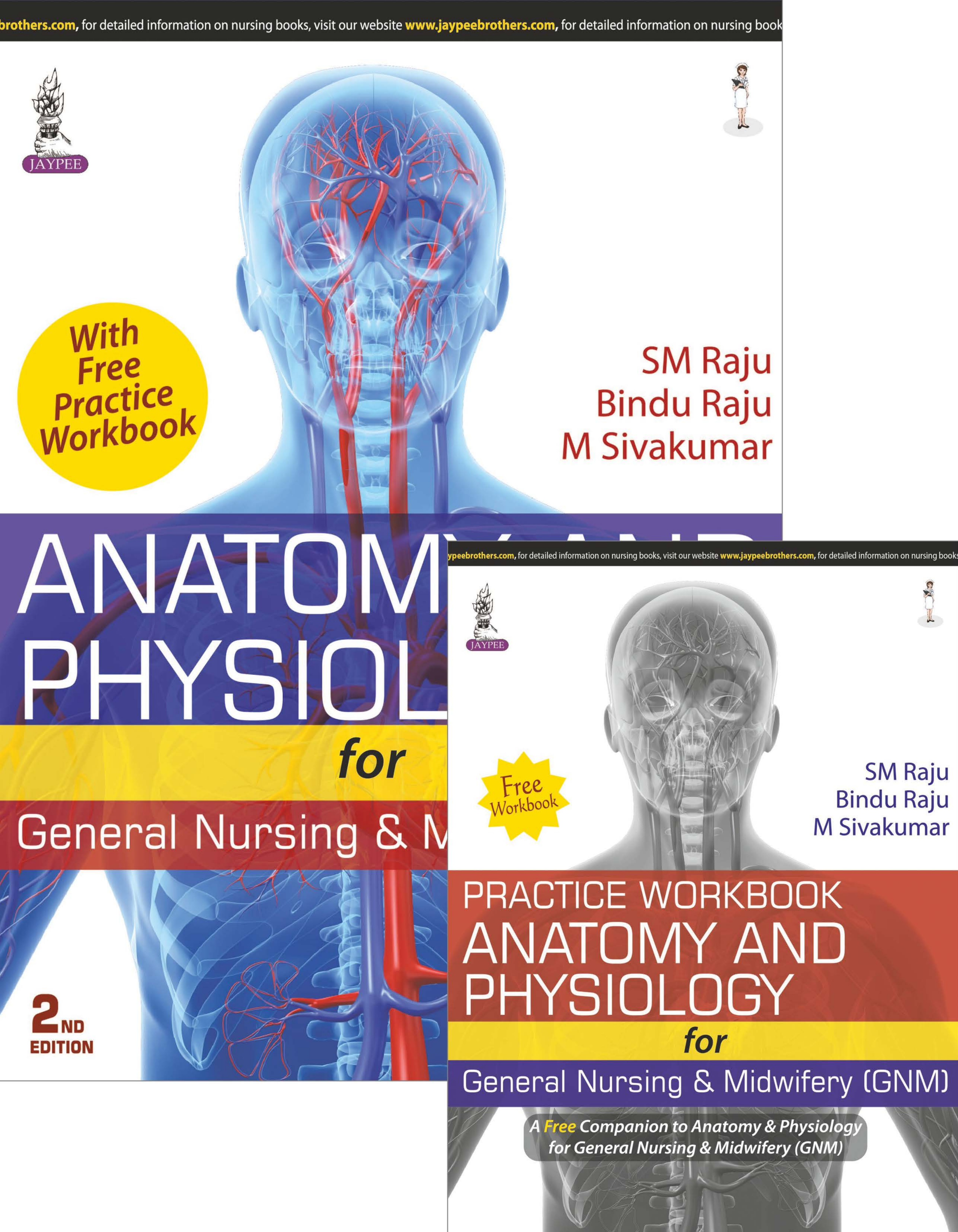
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Contents

Fluid and Electrolyte Balance

Chapter 4

The study of fluid and electrolyte balance gives an overall understanding of its imbalance in the body and its implications.

FLUID BALANCE

- Water has a specific gravity of 1.000
- In a lean adult, water makes up 60%–70% of body weight
- Every liter of surplus water increases body weight by 1 kg
- Adipose tissue contains less water, therefore in an obese person water, only accounts for 30% of total body weight
- Men have a greater proportion of water than women
- In neonates up to 75% of body is of water.

Some Important Definitions

Isotonic Solutions

The two solutions of the same concentration, which produce no resultant flow through a semipermeable membrane.

Hypertonic Solution

Solution with a higher osmotic pressure, i.e. a more concentrated solution.

Hypotonic Solution

Solution with a lower osmotic pressure, i.e. a weaker, more dilute solution.

Semipermeable Membrane

One that allows osmosis and diffusion to take place.

Diffusion

When a strong solution is separated by a semipermeable membrane from a weak solution, then provided the substance dissolved (i.e. the solute) can pass through the membrane, the solute will pass from the stronger to the weaker solution until both solutions have the same strength. The solute moves down a concentration gradient, this is how gases, nutrients and waste products move.

Osmosis

When a concentrated and a weak solution are separated by a semipermeable membrane, which will not allow the solute to pass, water will pass through the membrane until the solutions are equal in concentration, this is called as *osmosis*

FLUID AND ELECTROLYTE BALANCE

Fluid Compartments

Total body water (TBW) in an adult is about 40 L:

- Intracellular: 25 L
- Extracellular: 15 L (has two divisions—interstitial and plasma):
  - Interstitial: 12 L
  - Plasma: 3 L.

Normal Blood Volume

The normal blood volume is 5–6 in an adult:

- Blood comprises of blood cells and plasma
- Packed cell volume of blood (hematocrit) is 45%
- Plasma is 55%.

In order to maintain homeostasis, all systems need to function adequately; the amount taken in should equal the amount eliminated out.

Plasma Proteins

The important plasma proteins are albumin (55%), globulins (38%) and fibrinogen (7%). The important functions they perform are as follows:

- Exert colloid osmotic pressure (oncotic pressure) to keep fluid in the circulation, rather than leaking out into the tissues as edema

- Act as carriers for substances such as bilirubin and hormones
- Function as antibodies
- Act as clotting factors
- Form a protein reserve, which can be used by the body in starvation
- Buffer plasma, correcting acid-base balance
- Function as enzymes.

Fluid Movement Among Compartments

Osmotic and hydrostatic pressures regulate the continuous exchange and mixing of body fluids. Osmotic pressure is dependent on the ratio of solutes (plasma proteins and sodium) to solvent (water). Hydrostatic pressure equals blood pressure and is therefore dependent on anything that affects blood pressure (BP).

Forces Responsible for Fluid Flow at Capillaries

The direction of fluid movement is dependent upon the differences between two opposing forces. Hydrostatic pressure tends to push fluid out of the capillary and osmotic pressure tends to pull fluid back into the capillary.

At the arterial end hydrostatic pressure is 35 mm Hg and osmotic pressure is 25 mm Hg therefore the net filtration pressure is 10 mm Hg, it means fluid is forced out of the capillary and into the surrounding tissues.

At the venous end the hydrostatic pressure is 17 mm Hg, however osmotic pressure remains at 25 mm Hg, therefore net filtration pressure is –8 mm Hg. A negative value means the fluid is pulled back into the capillary; the small net leakage that remains behind in the interstitial space is picked up by lymphatic vessels and returned to the circulation.

Lymphatic System

Up to 3 L of intravascular fluid per day is lost to the interstitial space and this would lead to hypovolemia if this fluid were not returned via the lymphatic system.

Lymphatic vessels form a one way system in which lymph flows only to the heart. This transport system begins in blind-ended lymph capillaries, which we have between the tissue cells and blood capillaries in the loose connective tissue of the body.

Lymph capillaries are widespread, but they are absent in bone, bone marrow and the central nervous system. Lymph capillaries drain into lymphatic collecting vessels (similar to veins). These drain into lymphatic trunks, which eventually form two lymphatic ducts (right and left). Each lymphatic duct drains into the venous circulation at the junction of the internal jugular and subclavian veins.

Formation of Edema

1. Edema is an atypical accumulation of fluid in the interstitial space leading to tissue swelling. Edema may be caused by any event that steps up the flow of fluid out of the intravascular compartment or hinders its return.
2. Anything that affects the relative balance between hydrostatic and osmotic pressure leads to an increase in net filtration pressure, which results in edema. Causes of edema:
   - Elevated fluid pressure in the capillaries, e.g. in heart failure
   - Decreased osmotic pressure, e.g. loss of plasma proteins in severe burns
   - Increased osmotic pressure of interstitial fluid, e.g. in the inflammatory response
   - Blocked lymphatic channels, e.g. by tumors or surgical removal of lymphatic
   - Increased capillary permeability, e.g. in anaphylaxis or severe inflammation.

Excess fluid in the interstitial space increases the distance oxygen and nutrients must diffuse from the capillaries to the cells, therefore edema if not corrected can impair cellular function.

Control of Fluid Balance

Fluid balance is controlled by two mechanisms:

1. Input is regulated by thirst.
2. Output is regulated by antidiuretic hormone (ADH) and aldosterone.

Thirst Mechanism

Thirst is the driving force controlling fluid intake. A decrease in 10% of plasma volume or an increase of 1%–2% of plasma osmolality results in a dry mouth and stimulates the thirst center in the hypothalamus. The dry mouth is the result of a rise in plasma osmotic pressure, which causes less fluid to leave the bloodstream. The salivary glands need fluid from the blood to produce saliva, therefore if there is less fluid and less saliva the mouth feels dry. When the mouth is dry, we feel the need to drink therefore taking in fluid to restore fluid balance. The thirst center contains osmoreceptors, which respond to the increase in plasma osmolality by sending out messages to drink water and therefore increase fluid intake.

Osmoreceptors/ADH

Osmoreceptors found in the thirst center in the hypothalamus respond to a rise or fall in the osmotic pressure of the blood and extracellular fluid (ECF).

Osmoreceptors → hypothalamus → posterior pituitary → ADH

Increased tonicity (increased osmolality of plasma) → increased ADH production → fluid retained by kidneys → decreased tonicity (decreased osmolality of plasma and increased fluid volume)

Renin-angiotensin-aldosterone System

Renin-angiotensin-aldosterone system (RAAS) mechanism is given in Figure 4.1:

- Volume receptors in thorax detect decreased volume
- Kidney detects fall in BP
- Juxtaglomerular apparatus (JGA) detects fall in Na^+ concentration in distal tubule (Fig. 4.2).

These three changes lead to renin secretion, which stimulates angiotensin I secretion that is converted to angiotensin II. An elevated level of angiotensin II leads to:

- Stimulation of thirst center
- Constriction of blood vessels
- Increased reabsorption of Na^+ by proximal tubule accompanies reabsorption of water that results in increase in plasma volume
- Secretion of aldosterone by the adrenal cortex
- Reabsorption of Na^+ by distal tubule and again water is drawn back with the Na^+ increased secretion of K^+.

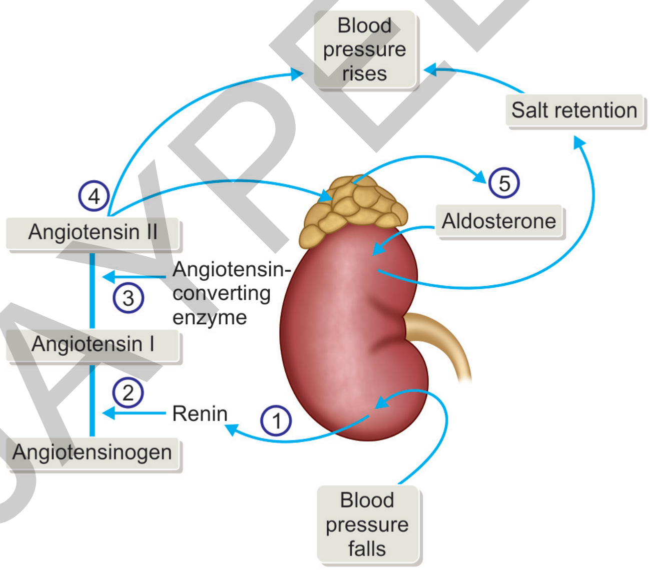

Figure 4.1: Renin-angiotensin-aldosterone mechanism

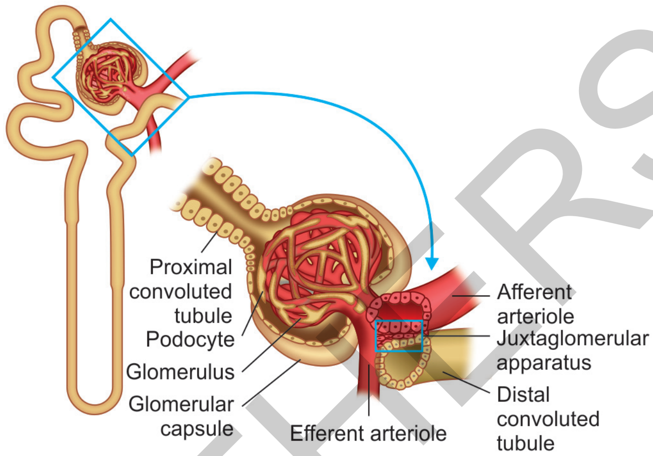

Figure 4.2: Juxtaglomerular apparatus

The RAAS also plays a vital role in short-term maintaining of BP by increasing blood volume along with vasoconstriction.

Atrial Natriuretic Peptide Causes Loss of Both Sodium and Water

When the blood volume is too high, as the blood enters the heart the atria are stretched more than normal. The stretching of atria causes release of atrial natriuretic peptide (ANP) from atrial cells.

The ANP inhibits aldosterone, renin and ADH secretion, and increases glomerular filtration rate (GFR) that causes the body to lose both Na^+ and water. Thereby the blood volume is restored to normal.

ELECTROLYTE BALANCE

Atoms

The atoms (Fig. 4.3) are made of a dense, positively charged nucleus comprising protons (P+) and neutrons (n) around which negatively charged electrons (e–) revolve in orbits/shells.

Neutrons carry no charge. It has the same mass as that of proton. Protons and neutrons together constitute the nucleus of atoms. Therefore, the atomic weight of an element will correspond to the total number of protons and neutrons present in the nucleus.

Electron is abbreviated as e– and is negatively charged. The mass of an electron is only 1/2,000 of a proton. The electrons are the fundamental unit of electricity. A stream of electrons produces an electric current.

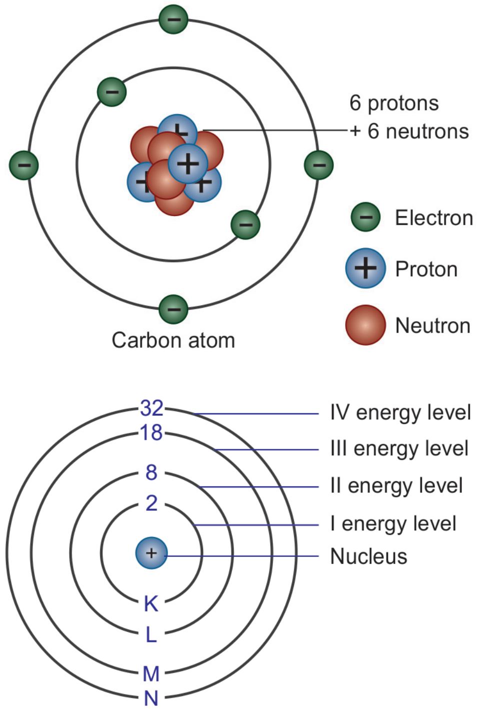

Figure 4.3: Structure of atom and its energy level

Theory of Ionization of Atom

The Greek word ion means, 'moving'. The ionized atoms and particles move in an electric field.

In an atom the number of positive charges (protons) is equal to the number of negative charges (electrons). When an atom loses an electron, it acquires a net positive charge and is called cation. For example:

$Na \rightarrow Na^+ + e^-$, $H \rightarrow H^+ + e^-$

Similarly, when an atom gains an electron, it acquires a net negative charge and is called anion. For example:

$Cl + e^- \rightarrow Cl^-$

Any atom with a net positive or negative charge due to loss or gain of an electron is called ion. The electrons take part in all chemical reactions. The electrons revolve around the nucleus at different energy levels or in shells. The inner most 'K' shell has the maximum capacity to accommodate two electrons, the second 'L' shell can accommodate eight electrons, the third 'M' shell can accommodate eight electrons and so on.

Sodium with an atomic number 11 has 11 electrons; two in K shell, eight in L shell and the remaining one in M shell. The natural tendency for an atom is to completely fill up the shells with electrons. Thus an atom having a single electron in the outermost M shell tends to lose it, so that the K and L shells are completed. Hence, the sodium atom with 11 electrons tends to ionize easily.

Similarly, chloride with an atomic number of 17 has 17 electrons; two in K shell, eight in L shell and seven in M shells, if the sodium atom accepts one more electron, the outer most shell will be completed. Hence, chlorine has the tendency to accept one electron to become ionized. Thus, sodium can donate one electron and chlorine can accept it. This is the basis of the chemical reaction between sodium and chloride. In the above example, the valence of both sodium and chlorine is one, because the exchange is with regard to one electron.

When all the shells are completely saturated with electrons, the atom becomes sluggish in chemical reactions. Helium with two electrons, neon with 10 electrons, and argon with 18 electrons is inert gases, since all the shells are saturated with electrons.

Ions

Ions are charged atoms or molecules that can conduct electricity (Table 4.1). Cations (+ve charge) are those that have lost electrons, and anions (–ve charge) are those that have gained electrons. Since ions are charged they conduct electricity. Without ions there can be no nerve impulse or excitability.

The Na^+ and K^+ are monovalent (one charge) cations, but Ca^{2+} and Mg^{2+} are divalent (two charges) cations. They control metabolism, trigger muscle contraction, control secretion of hormones and transmit nerve impulses.

Table 4.1: Functions of physiologically important ions

Physiologically important ions	Functions
Sodium (Na^+) and potassium (K^+)	Sodium and potassium are monovalent cations that carry electricity in excitable cells, such as nerves and muscles
Calcium (Ca^{2+})	Calcium and magnesium form divalent cations Calcium triggers muscle contraction and transmitter release
Magnesium (Mg^{2+})	Magnesium is involved in metabolic reactions of adenosine triphosphate
Chlorides (Cl^-)	Chloride is the main monovalent anion of the blood
Hydroxyl (OH^-) and protons (H^+)	Hydroxide anion and hydrogen cation are the ions of acidity
Bicarbonate (HCO_3^-), phosphates (HPO_4^{2-}), acid phosphates (H_2PO^-)	Bicarbonate and the phosphate anions (monovalent and divalent) stabilize the pH of the body fluids

Na^+ and K^+ are the Major Cations in Biological Fluids

Potassium (K^+) concentration is high inside cells and sodium (Na^+) concentration is high outside cells. Such ion gradient is maintained by Na^+/K^+-ATPase pump that utilizes about one third of basal metabolic energy.

The Na^+ and K^+ gradient across the cell interior and exterior are like electrical energy stored in a battery. Energy stored in the form of Na^+ and K^+ gradient can be tapped when ions flow. That is how Na^+ and K^+ produce action potential of excitable cells.

Sodium

Sodium is the most abundant cation in ECF, which is mainly responsible for the osmotic pressure of ECF and linked closely with water. Sodium concentration affects kidney regulation of water and electrolytes (think about the action of aldosterone).

Sodium is necessary for the transmission of impulses in nerve and muscle fibers. In excess, sodium causes thirst, dry mucous membranes, oliguria, twitching and seizures. Sodium deficit leads to neurological dysfunction manifested as weakness, tremors, irritability, convulsions; it also causes edema and hypotension.

Physiological range of serum sodium ranges from 135 to 145 mEq/L.

Hyponatremia: It is a common electrolyte imbalance that refers to a deficiency of sodium in relation to body water. In hyponatremia the plasma level of sodium is less than 135 mEq/L.

Causes of hyponatremia are GI losses through vomiting, diarrhea and nasogastric suction, renal losses through diuretics, skin losses from wound drainage and burns, and adrenal insufficiency.

Hypernatremia: Refers to excess of sodium in relation to body water. In hypernatremia, plasma level of sodium is more than 145 mEq/L.

Causes of hypernatremia are excessive intake of sodium chloride in food, sodium bicarbonate preparations and sodium containing IV fluids or decreased renal secretion due to renal insufficiency, and use of cortical steroid. It can also result from loss of body water, which leads to an over concentration of sodium, decreased fluid intake or increased fluid loss, diaphoresis, hyperventilation, fever and diarrhea.

Potassium

Potassium is the dominant intracellular electrolyte. It controls cellular osmotic pressure.

It helps regulate acid-base balance. Potassium activates several enzymatic reactions. It helps maintain neuromuscular excitability. Potassium influences kidney function. In excess it causes weakness, malaise, muscle irritability, bradycardia and arrhythmias. A deficit leads to muscle weakness, arrhythmias, possible cardiac arrest, alkalosis and hypoventilation.

Physiological range of serum potassium ranges from 3.5 to 5.0 mEq/L.

Hypokalemia: Deficiency of potassium in relation to body water is less than 3.5 mEq/L.

Causes of hypokalemia are excessive loss of potassium due to diuretics, vomiting and diarrhea or inadequate replacement of lost potassium.

Hyperkalemia: Excess of potassium in relation to body water is more than 5 mEq/L.

Causes of hyperkalemia are renal failure, cellular damage, insulin deficiency, adrenal deficiency and rapid IV infusion of potassium.

Calcium

Calcium is needed for blood clotting, cell membrane permeability and to help maintain neuromuscular excitability. About 99% of body's calcium is found in bones. Calcium deficiency produces tetany and seizures. Calcium in excess leads to lethargy, dehydration, cardiac arrhythmias and coma.

The physiological range of serum calcium is from 8.9 to 10.1 mg/dL.

Hypocalcemia: Serum calcium is less than 8.9 mg/dL.

Causes of hypocalcemia are parathyroid deficiency, vitamin D deficiency, renal disease, cancer, pancreatitis, massive blood transfusions, enema and laxative abuse.

Hypercalcemia: Serum calcium is more than 10.1 mg/dL.

Causes of hypercalcemia are cancer, excessive intake of vitamin D, excessive intake of milk or alkaline antacids, hyperparathyroidism, immobilization and reduced renal function.

Magnesium

Magnesium is the second most abundant intracellular cation. It activates several enzymatic reactions and is essential for myocardial function. It is needed for neurotransmission and neuromuscular activity. Elevated levels of magnesium in serum leads to lethargy, impaired central nervous system (CNS) functioning, coma and respiratory depression. A deficit causes tremors, increased neuromuscular activity and seizures.

Physiological range of serum magnesium is from 1.5 to 2.5 mEq/L.

Hypomagnesemia: The serum magnesium level is less than 1.5 mEq/L.

Causes of hypomagnesemia are impaired intake, impaired intestinal absorption, excessive urinary excretion and secondary to diuretics, and chronic alcoholism.

Hypermagnesemia: The serum magnesium level is more than 2.5 mEq/L.

Causes of hypermagnesemia are renal failure, diabetic ketoacidosis, magnesium sulfate therapy and use of magnesium-based laxatives.

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