# Fundamental Principles of Physiology

## Units of Measurement

The following units are used fairly f'equently in Physiology:

**Length**

Kilometer (km)= 1,000 m= 0.62 mi

mi= 1.61 km= 1,760 yd

1 meter (m) = 39.37 in. = 1.09 yd
1 decimeter (dm) =.1m = 10 cm
1 centimeter (cm) = .001m= 10 mm= 0.3937 in. 1 in.= 2.54 cm
1 millimeter (mm)=.0001m= 1,000 µm

1 micrometer (µm)= one-millionth m = 1,000 nm= 1 micron
1 nanometer (nm)= one-billionth m = l mµm = 10 A
angstrom (A)= 0.1 nm
picometer (pm) = one-trillionth m

**Volume**

liter (L)= 1,000 ml= 1,000 cc= 1.05 qt= 0.264 gal
deciliter (di)= 0.1 L= 100 ml
milliliter (ml)= $\frac{1}{1000}$ L= 1,000 pl
ounce (oz) (fluid) = 8 fl drams= 29.57 ml
quart (qt) (fluid)= 32 oz= 946 ml= 0.946 L

**Weight**

metric ton= 1,000,000 g= 2204.62 lb
kilogram (kg)= 1,000 g= 2.2 lb= 35.27 oz
gram (g)= 1,000 mg
454 g = 1 lb= 16 oz
1 oz= 28.35 g
milligram (mg)= 1/1000 g= 1,000 pg
microgram (µg)= 1/1000 mg= 1 gamma

**Temperature**

centigrade (°C)= 32° Fahrenheit (°F)= 273 Kelvin (K)

°C= $\frac{5}{9}$ (°F -32)

°F= $\frac{9}{5}$ °C + 32

### Pressure

Pressure is force per unit of area.

1 atmosphere= 3'f.0 ft of water= 760 mm (or *29.92* in.) of mercury (Hg)= 14.7 lb/in.$^2$

### Energy

One calorie (cal is the amount of energy required to heat 1 g of water 1°C .

One kilocalorie (large calorie or kcal is the amount of energy required to heat 1 kg of water = 4°C (at 15°C)

1 kcal= 1,000 cal= 3.086 ft-lb= -126..+ kg-m

1 g of carbohydrate= 1 kcal

L of oxygen used in burning glycogen (RQ of 1) 5.07 kcal = 15,575 ft-lb= 2.153 kg-rn [RQ= (volume $CO_2$ produced)/( volume $O_2$ consumed) during metabolism)

L of oxygen in a closed circuit system= -1.825 kcal in the postabsorptive state lRQ assumed to he 0.82) and --1.862 kcal on an ordinary mixed diet (RQ assumed to he 0.85)

### Work

Work is force times the distance through which it acts.

1 ft-lb= 1 lb of force times 1 ft

1 kg-m= 7.23 ft-lh

### Power

Power is work or energy per unit of time.

1 horsepower (HP)= 3:3,000 ft-lb/min= 550 ft-lb/sec= 4,564 kg-m/min= 76.07 kg-m/sec= 746 watts (\XI)= 10.694 kcal/min = 0.178 kcal/sec

1 kilowatt (kw)= 1,000 W= 1.341 HP= 0.239 kcal/sec

## Concentration of Solutions

."v1any of the physiological properties of solutions depend on the number of molecules, ions, or particles in the solution; therefore, it is important that you understand the various means of expressing concentrations used in physiology.

### Percentage (%) Solutions

This is probably the simplest means of expressing concentration and one that is commonly used. Percent means "parts in 100. Percentage is the number of grams of solute dissolved in 100 ml (1 deciliter) of solution. It is calculated using this formula:

$$\text{Percentage} = \frac{\text{grams of solute}}{\text{\'olume of solution}} \times 100$$

Thus, a 12'% solution **weight to volume (W**/V) of glucose would contain 12 g of glucose in each 100 ml of solution (12g/dl), or 120 *g/L.* If 2 g of NaCl is dissolved in 25 ml of water, the percentage \vill be:

$$\text{Percentage} \quad \frac{2\text{g}}{25\text{ ml}} \times 100$$

In living organisms, the concentration of many substances is so low that it is more easily expressed as **milligrams/deciliter (mg/dl).** For instance, the average blood glucose concentration is approxi-mately 90 mg/di. This simply means that in every lOO ml of blood, there is 90 mg of glucose. If this concentration were expressed as percentage, it \Votild be 0.09%,, which is a more awkward number to use.

### Molar (M) Solutions

A 1 molar (M) solution contains 1 mole of solute in 1 L of solution. One mole of a substance contains $6.024 \times 10^{23}$ molecules (Avogadro's number). Thus, solutions of equal molarity have the same number of molecules in solution, even though their molecular weights might be different. One mole is equal to the molecular weight (MW) or atomic weight of the solute in grams.

For example, the MW of glucose is 180. To prepare a 1 M solution of glucose, we would weigh out 180 g of glucose and dissolve it in a total vol-ume of solution (solvent + solute) of 1 L Eighteen grams of glucose in 100 ml of solution would also be a 1 M and 18'X, solution. Why?

To make a 1 M solution of NaCl (58.5 MW), we would dissolve 58.5 g of NaCl in 1 L of solution. This would be the same as 5.85 g of NaCl in 100 ml, or a 5.85':Yo solution. You can see from these exam-ples that decreasing the amount of solute and solu-tion by the same proportion does not change the concentration of the solution.

Because of the low concentrations of solutes in body fluids, e often use millimolar (mM) meas-urements in physiology. If 180 mg of glucose is dissolved in 1 L of solution, a 1 mM concentration is produced.

Glucose concentration in the blood = 90 *mg/* 100 ml = 900 mg/L.

$$\frac{900 \text{ mg}}{180 \text{ mg/mM}} = \text{S mM glucose}$$

**Osmolar (Osm) Solutions**

Osmolar concentrations are used mainly in the biological sciences to express the osmotic effect of a solution. To understand their use, \Ve will look at some examples. (Osmosis and osmotic effects are further explained in Chapter 2. "Movement Through Memhranes.")

A membrane permeable only to water separates a container into t\vo compartments (Figure 1. la. Water molecules are in side A, and glucose molecules are trapped in side B. In an effort to reach equilibrium, the water molecules pass through the membrane into side B, moving from a higher to a lower water concentration. We cal I this water movement **osmosis.** The force of the water movement on the membrane is called the **osmotic pressure** and is determined by the num-ber of molecules in side B that cannot penetrate the membrane. The 1 M glucose solution is 1 Osm in the osmotic pressure it produces on the mem-brane.

If the concentration of glucose (a nonelectrolyte is doubled in side B to 2 M (Figure I.lb, the water moves across with twice the osmotic pressure because there are twice as many osmoti-cally active particles in solution. Thus, the 2 M glu-cose solution is 2 Osm in its osmotic effect.

Some electrolyte molecules, such as NaCl (table salt, do not remain as molecules in solution but dissociate into ions.

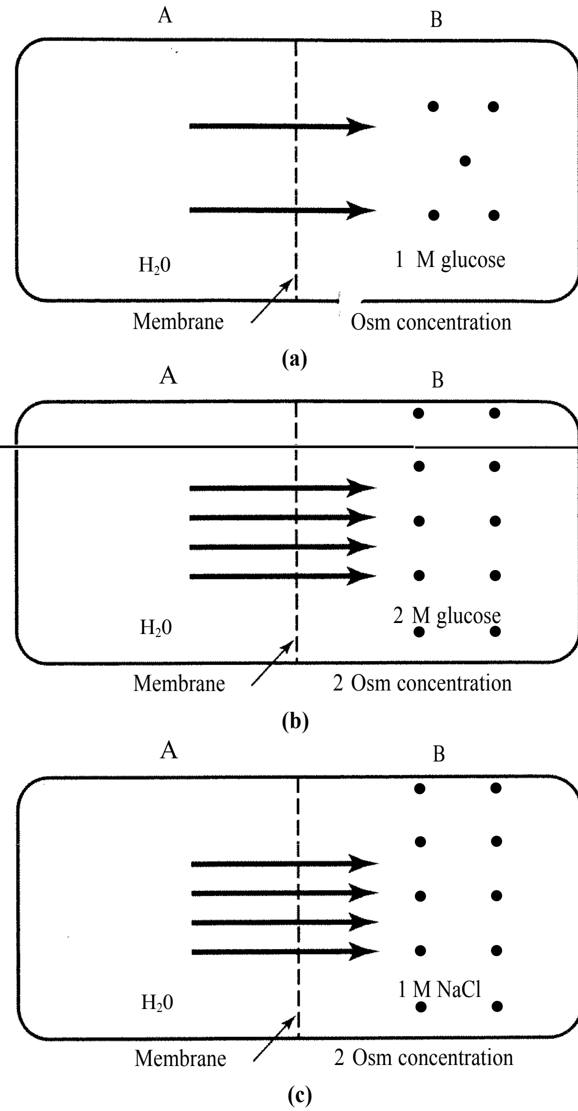


**FIGURE 1.1** Examples of osmotic effects of solutions.

1 mole NaCl - 1 mole $Na^+$ + 1 mole Cl-

Each ion acts as an osrnotically active particle to cause water movement into the region of higher solute concentration (osmosis. Thus, a 1 M NaCl solution produces the same osmotic pres-sure as a 2 M glucose solution (Figure 1. lc J. Both solutions are therefore 2 Osm in their osmotic concentration. The osmole provides a measure of a solution's ability to produce osmosis or osmotic pressure.

The osmotic particles in the cells of a mammal have a concentration of 0.3 Osm. If we bathe the cell in a solution having the same osmolar concen-tration (e.g., 0.3 M glucose or 0.15 M NaCl, there will be no net movement of water in or out of the cell, and the cell will retain its size and shape (Figure 1.2). Solutions having the same osrnolar concentration as the concentration inside the eelI are said to he **isotonic** (same "'tone"' or ··tension"' J. Solutions with a higher osmolar concentration are called **hypertonic,** and those \Vith a lower osmo-lar concentration are **hypotonic.** \'\'hich way will water move if a cell is placed in each of these solutions' Some examples of osmolar calculations are as follows:

To make a 1 Osm solution of NaCl (58.5 M\'\'J, dissolve 58.5 g/2 = 29.2'5 g in each liter of solution (two ions formed in solution).

To make a 1 Osm solution of $CaCl_2$ (110 M\\'). dissolve 110 g/3 = 36.6 g in each liter because $CaCJ_2$ dissociates into three ions in solution.

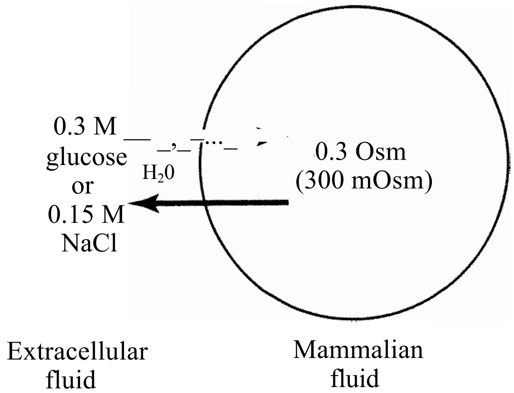


**FIGURE 1.2** Example of osmotic equilibrium.

### Equivalent (Eq) or Milliequivalent (mEq) Solutions

This means of expressing the concentration of ions is used extensively in chemistry and the various biological sciences. We will not use it in this manual, but you should be aware of it because it appears often in textbooks and research papers. Equivalent weights reflect the combining power of substances during a chemical reaction, which in turn depends on the valence (charge) of the atoms involved. For univalent ions such as $Na^+$, $K^+$, and c1-, the milliequivalents are equal to millimoles. Only when we deal with divalent ($Ca^{2+}$) or triva-lent ($Fe.3^+$) ions will the milliequivalent and mil-limole concentrations differ.

### Concentration of Solutions

To solve concentration problems, we need to know the relationships between percentage, molarity, and osmolarity concentrations. If these are related in a stepwise fashion, it is easier to understand and solve such problems. As an example, let us use a series of steps to solve the following problem: What is the osmolar concen-tration of a 2% solution of KCl?

1. Percentage refers to the number of grams in 100 ml of solution.

   2% KCl = 2 g of KC! dissolved in 100 ml of solution

2. To go from percentage to molarity, we must first determine the number of grams in 1 L (1,000 ml) of solution.
   2 g KCl in 100 ml= 20 g KCl in 1;000 ml (1 L) (because 1,000 is 10 x 100)

3. To determine molarity, we first determine the number of grams per liter in a 1 M solution of the substance.

   1 M KCl (74 MW) = 74 g/L
   Therefore, 20 g/L of KCl is less than 1 M. Specif-ically, we have 20 g/74 g = 0.27 M of KCl.

4. To go from molarity to osmolarity, we need to know whether the substance is an electrolyte, which dissociates into ions in solution, or a nonelectrolyte, which remains as molecules in solution. KCl is an electrolyte that forms 2 ions ($K^+$ and $Cl^-$) in solution.

   Moles x Number of ions -Osmoles

   Therefore, 0.27 M x 2 ions= 0.54 Osm KCl.

**CLINICAL APPLICATION**

### Treating Severe Dehydration

Dehydration. a condition in which more water is lost from the body than is taken in. is a life-threatening condition usually brought about by conditions such as diarrhea, vomiting, disease, or too much exercise and heat exposure. As fluids are lost from the body. so are essential salts, prevent-ing the body from functioning normally. Severe dehydration can cause rapid, weak pulse; fever; fast, deep breathing; or con-vulsions. Left untreated. it is fatal. Commercial oral rehydration fluids such as Pedialyte® or Enfalyte® contain a carbohydrate, sodium. potassium. and chloride ions and a citrate with an osmolarity between 200 and 300 mOsm/L. These solutions can be administered to alleviate the symptoms of dehydra-tion by restoring hydration levels and replenishing the lost electrolytes.

## Acid-Base Balance

It is critical for the body's homeostasis (mainte-nance of a constant internal environment) that the concentration of hydrogen ions ($H^+$) in the blood be maintained within the narrow range of pH 7.0 to 7.8. If the pH goes below or above these limits, death results because most enzymes cannot operate properly if the pH is outside this range. In light of the great importance of $H^+$ reg-ulation, let us review the concepts of pH and acid-base balance.

### pH

The pH scale is simply a way of expressing small molar concentrations using whole numbers (Figure 1.3). It was devised by the Danish chemist

| | Acid | | | | | | | Neutral | Basic (Alkaline) | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| H+ conc. | $10^0$ | $10^{-1}$ | $10^{-2}$ | $10^{-3}$ | $10^{-4}$ | $10^{-5}$ | $10^{-6}$ | $10^{-7}$ | $10^{-8}$ | $10^{-9}$ | $10^{-10}$ | $10^{-11}$ | $10^{-12}$ | $10^{-13}$ | $10^{-14}$ |
| pH | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 |
| OH- | | | | | $10^{-10}$ | $10^{-9}$ | $10^{-8}$ | $10^{-7}$ | $10^{-6}$ | $10^{-5}$ | $10^{-4}$ | $10^{-3}$ | $10^{-2}$ | $10^{-1}$ | $10^0$ |

## Acids and Bases

**Acid.** Substance that dissociates into hydrogen ions ($H^+$).

**Base.** Substance that dissociates into hydroxyl ions (OI-r-).

**Salt.** Substance that dissociates into neither $H^+$ nor OH-in solution.

A major problem for the body is that many acids are produced during metabolism. One of the most important of these is carbonic acid, formed when carbon dioxide ($CO_2$) dissolves in body fluids:

| $CO_2$ + | $H_2O$ ↔ | $H_2CO_3$ ↔ | $H^+$ + | $HCO_3^-$ |
|---|---|---|---|---|
| carbon dioxide | water | carbonic acid | hydrogen ion | bicarbonate ion |

This is one of the most important chemical reactions you will encounter in your study of physiology. Other acids that lower the pH of body fluids are phosphoric, sulfuric, hydrochloric, lactic, keto, and fatty acids.

## Buffer Systems

Even though the body produces tremendous quantities of acid each day, blood pH usually remains within the range of 7.35 to 7.45. This is made possible by the action of various buffer systems in the body fluids.

**Buffer.** Substance that prevents (resists) a drastic pI1 change when acids or bases are added to a solution.

**Buffer mechanism.** Mechanism that replaces strong acids or bases with weak acids or bases that produce less $H^+$ or Olr in solution.

The major buffer systems found in most animals are the protein, phosphate, and bicarbonate systems. **Proteins** are the most abundant buffers, playing a critical role inside body cells as ,veil as in the blood Ce.g., albumins. hemoglobin). **Phosphates** are less abundant but perform important buffering in the intracellular fluid and kidney tubules.

**Bicarbonates** are most important in the buffer-ing of the extracellular fluid (interstitial fluid and plasma). The bicarbonate system is a unique buffer because its components ($HCO_3^-$ and $CO_2$) cm he regulated by the renal and respiratory systems. This makes it a very powerful ancl flexible buffer. one that deserves closer scrutiny.

| Bicarbonate buffer | = | $H_2CO_3$ carbonic acid (weak acid) | + | $NaHCO_3$ sodium bicarbonate (conjugate base) |
|---|---|---|---|---|

Adding a strong acid or base to this system produces the follmving reactions:

| HCI hydrochloric acid (strong base) | + | NaHCC}, | → | $H_2CO_3$ NaCl (weak acicl) (salt) |
|---|---|---|---|---|
| NaOH sodium hydroxide (strong base) | + | $H_2CO_3$ | → | $NaHCO_3$ (weak base) + $H_2O$ |

Thus. the bicarbonate buffer chemicals replace strong acids and bases with weak acids and bases that dissociate only weakly and therefore produce little change in pH. The following activity demonstrates how buffers moderate the pH effects of acids and bases.