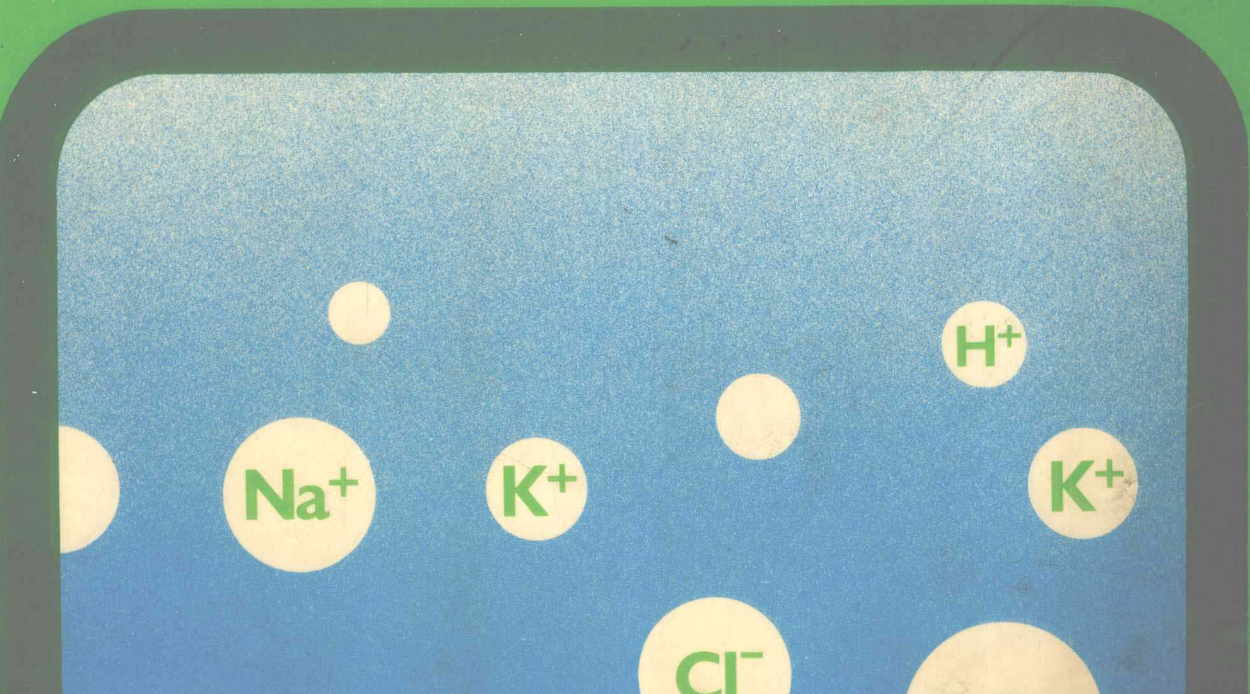
FLUIDS & ELECTROLYTES

A CONCEPTUAL APPROACH



Kinsey Smith, M.D.

Churchill Livingstone

FLUIDS & ELECTROLYTES

A CONCEPTUAL APPROACH

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Preface

This illustrated text was developed primarily for undergraduate medical students at McMaster University. Some of these students do not have any background in the physical or biological sciences, and many of the basic concepts they need for the understanding of body fluid regulation are foreign to them. Moreover, the constraints of a three year undergraduate course emphasize the value of clear introductory resources which link basic concepts to relevant clinical problems.

This book attempts to introduce the idea of a regulated internal environment and its responses in health and disease. The illustrations provide a visual summary, the text a simple and direct description of the illustrated concepts. It does not pretend to be comprehensive and the student should *not* use it to replace more detailed and scholarly resources. The method of presentation is not conventional, but the underlying concepts are well established and lean heavily upon the influence of other authors; the references provided at the end of the book represent only a small selection of useful resources and do no more than point the way to wider reading. The lucid writings of the late L.G. Welt and R.F. Pitts have been especially valuable to me and I make no apology for the major influence they have had in the development of the concepts that are illustrated here. Many ideas for visual presentation have come from the enthusiasm of Dr. Elizabeth Brain and members of the Audio Visual Department, and thanks are due to those colleagues amongst students and faculty who have provided stimulation and advice over the past decade.

This text is based in part upon material that has been used in a slide/tape format for a number of years. It is now offered to a wider readership in the hope that it may prove useful in other medical, nursing and paramedical programmes and perhaps as a reminder for more advanced students.

Kinsey Smith

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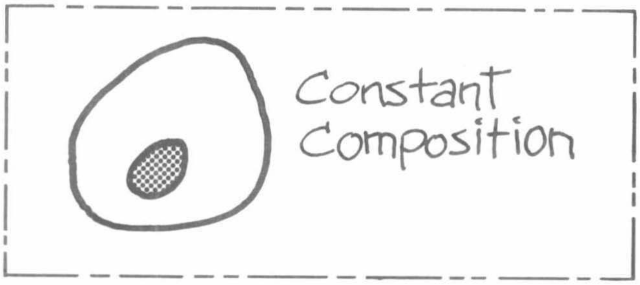
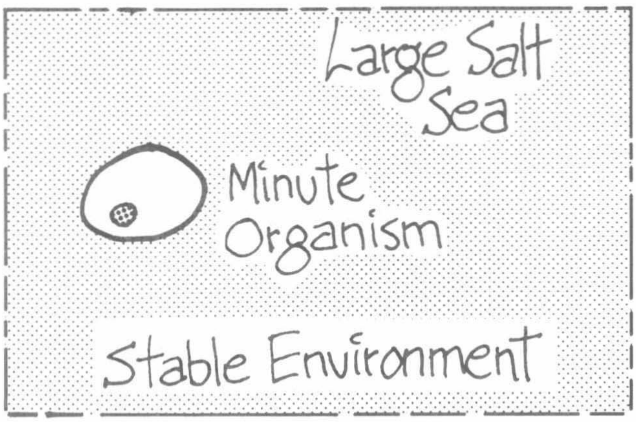
The Cellular Environment

The Cell...

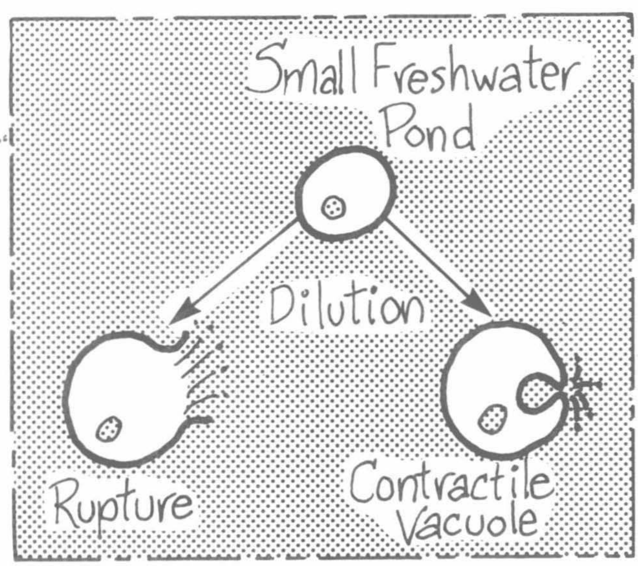


The unit of biological function is the single cell which requires a defined composition to function normally. It must be capable of acquiring those vital nutrients which may become depleted, and of rejecting those end products which are not required.

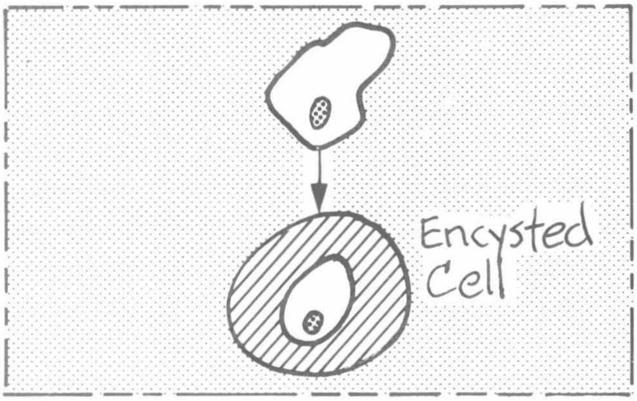
...and its Surroundings



Simple, single-celled organisms evolving in an almost infinitely large salt sea may be considered as having an unvarying external environment. In this setting, regulation of their volume and composition is relatively simple. Surrounding osmotic pressures do not change appreciably and the concentration of solutes around them is constant. Waste products can leave the cell and become infinitely diluted in the surrounding fluid.

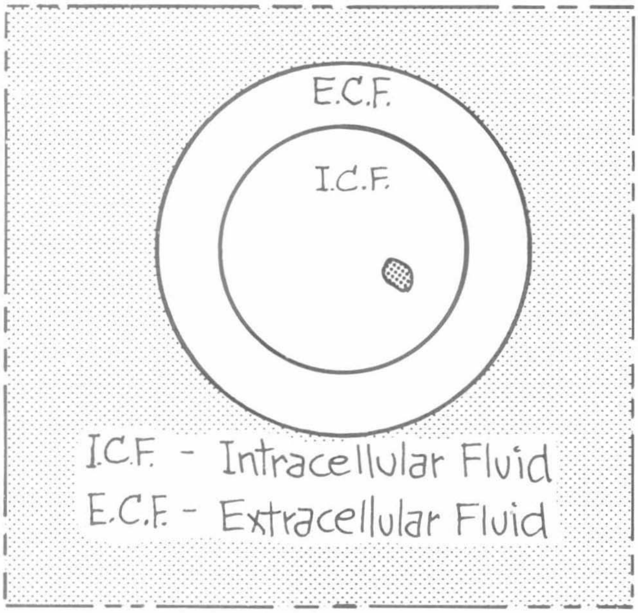


A single-celled organism (such as an ameba) living in a small fresh water pond faces a more hostile environment. A vigorous rain storm may dilute the already solute-poor water in the pond and produce increasing osmotic pressure gradients which cause water to enter the cell which will swell up to the point of bursting. Adaptations which prevent this happening include the evolution of such devices as "contractile vacuoles" which can eject unwelcome volume.

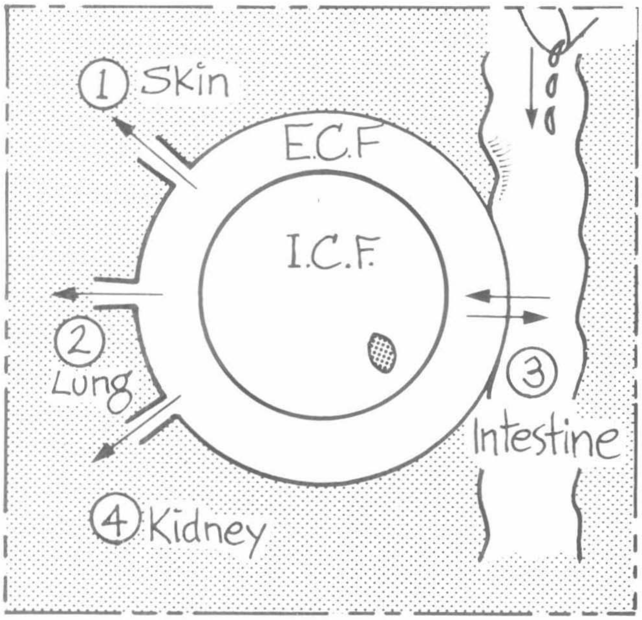


If the pond dries up, the reverse process occurs and the cell becomes shrivelled and dehydrated. The protection such an organism can provide for itself is to become encysted, surrounding itself with a ''waterproof coat'' which will allow it to withstand desiccation and become reactivated when conditions improve. The price paid for this survival is to undergo periods of immobility and inactivity.

"Milieu Interieur"



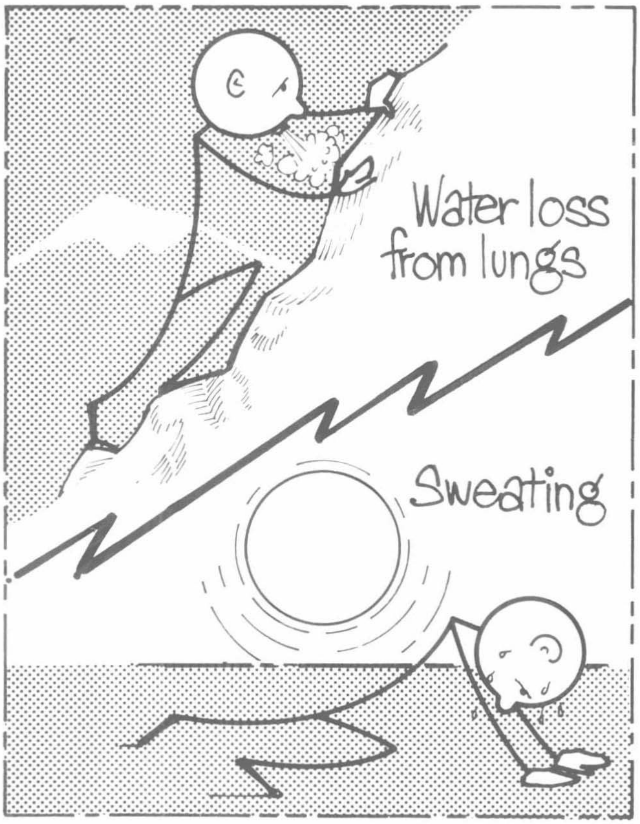
Warm blooded multicellular animals, like man, have adapted to life on dry land by taking with them a ''personal environment'', the composition and volume of which are precisely regulated even in the face of widely varying external conditions. This environment is like a ''shell'' of fluid which allows the cells to ignore changes in the outside world. This insulating shell is the ''milieu interieur'', first recognized by Claude Bernard. The internal environment is provided by the extracellular fluids.



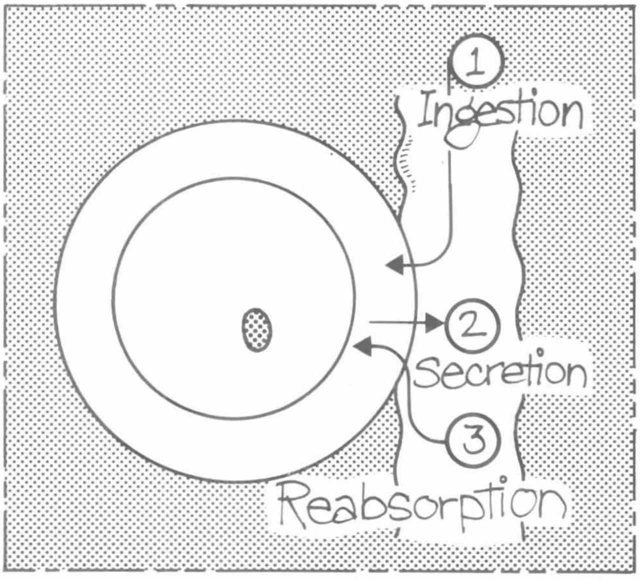
The internal environment is provided by the extracellular fluids. The only natural entry point to this fluid ''compartment'' is via the mouth and intestinal tract. There are four exit routes from the extracellular fluid space:

1) The skin, where loss occurs by perspiration and is related to temperature and humidity.
2) The lung, where loss is related to the need to moisten the air we breathe.
3) The intestine, where diarrhea or vomiting may cause abnormal losses.
4) The kidney.

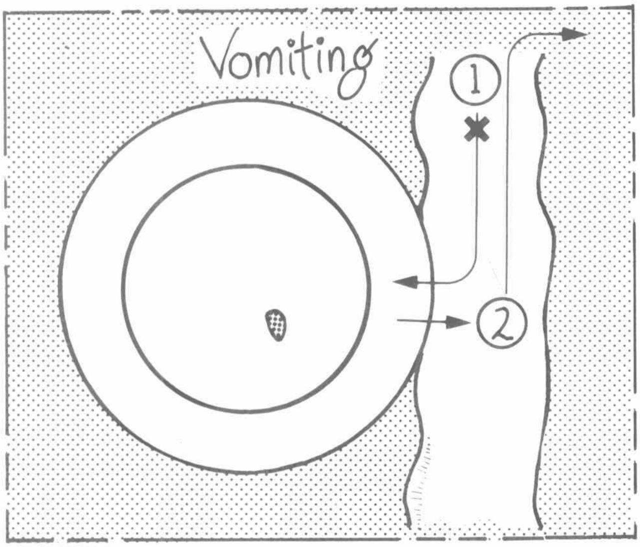
Fluid Loss from the E.C.F.



Losses via the skin and the lung are dependent upon external factors which cannot be controlled. Thus men climbing high mountains in cold, dry air will have enormous water losses from the lungs as hypoxia demands increased ventilation; men suddenly transported to a hot climate may sweat unmanageably.

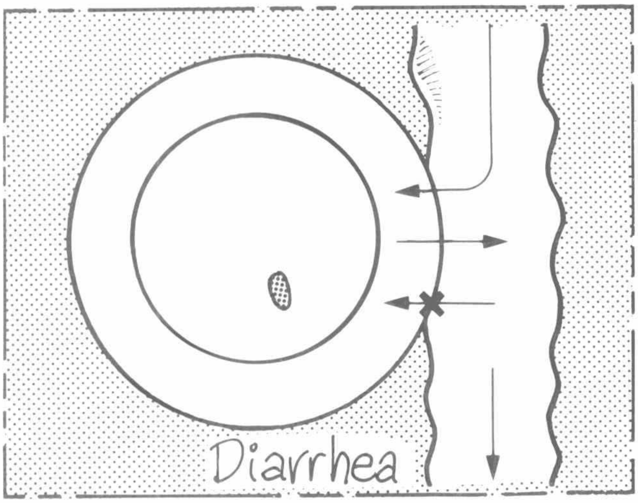


Intestinal losses are not "physiological" (as are losses from skin or lung), and are related to abnormal states where vomiting or diarrhea occur. The normal intestine absorbs fluids that are ingested (1); secretes large amounts of digestive fluids (2); and then reabsorbs virtually all that it secretes (3). The fluids in the intestine are separate from E.C.F., but because of the large surface area of the intestinal mucosa and its close contact with the E.C.F. compartment, potential losses from the E.C.F. into an abnormal intestine can be large. If mucosal function is disturbed the intestinal wall can cease to be a barrier to the E.C.F. with the result that diarrheal losses or losses into a dilated bowel, as in paralytic ileus, represent direct losses from the E.C.F.

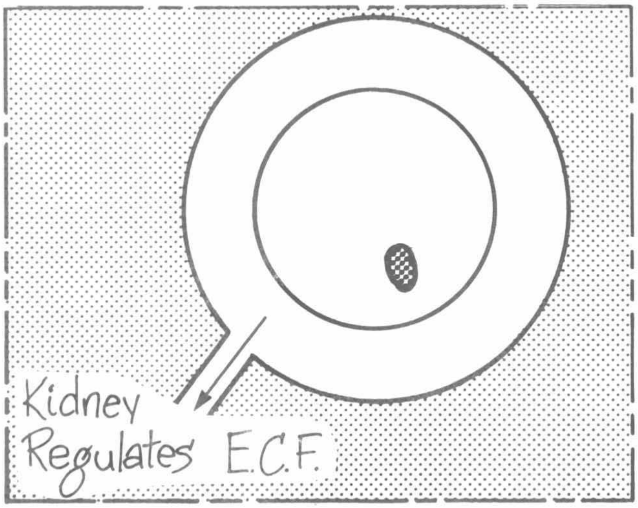


Vomiting causes fluid loss in two ways:

1) By failure to allow intake of normal fluid volumes,
2) By the ejection of fluids secreted into the upper intestine.

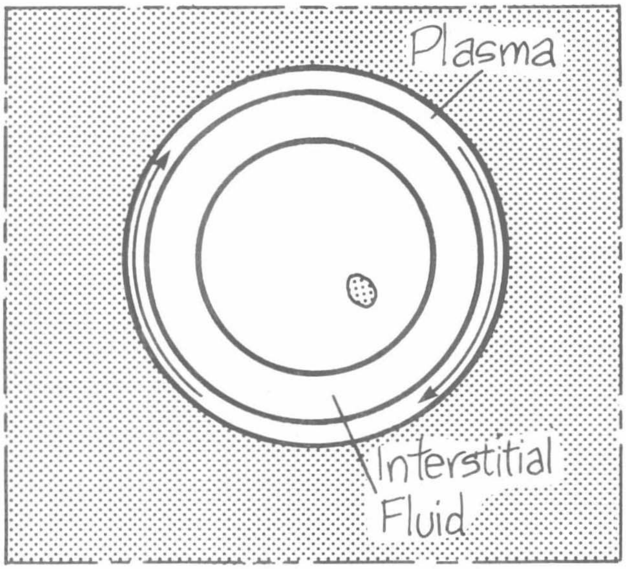


Diarrhea involves a failure to reabsorb the fluids secreted into the intestine and often a change in permeability of the mucosa. This allows the intestine to become the site of what, in effect, are direct losses of E.C.F. Thus most intestinal losses (either up or down) tend to be isotonic with respect to the E.C.F.

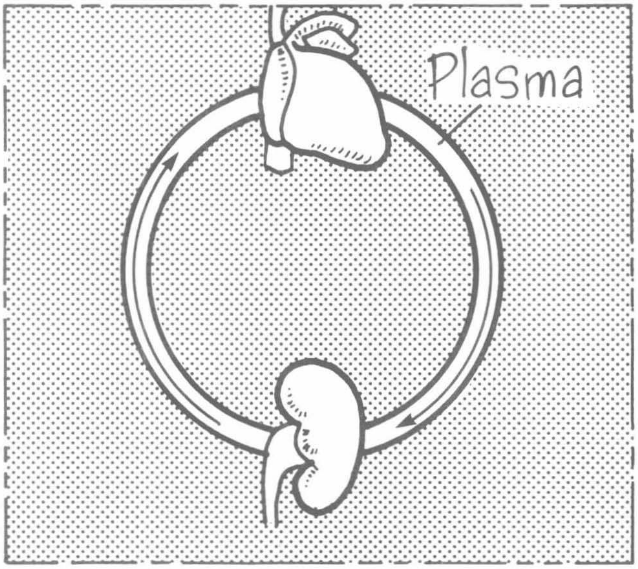


Only the losses from the kidney can be regulated precisely and this organ therefore plays a crucial part in the regulation of the E.C.F. volume.

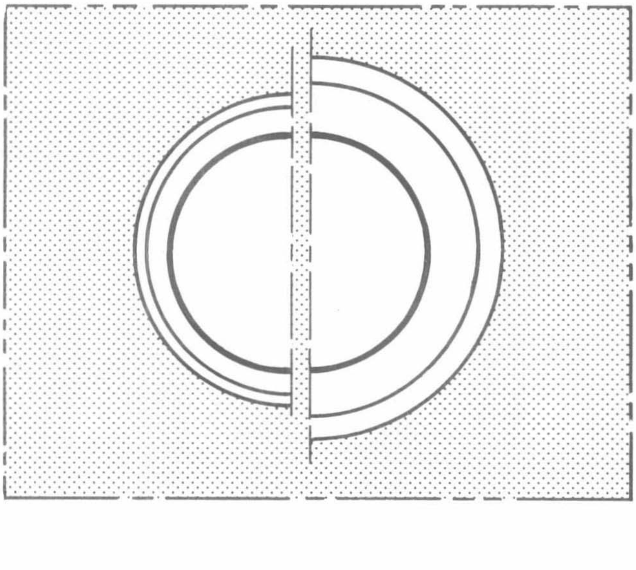
Subdivision of E.C.F.



The E.C.F. is a little more complicated than we have indicated so far since it can be subdivided into two compartments. One, the larger part, contains the interstitial fluid which surrounds the cells. The second contains the plasma which, of course, circulates throughout the body and can therefore act as a "bulk transporter" of water and solutes in the E.C.F. It can also serve as a route for the even and rapid distribution of very small quantities of substances such as hormones and drugs.

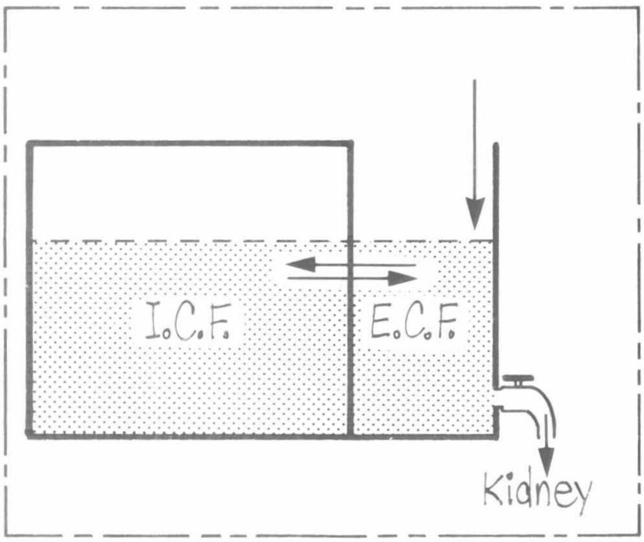


In some diagrams we will show the plasma compartment in this way, which indicates the importance of the heart as a pump for the plasma and the kidney as a sensor and regulator of its volume.

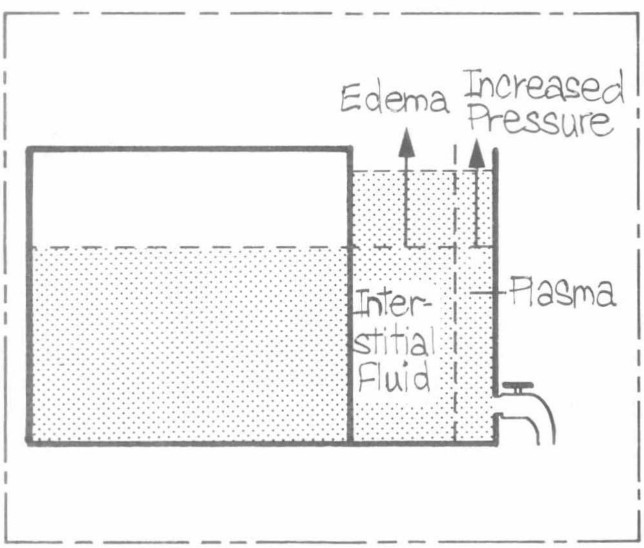


In normal health, changes in the volume and composition of the E.C.F. are within narrow limits. In most clinical situations the plasma and interstitial volumes vary in the same direction although sometimes they may change in opposite directions. Significant change in the E.C.F. can occur without any appreciable change in the I.C.F. because the E.C.F. provides a "protective shell".

The Tank Model

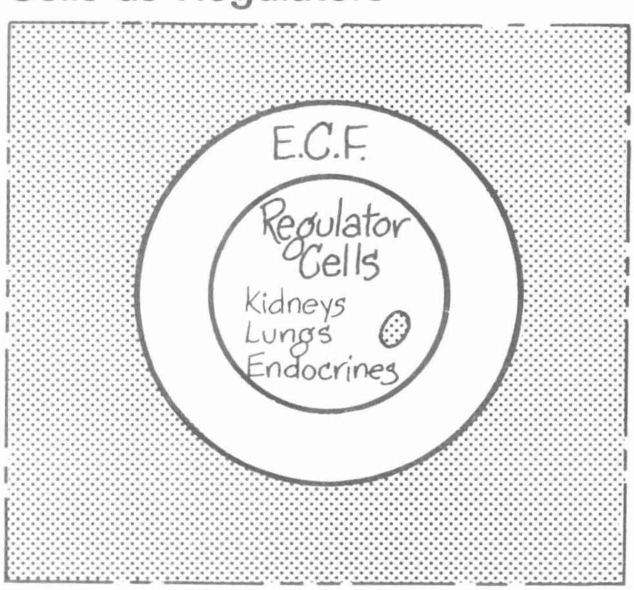


Whilst in reality the E.C.F. surrounds the I.C.F. like a shell, it is often more convenient to depict the compartments as shown here. The I.C.F. is drawn as a closed space which indicates that there are limits to its ability to expand, and the only way into and out of the I.C.F. is via the E.C.F. The tap represents the kidney, and the dotted line the fluid volume in the compartments.



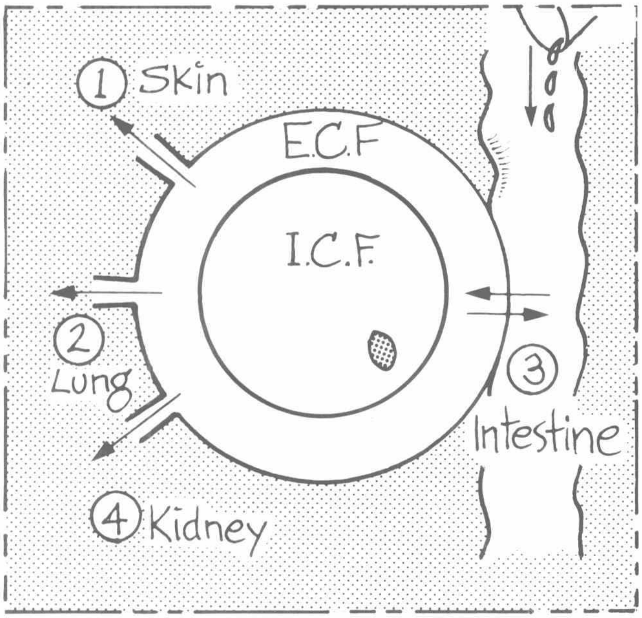
The E.C.F. includes the plasma and interstitial fluid compartments. Expansion or contraction of these spaces can be recognized by such changes as the presence or absence of edema (for the interstitial space) or changes in venous or arterial pressure (the plasma space). These will be reviewed in more detail in Chapter 3.

Cells as Regulators

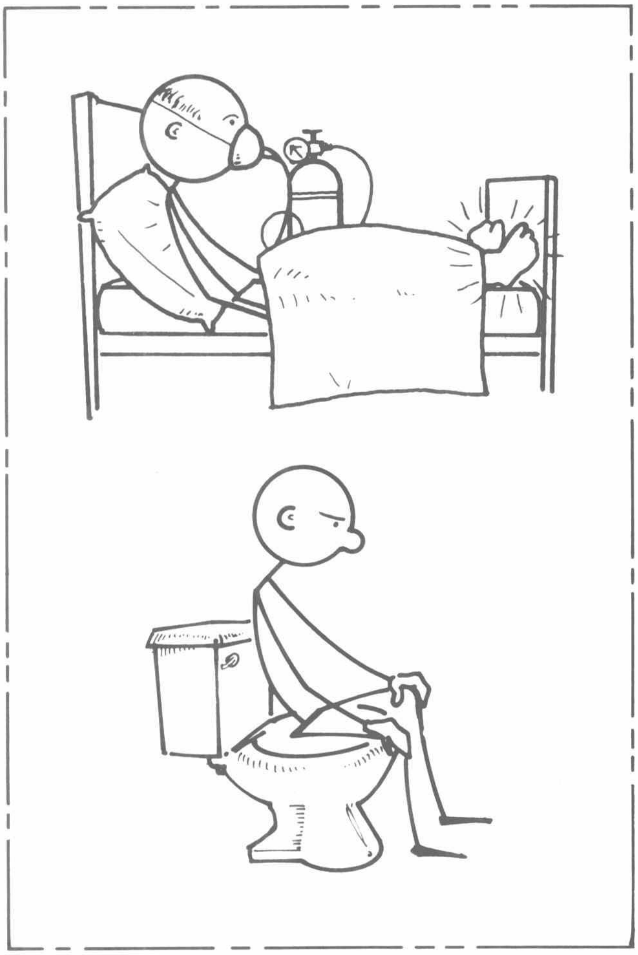


Whilst the body cells in general are protected from environmental changes by the constancy of the E.C.F., some of the cells in the body are specially adapted to regulate the volume and composition of the E.C.F. These include the cells of the kidney, the lung, and some of the endocrine glands.

Purpose of this Book



This book is about the body fluid compartments and the principles governing the regulation of both their volume and composition. It is concerned with *concepts,* and not with the details of distribution of every solute in every body fluid compartment.



These concepts are fundamental to the understanding of the practical management of disorders of the body fluids. They explain such apparently different situations as heart failure and cholera.

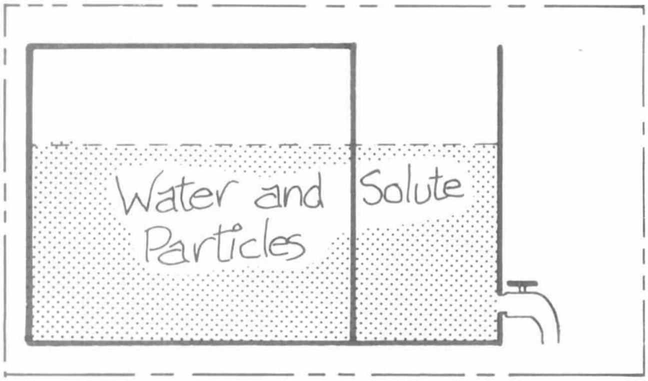
They can be applied to the understanding of such things as diuretics, diabetes and drug distribution. They are, quite simply, basic building blocks for good medicine.

Chapter 2

Coming to Terms with Terms

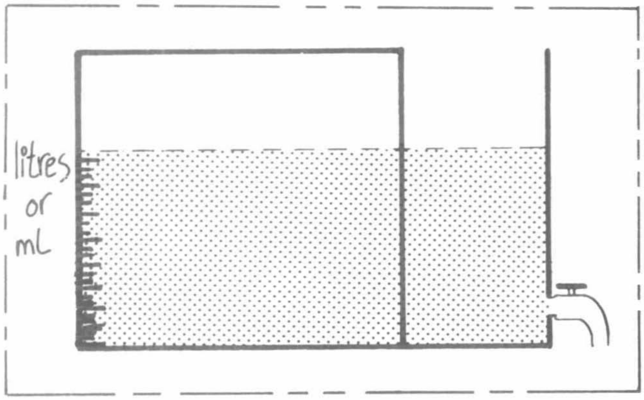
Before going any further into the distribution and regulation of fluids and electrolytes it is important to understand their measurement and the units by which they are expressed. The problem here is that changes are occurring as the S.I. system of units is being introduced. ''S.I.'' stands for Système International des Unités which attempts to relate all units of measurement to seven ''base units.'' Where such units, together with the units derived from them, are applicable to clinical science they are being introduced as a rational advance. The rate at which these units are being introduced and accepted in clinical practice is more rapid in Europe than North America and the completeness with which they will be accepted is not yet clear. For these reasons the terms used in clinical medicine are not ''pure'' and for the time being this is likely to remain so. This chapter will attempt to clarify the concepts of current usage, with the understanding that the S.I. system is likely to become more widely used as time passes.

Body Fluids



All body fluids are aqueous solutions and therefore consist of water (the solvent) and dissolved particles (the solutes).

Water - The Solvent

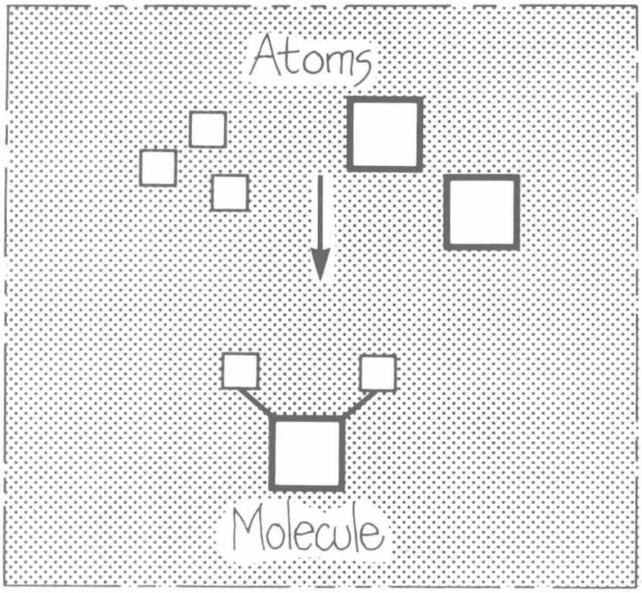


When we talk about a ''volume'' we mean a volume of water and its dissolved solutes. Water can be regarded as the major solvent for biological systems. The volume occupying any ''space'' or ''compartment'' is measured in litres (L) or millilitres (mL).

Solutes

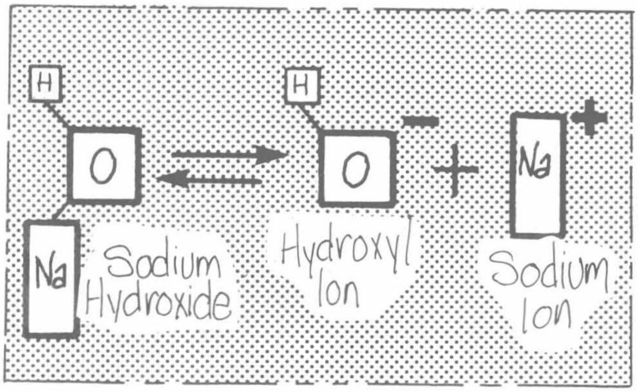
The solutes are minute particles which may be molecules or fragments of molecules.

Molecules

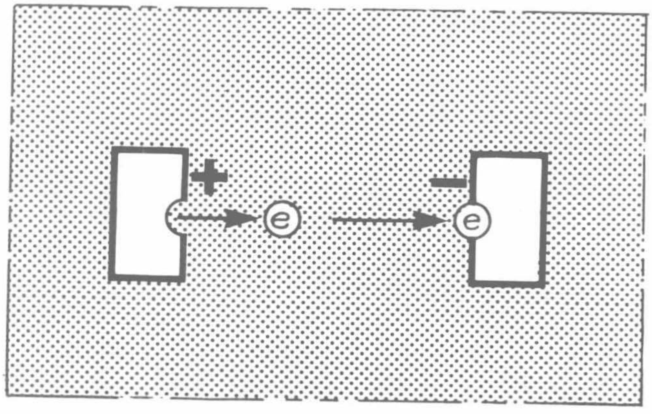


A molecule is the smallest particle into which a compound may be divided whilst still retaining its chemical identity. Molecules are made up of collections of *atoms* which are electrically neutral with a balance between positive charges in the nucleus and negatively charged electrons in the outer shell.

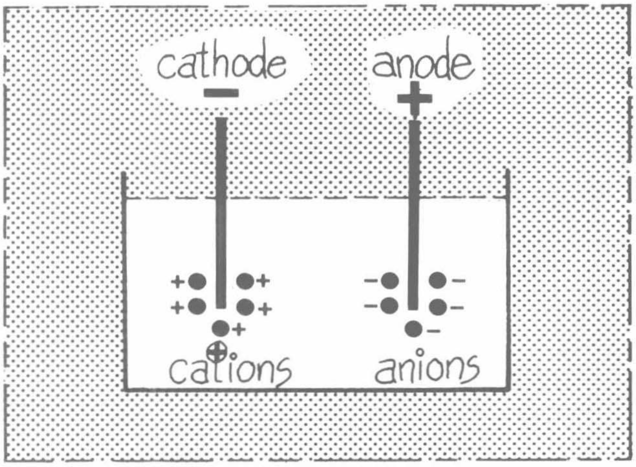
Ions



When molecules dissolve in water they may dissociate to a greater or lesser extent into their component parts which then carry electrical charges and are called *ions*. These ions may contain part of a single atom (such as sodium) or more than one atom (as in the hydroxyl ion).



Positively charged ions have given up an electron, and negatively charged ions have gained an electron.



If electrodes are placed in a solution the positively charged ions migrate to the cathode and are called *cations*. Negatively charged ions migrate to the anode and are called *anions*.

Cations are positively charged.
Anions are negatively charged.

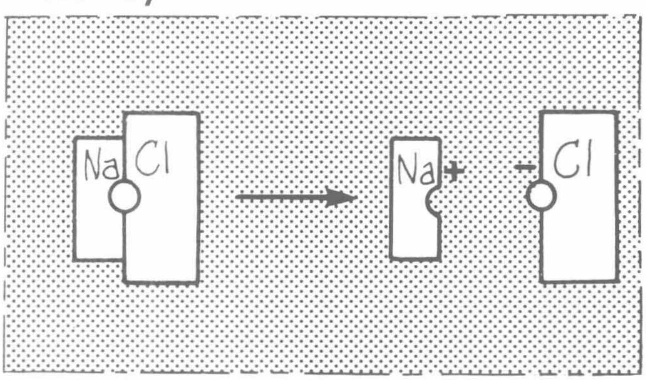
Electrolytes

$$NaCl \rightleftharpoons Na^{+} + Cl^{-}$$

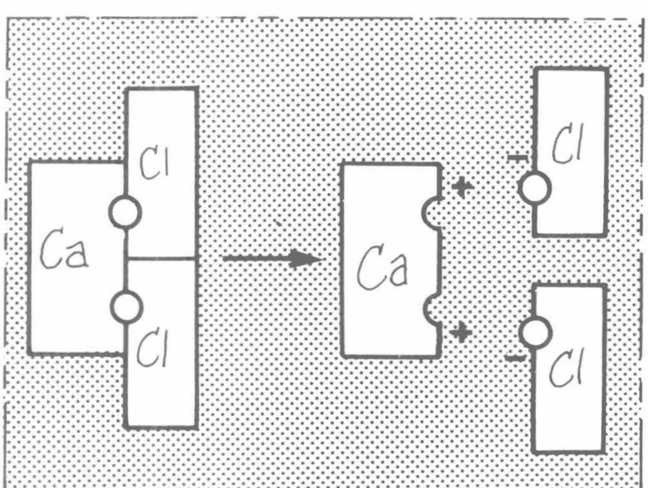
The interaction between the constituent ions of a substance in solution is an electrochemical one.

The charged nature of the particles in such a solution allows it to act as a conductor of electrical current. Such ionizing substances are therefore called *electrolytes*. Sodium chloride is an example of such a substance.

Valency

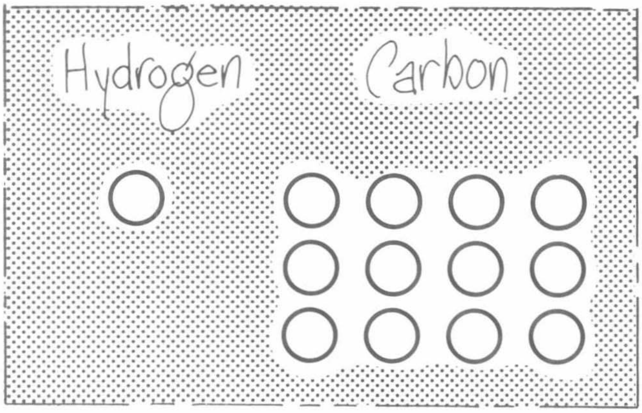


When sodium chloride dissociates, the chloride ion acquires one electron and becomes an anion, whilst the sodium ion loses *one* electron to become a cation. Sodium and chloride are each *univalent* ions.



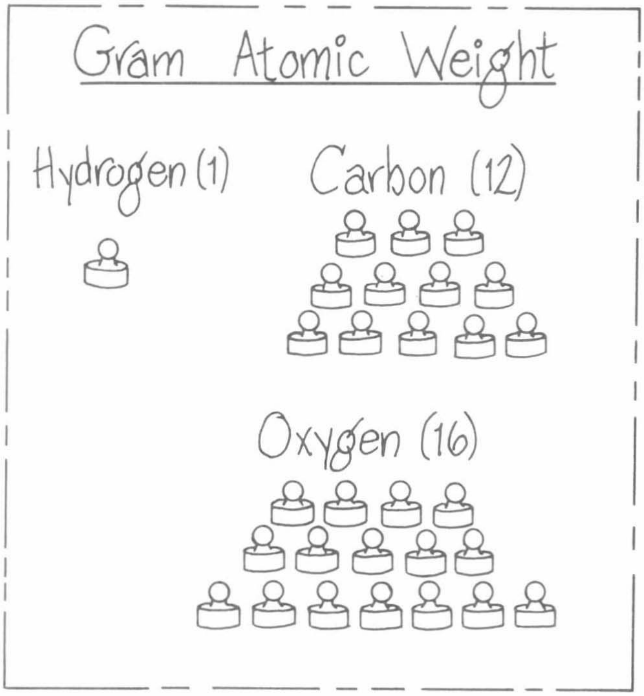
Calcium chloride, on the other hand, dissociates into one calcium ion with two positive charges and two chloride ions each with one negative charge. Calcium is a *divalent* ion.

Atomic and Molecular Weights



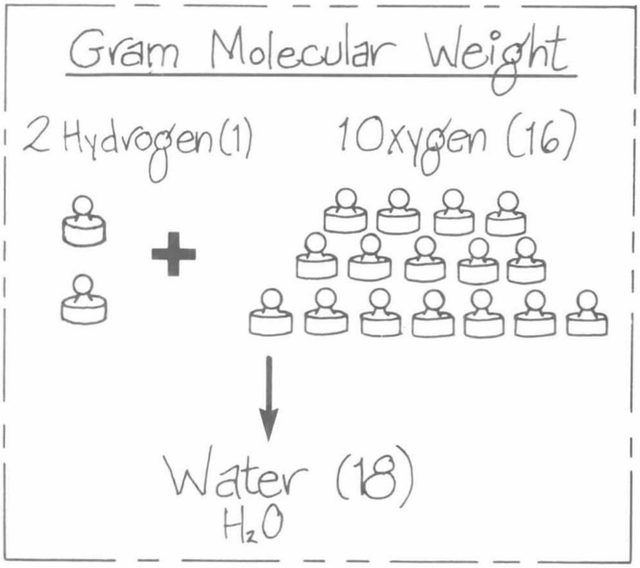
The atoms which make up a substance can be related to one another in terms of mass (*the atomic weight*). If the atomic weight of *hydrogen* is taken to be unity, then *carbon* has an atomic weight of 12, indicating that it is twelve times as heavy as hydrogen. Atomic weights are therefore *relative* masses to a reference atom and not actual weights.

Although the "reference atom" is, historically, hydrogen, *carbon*, with an atomic weight of 12, is now used as the absolute standard against which other atomic weights are compared.



Atomic weights can be expressed in any unit of mass, but most commonly it is the gram. Thus the *gram atomic weight* of hydrogen is 1 gram, and of carbon 12 grams, but since atomic weights are relative to one another *any* unit of mass can be used for comparison so long as the two atoms being compared are expressed in the same unit.

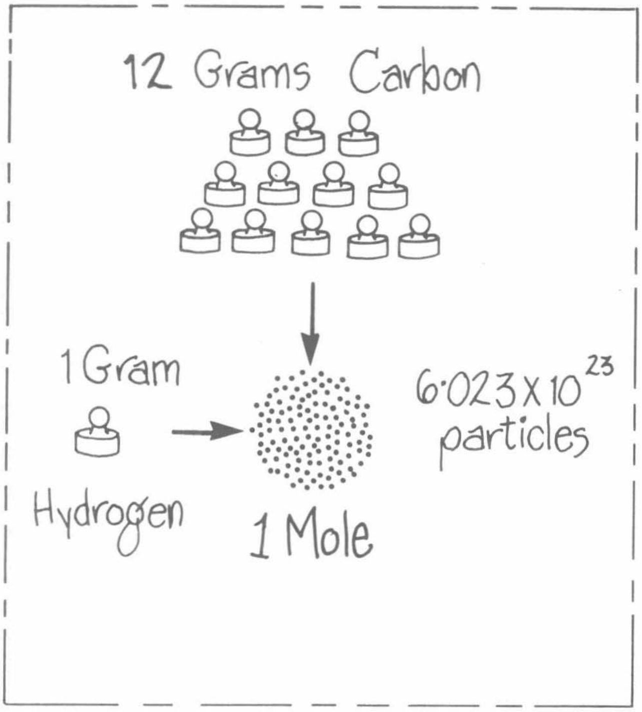
Whatever unit of mass is used, an atom of oxygen will always be sixteen times as heavy as hydrogen, and one and a third times the mass of a carbon atom.



Since molecules are made up of collections of atoms their mass can be compared one to another as the *molecular weight*, which is the sum of the atomic weights of the constituent atoms. Just as atomic weights are relative to an absolute standard (hydrogen or carbon), so molecular weights are related to the *same* standard since they are made up of collections of atoms.

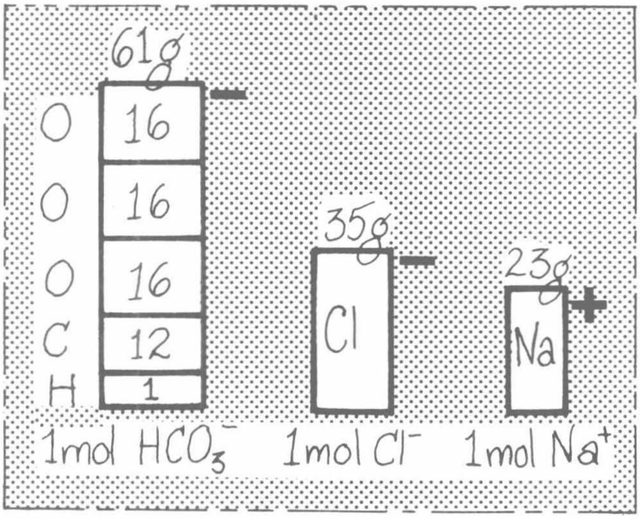
Thus a *molecule* of water has eighteen times the mass of an *atom* of hydrogen and one and two-thirds the mass of a carbon *atom*.

Mole - Amount of Substance

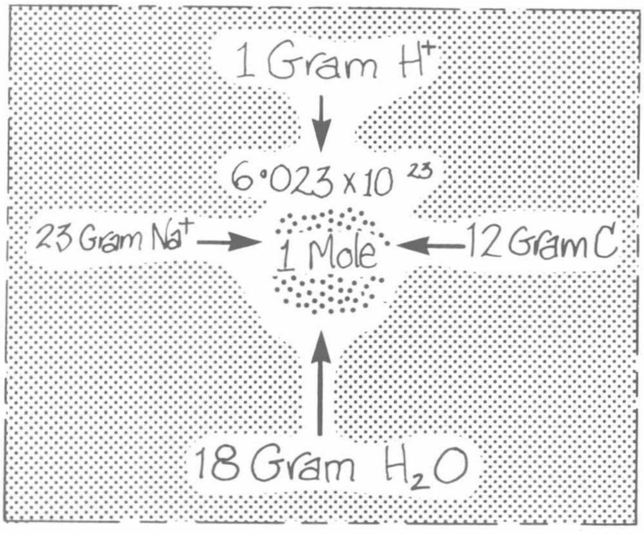


Measurements of the *amount* of any substance in biological systems is related to the basic composition of matter. The S.I. unit for *amount* is the *mole* (mol) which, not surprisingly, is related to the reference unit of atomic mass, namely carbon, (and thus indirectly to hydrogen).

A *mole* is the amount of any substance that contains the same *number* of elementary particles as there are atoms in 12 grams of carbon. (For the purist, this number is 6.023×10^{23} particles and is referred to as Avagadro's number.)



The particles may be atoms or molecules or ions, *all* of which can be measured in *moles*. Thus, 61 grams of bicarbonate ions will contain the same number of particles as 35 grams of chloride ions, 23 grams of sodium ions and (of course) 12 grams of carbon atoms.



In practical terms, the gram molecular or atomic weight will contain the same number of particles as 12 grams of carbon. That is to say, the amount of substance in the gram molecular weight is one *mole*.

Similarly the amount of substance in the gram atomic weight or the gram ionic weight is also one mole.