5 \times 10^{-8}$

K_{SP} of CaCO$_3$ = 8.7×10^{-9}

The dialysate concentration is higher than the K_{SP} of CaCO$_3$, so precipitation will form.

At low levels the the reaction is metastable, hence, precipitation forms slowly.