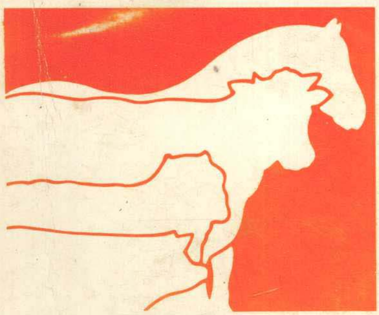
An Introduction to Animal Physiology



Second Edition

Per Svendsen
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Preface

This revised edition of *'An Introduction to Animal Physiology'* is intended for students of Agriculture Science and as an introductory text in physiology for veterinary students. The main emphasis is on the two areas of physiology that are of most importance in animal production: nutrition and digestion and the reproductive processes. The book has been brought thoroughly up to date taking care to preserve one of its essential features, which is simplicity of presentation. The description of the nervous system and endocrine glands emphasizes their participation in control systems that regulate bodily functions and maintain a constant internal environment. The nutrition of farm animals and the digestive processes of ruminants and non-ruminants are given special emphasis. Recent advances in reproductive physiology have given a better understanding of topics such as nourishment of the fetus and the mechanisms initiating birth. These are now described in the chapter on reproduction together with a description of the reproductive cycle and its endocrine control.

Odense, October 1984 *Per Svendsen*
Anthony Carter

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The cell and its environment

Living matter, whether animal or vegetable, consists of cells. In its most primitive form it is a single cell. The cells of animals have a common structure in which the cell membrane, the nucleus, and the cytoplasm are the most important elements (Figure 1.1).

CELLULAR STRUCTURE

The cell membrane

The membrane which surrounds the cell is a remarkable structure. It is not only semipermeable, allowing some chemical substances to pass through it and excluding others, but its permeability can be varied. It is generally referred to as the unit membrane or plasma membrane, and despite differences in functional characteristics, its basic structure seems to be the same throughout the whole animal kingdom. The unit membrane is also found inside the cells, surrounding the nucleus and the organelles.

The unit membrane is approximately 7.5 nm thick. It is made up of an inner 2.0 nm layer of protein, a middle 3.5 nm layer of lipid, and an outer 2.0 nm layer of protein and polysaccharide. The membrane behaves as if it contained holes or pores 0.3 nm in diameter. These pores allow small molecules to pass through the membrane, whereas larger molecules gain entry by other processes.

The nucleus

A nucleus is present in almost every cell. It is separated from the cytoplasm by a membrane and contains the chromosomes that

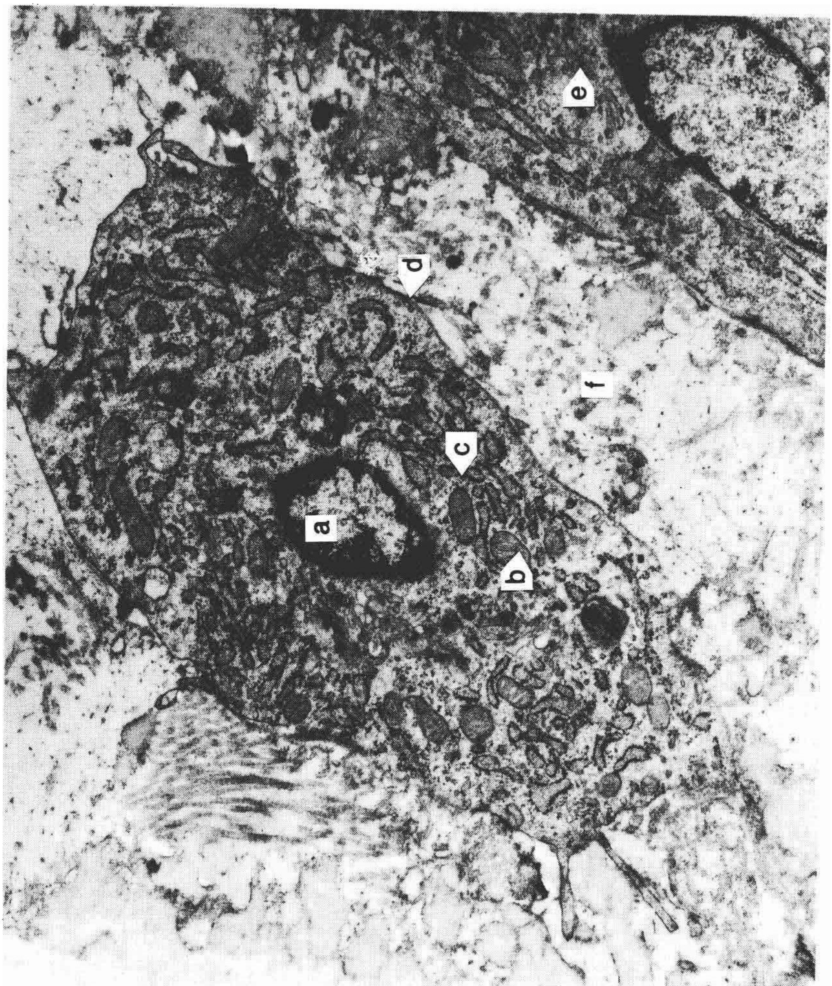

Figure 1.1. Smooth muscle cell from the aorta of a rabbit (× 20 000) (a) nucleus, (b) mitochondria, (c) endoplasmic reticulum with ribosomes, (d) cell membrane, (e) Golgi complex, (f) interstitial space. (By courtesy of Dr. John Chemnitz, Department of Anatomy and Cytology, University of Odense)

determine the heritable characteristics of the animal. Each chromosome is made up of supporting protein and a giant molecule of deoxyribonucleic acid (DNA). The ultimate units of heredity are the genes on the chromosomes, and each gene is a portion of the DNA molecule.

Chromosomes are usually found in pairs. During normal cell division by mitosis, the chromosomes are duplicated and each daughter cell receives a full set of paired chromosomes. During the final maturation of germ cells, however, there is a cell division in which the chromosomes are not duplicated. Instead half of each pair goes to one of the daughter cells. As a result of this meiosis, mature spermatozoa and ova contain only half the normal number of chromosomes. When spermatozoa and ova unite, each of the resultant cells has a full complement of chromosomes.

The cytoplasm

The cytoplasm outside the nucleus contains several different organelles, each enclosed by unit membrane and each with a distinct function.

The mitochondria are oval-shaped structures containing enzymes concerned with the synthesis of the high energy phosphate compound adenosine triphosphate (ATP). This molecule is the principal energy source of the cell. The enzymes in the cytoplasm outside the mitochondria are mainly concerned with biological oxidations, providing raw material for the citric acid cycle inside the mitochondria (Chapter 13). The mitochondria are thus the power generating units of the cell, and are most plentiful in parts of cells where processes requiring energy take place.

The enzymes of the mitochondria and cytoplasm are proteins and are synthesized in the ribosomes. These are tiny granules, 15 nm in diameter, attached to a network of membranes known as the endoplasmic reticulum.

Lysosomes are large, somewhat irregular structures surrounded by unit membrane. These organelles contain a variety of enzymes believed to function as a form of digestive system for the cell. Exogenous matter, such as bacteria, which becomes engulfed by the cell, ends up in a vacuole where it mixes with the contents of a lysosome. Some of the products of this process are absorbed into the cytoplasm, and the rest are removed from the cell by rupture of the vacuole at the cell surface.

Other structures in the cell are the centrioles, which are concerned with the movements of chromosomes during cell division, and the Golgi complex, which is concerned with the formation of lysosomes and with the secretion of enzymes and hormones from the cell.

Chemical composition of the cell

About 75–80 per cent of the cell is water and about 10–20 per cent is protein. Much of the water is adsorbed to the surface of the protein molecules. Proteins function as enzymes and as structural matter, and help to maintain the osmotic pressure of the cell. Lipids are mainly found in the cell membrane and account for only 2–3 per cent of the cell. Carbohydrates and inorganic substances each make up about 1 per cent of the cell.

BODY FLUID COMPARTMENTS

The cells of the body are surrounded by extracellular fluid, from which they take up oxygen and nutrients, and into which they discharge the products of their metabolism. The extracellular fluid has two components, the interstitial fluid and the circulating blood plasma.

The volume of a body fluid compartment can be measured with a substance that is known to distribute itself evenly and completely throughout the compartment in question, for example the blood plasma. A known amount of the substance is injected and after a mixing period a sample of the fluid is withdrawn and the concentration of the substance is determined. The volume can then be calculated in the following way:

$$\text{Volume} = \frac{\text{amount injected}}{\text{concentration in sample}}$$

Plasma volume has been measured by using dyes which become bound to plasma proteins, particularly Evans blue. Nowadays albumin labelled with radioactive iodine is more commonly used. The volume of extracellular fluid is more difficult to measure because the limits of this space are ill defined and because few substances mix rapidly enough with all parts of the compartment. The most accurate measurements of extracellular fluid volume are obtained by using inulin. The intracellular fluid volume cannot be measured directly, but it can be calculated by subtracting the extracellular fluid volume from total body water. Total body water can be measured by exactly the same principle as is used to measure the other fluid compartments. Deuterium oxide (heavy water) is the substance most frequently used.

In the adult domestic animal water accounts for about 70 per cent of body weight. 50 per cent of the body weight is intracellular fluid, 15 per cent is interstitial fluid, and 5 per cent is plasma.

Composition of body fluids

The intracellular and extracellular fluid compartments differ in electrolyte composition (Figure 1.2). The most striking difference is that Na^+ and Cl^- ions are largely extracellular, whereas most of the K^+ is intracellular. In addition there is a much lower concentration of protein anions in the extracellular fluid than in the intracellular fluid.

The differences in composition of the various body fluid compartments can be maintained because of the nature of the cell membranes that separate the intracellular and interstitial fluid, and of the capillary walls that separate the plasma from the interstitial fluid. The forces producing movement of water and small molecules across these barriers are diffusion due to concentration gradients and electrical gradients, differences in osmotic pressure and hydrostatic pressure, differences in membrane permeability, and active transport of some molecules or ions across the membrane.

FORCES ACTING ACROSS MEMBRANES

Diffusion

Diffusion is the process by which a gas or a substance in solution spreads from areas of high concentration to areas of low concentration because of the motion of its particles. The diffusion of ions is also affected by their electrical charges. When there is a difference in potential between two areas, positive ions will move down the electrical gradient to the more negatively charged area whilst negative ions will move in the opposite direction.

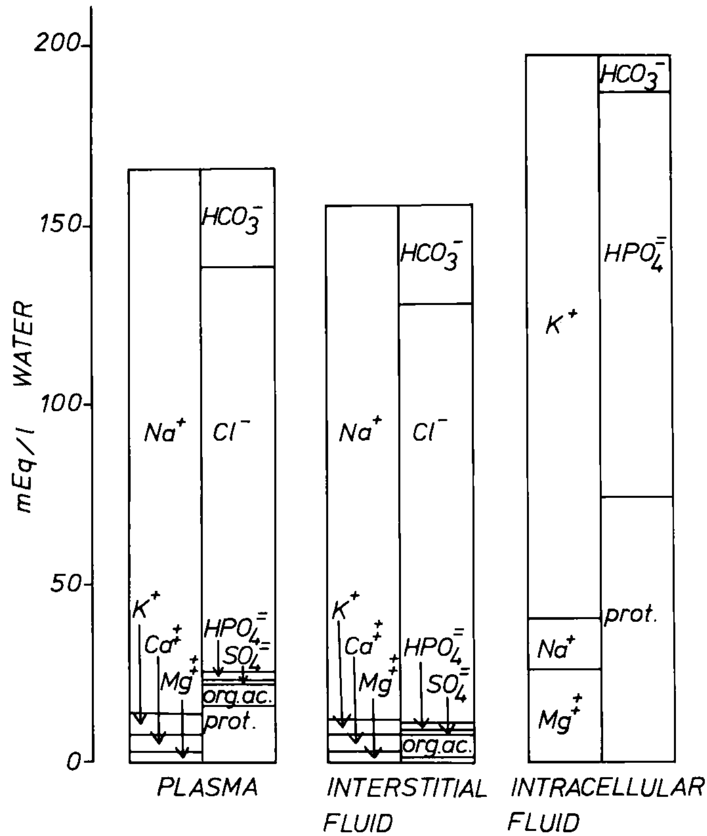

Figure 1.2 The ionic composition of the body fluids (prot. = protein, org. ac. = organic acids)

Osmosis

Osmosis is the movement of solvent molecules across a membrane into an area in which there is a higher concentration of a solute to which the membrane is impermeable. The movement can be prevented by applying pressure to the more concentrated solution. The pressure necessary to prevent solvent movement is known as the effective osmotic pressure.

The Donnan effect

An ion that cannot diffuse through a membrane will have a predictable effect on the distribution of the ions that can. Consider a membrane separating two solutions, one containing protein anions (Pr^-), to which the membrane is impermeable, and both containing potassium and chloride ions (Figure 1.3a). If the solutions are isotonic, there will be a lower concentration of chloride ions on the left side of the membrane. Initially, Cl^- will move from right to left down its concentration gradient whereas Pr^- will remain on the left side of the membrane. To maintain electrochemical neutrality (equal numbers of positive and negative ions on each side of the membrane) K^+ ions will also tend to move from right to left. This will create a concentration gradient for potassium that eventually will restrict the movement of K^+ ions. Negative charge will then accumulate on the side where Pr^- is present. When the electrical gradient keeping Cl^- ions out balances with the concentration gradient pulling them in, net movement of Cl^- will finally cease (Figure 1.3b).

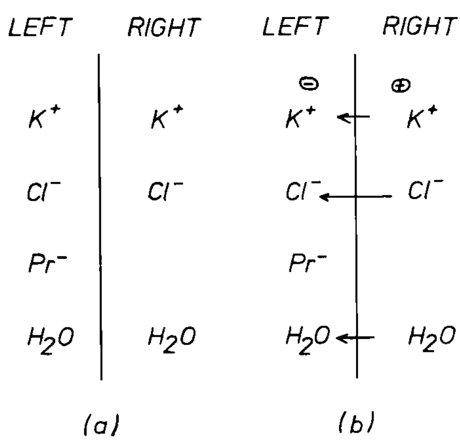

Figure 1.3 The Donnan effect. The membrane is impermeable to protein anions and this has a predictable effect on the distribution of ions that can pass the membrane. (a) Initial situation: There is the same concentration of cations (K^+) on both sides of the membrane and the concentration of Cl^- on the right side is equal to the concentration of Cl^- + protein$^-$ on the left side. (b) Resultant movements of ions and water, leading to higher concentrations of cations and anions on the left side of the membrane and a slight excess of negative charge on the same side. At equilibrium there is no net movement of ions or water