THE ESSENTIALS OF NEUROANATOMY

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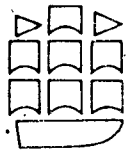
THIRD EDITION



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Preface to the Third Edition

With the help of Professor D. Mayor of Southampton University the text has been revised and improved. It now provides additional information about interconnections, tracts, microscopic structure and functional neuroanatomy and most of the diagrams have been modified and redrawn. However the deletions and additions have been almost balanced; consequently this new edition is only slightly enlarged.

Most students are confused by the numerous articles and monographs on the nervous system and by the ever-lengthening sections dealing with it in anatomical textbooks. Furthermore there has been a significant decrease in the amount of time available in many modern medical curricula for studying the nervous system. Therefore, we have selected the most important and confirmed information about the human central nervous system as revealed by macroscopic, microscopic, physiological and clinical studies of the brain and spinal cord. Reference to unconfirmed findings based on experimental studies on lower animals with relatively simple nervous systems has been omitted.

Throughout this new edition the terminology (or the English equivalent) accredited internationally in Nomina Anatomica has been used. Readers who develop a special interest in this, the most fascinating and important of the bodily systems, can extend their knowledge by consulting the books suggested for further study. These contain a large number of references to specialised articles and monographs.

We wish to record our thanks to Mr W.J. Allen, Director of the Department of Teaching Media, Southampton University and his staff for their valuable help. In particular we are grateful to Terry Baker, Sue Jacobs and Liz Roberts for preparing the new illustrations; to Mrs J.A. Stead and Miss J. Luscombe who have typed the revised manuscript; to Mr B. Backhouse for photographic assistance; and to the publishers, Churchill Livingstone, for their guidance and expert advice in the preparation of this new edition.

Manchester, 1977 G. A. G. Mitchell

From Preface to the First Edition

This simple account of the central nervous system was first published privately (Morris & Yeaman, Manchester) 16 years ago for the use of my own students. It attracted a wider audience, however, and I received so many requests for copies that I decided to publish it more widely.

Our knowledge of the nervous system has increased enormously in the past 50 years and this is reflected in the ever-lengthening sections devoted to it in textbooks and by the appearance of specialized monographs. Most of these are excellent, but they are more suitable as works of reference and it is difficult for students to sift the essentials from the mass of information provided. One has attempted to make such a selection on their behalf and some of the more important facts about function and applied anatomy have been added: (the terminology used conforms to the international nomenclature, Nomina Anatomica, Editor G. A. G. Mitchell, Excerpta Medica Foundation, 1966).

It is a pleasure to record my thanks to Dr. E. R. A. Cooper, Dr. E. L. Patterson and Dr. G. T. Ashley for their advice on various matters; to Dr. J. H. Scott and Professor A. D. Dixon for permission to produce diagrams from their *Anatomy for Students of Dentistry* (Figs. 14, 19, 20, 21, 41, 44 and 55 in this edition), to Miss M. Gillison for Figs. 2, 3, 4, 5, 8 and 12 which are taken from her *A Histology of the Body Tissues* and to Professor Wilder Penfield for Figs. 31 and 34 from his *The Cerebral Cortex of Man;* to Mrs J. E. Kern and F. Kern for secretarial and other help; to Mr G. Wilson and the staff of the Medical Library; to Mr R. F. Neave who prepared some of the illustrations; to Mr C. K. Pearson and Mr P. Howarth for technical and photographic help; and to Messrs E. and S. Livingstone for placing so freely at my disposal their great experience in medical publication.

Manchester, 1966 G. A. G. Mitchell

Contents

The essentials of neuroanatomy

The nervous system consists of *central* and *peripheral* parts. The former comprises the brain and spinal cord, which are connected to structures in every part of the body by peripheral nerves containing *afferent* and *efferent* fibres. The afferent nerve fibres convey sensory impulses from the skin, muscles, bones, joints, vessels, viscera and special sense organs to different parts of the central nervous system where they are decoded and correlated. As a result, fresh impulses are initiated in the central nervous system which are transmitted by the efferent nerve fibres in peripheral nerves to the muscles, vessels and organs; these efferent impulses produce an appropriate response (based on the nature of the information resulting from afferent impulses) such as muscular contraction or relaxation, glandular secretion or inhibition, and increase or decrease in cardiac, respiratory, alimentary and other bodily activities. The possession of a nervous system therefore endows animals with the ability to appreciate and to react to their environment and provides the means to control the internal state of their bodies. This master system regulates and integrates the activities of all the other bodily systems for the benefit of the organism as a whole.

The simplest forms of animal life, such as the unicellular amoebae, have no nervous tissues and the reaction to any stimulus is merely the expression of the inherent *excitability* of protoplasm. Rising one step in the scale, the simplest multicellular organisms show early evidences of cellular specialization. Some cells develop contractile properties and the surface or ectodermal cells form a protective cuticle. A few of the latter become further specialized to appreciate changes in the environment of the organism and these primitive cuticular sensory cells send out delicate processes from their deep surfaces which make contacts with the contractile or motor cells (Fig. 1). These processes transmit or *conduct* the excited state to the contractile cells. Thus the simplest form of *reflex arc* is established, in which a sensory or *receptor* cell is linked to a contractile or *effector* cell and pleasant or unpleasant

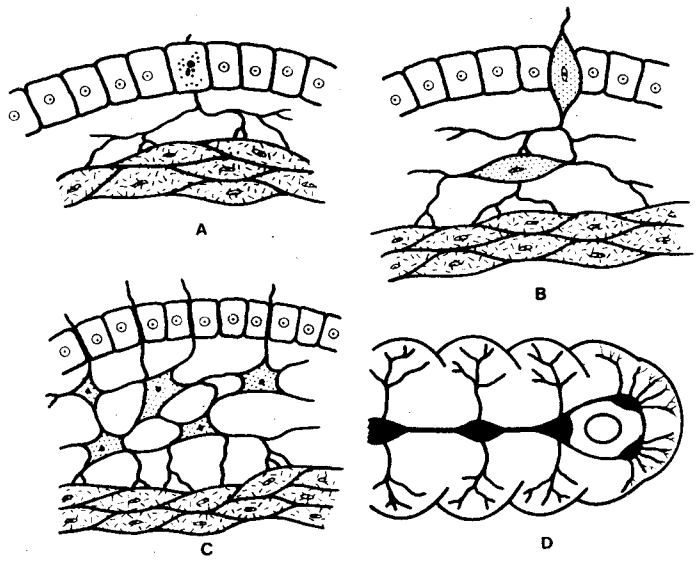

Fig. 1 Diagram showing evolution of simple types of nervous systems.
A. Primitive cuticular sensory (receptor) cell forming contacts with underlying contractile (motor) cells.
B. A receptor cell has sunk beneath the surface, but retains its contacts with cuticular sensory cells and subjacent motor cells.
C. A more advanced stage of B in which there is a subcuticular ganglion cell plexus.
D. Ganglionated chain seen in segmented forms such as worms, with an enlarged 'head' ganglion.

stimuli can now evoke a suitable response, such as movement towards or away from the source of stimulation.

A more advanced stage is reached when some of the receptor cells sink beneath the cuticle, maintaining contact with the surface by one process and making contacts with corresponding cells and with effector cells by other processes. Such an arrangement is known as a subcuticular ganglion cell plexus and it permits a local stimulus to produce a generalized response (Fig. 1).

Rising still higher in the animal scale, segmented forms appear, and the diffuse ganglion cell plexus becomes aggregated into a chain of interlinked segmental ganglia which are connected by afferent and efferent processes to the receptor and effector cells in their own segments. By this means stimuli applied to one segmental area may provoke a co-ordinated response by all the segments and an element of correlation of stimuli from external and internal sources is possible—a primitive form of integration. As segmented forms are elongated and move predominantly in one direction, the receptor apparatus at the

advancing or head end receives a higher number of stimuli and the ganglion in the foremost segment becomes relatively enlarged to deal with these impulses. This ganglionic enlargement at the forward or head end is the first indication of the development of a supreme centre of control and may be regarded as the most lowly form of brain. Up to this level in the animal world the nervous system is still relatively simple, so that the responses to the same stimuli are almost instantaneous and stereotyped, while gradations of behaviour based on the lessons of previous experience are lacking.

The evolution of higher forms, and particularly of the vertebrates, required the elaboration of more and more complex nervous systems. The acquisition of special senses such as sight, smell, taste and hearing necessitated increases both in size and complexity, since these special sensory impressions had to be correlated with afferent impulses from the skin and deeper structures, and all had to be linked to their neighbours and to the effector side of the system by nerve pathways of ever-increasing complexity. The higher animals have acquired yet another characteristic—the ability to memorize experiences and to use them for future guidance. This has entailed great expansion of the so-called association areas of the brain, a highly important development most evident in the nervous system of Man. In consequence the possible reactions or responses of the higher animals to stimuli are almost infinite in their variety and gradations; their behaviour is no longer automatic and stereotyped as in lower forms, but purposive, controlled and protean. It is intelligent rather than instinctive.

NEUROGLIA AND NEURONS

The nervous tissues are composed of billions of nerve cells and their processes—*neurons*—supported in the brain and spinal cord by a special variety of connective tissue known as *neuroglia*.

NEUROGLIA

This is the supporting tissue of the brain and spinal cord and consists of three main types of cells:

1. *Astrocytes*

These have many radiating processes, some of which end on nerve cells and others on capillaries. They are neurectodermal in origin and may assist in the transfer of nutrient and waste products between the neurons and the blood.

2. *Oligodendrocytes*

These are smaller and have fewer branching processes; they tend to lie

in rows between nerve fibres and they are concerned with the production and nourishment of myelin. They are neurectodermal in origin.

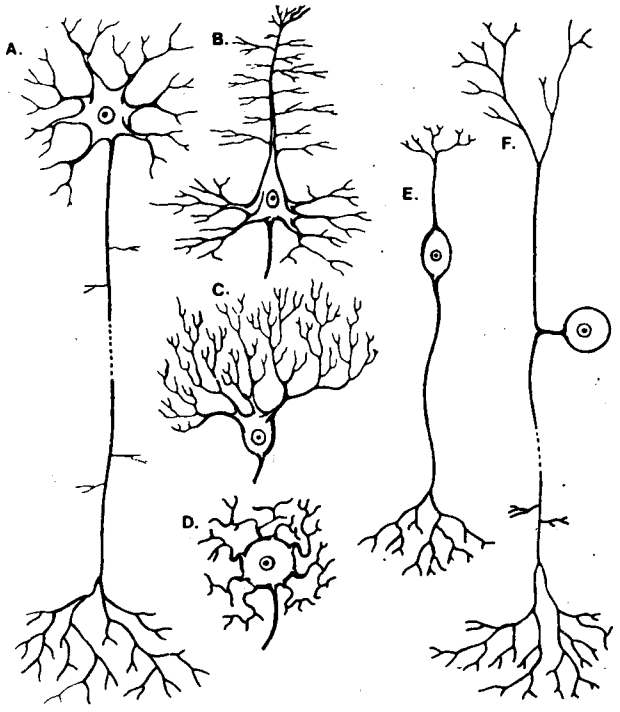

Fig. 2 Diagram of various types of neurons:

A. Multipolar—these have multangular cell bodies with one axon and numerous dendrites. They constitute the majority of the nerve cells within the central nervous system.

B. Pyramidal—really a variety of multipolar neuron with a pyramidal shaped body. Typical examples are found in the cerebral cortex, and large ones exist in the precentral (motor) gyrus.

C. Flask-shaped cells—these cells are peculiar to the cerebellar cortex and their dendrites are notable for their rich arborescence.

D. Ganglion cell—the spherical type illustrated is commonly found in autonomic ganglia.

E. Bipolar—these neurons are afferent in type and have two processes. The one carrying impulses towards the cell is classed as a dendrite and the other, transmitting impulses away from the cell, is the axon. They are relatively uncommon types and are found mainly in association with special sense organs.

F. Unipolar (pseudo-unipolar)—In these the processes of embryonic bipolar cells have become approximated and apparently fused over a short distance and the single process soon bifurcates in a T-shaped fashion. They are afferent in function and are found, for example, in the ganglia on the dorsal roots of the spinal nerves.

3. *Microglia*

These are diminutive cells which permeate the entire central nervous system. They are modified macrophages and form part of the reticulo-endothelial system and are probably mesodermal in origin.

NEURONS

These are the *structural* units of the nervous system. They are mainly grouped in the orain and spinal cord, but other collections termed *ganglia* are found in association with various peripheral nerves. In mass, nerve cells are greyish in colour and areas of the brain and cord in which they predominate are referred to as the *grey matter*.

Each neuron possesses a nucleated cell body (cyton) and one or usually more branching processes. The cytoplasm may be finely fibrillated and typically contains granules which stain with basic dyes such as methylene blue, while in a few areas of the brain it contains naturally pigmented particles. The nucleus and its nucleolus (or nucleoli) are well defined. The processes are extensions of the cell body which conduct impulses to or from the cyton, and they vary in length from a few microns to a metre or more: the longest interconnect the brain and the lower end of the spinal cord, or extend to and from the cord in the nerves supplying peripheral structures such as the hands and feet. One process conducts impulses away from the cell and is termed the *axon*. It does not branch freely except at its termination, although it gives off side branches or collaterals by which it establishes interconnections with other neurons. Most neurons have a variable number of other processes or *dendrites* which conduct impulses to the cyton; they are usually short and aborize freely. Neurons whose axons transmit impulses to muscles or glands are motor or secretomotor and those conveying impulses from receptor structures are sensory: the former are often referred to as efferent and the latter as afferent because of the direction of the impulses they transmit.

Neurons are classified according to their size, shape, the type and number of their processes, or by various other criteria. Thus they are described as small, medium or large (in Man the range is between 10 and 200 μm); as spherical, fusiform, flask-shaped, pyramidal or multangular; or as unipolar, bipolar or multipolar, depending on the type and number of their processes (Fig. 2).

Myelin and neurolemmal sheaths

The axonal processes of neurons together with their covering sheaths are often referred to as nerve fibres. In particular this term is applied to aggregations of axons which form tracts within the central nervous system and to the collections of axons constituting peripheral nerves.

The axons are protected and insulated by *myelin* and/or by *neurolemmal sheaths* (Figs. 3 and 4).

The myelin sheaths vary in thickness and are composed of a whitish lipid and protein substance. The areas of the brain and spinal cord in which myelinated nerve fibres predominate are known as *white matter*. Those axons which do not have a myelin sheath but are only supported by neurolemmal (Schwann) cells are called *unmyelinated fibres*, while those which in addition have a definite covering of myelin are referred to as *myelinated fibres*. However, near their origins and terminations myelinated axons lose their myelin sheath and are either covered only by the neurolemmal sheath or are devoid of any covering. With the exception of the peripheral processes of the afferent unipolar neurons in sensory ganglia, which in many respects resemble axons, other dendrites are usually unmyelinated.

The myelin sheath is interrupted by *nodes of Ranvier* (Fig. 3) at intervals of between 0.1 to 1 μm depending upon the length and thickness of the fibres and they may also show oblique clefts in the internodal segment. The axons are more uniform in calibre than their myelin coats. Unmyelinated fibres vary in diameter from 0.2 μm to 1.5 μm, while the total diameter of myelinated fibres varies from 1 μm to 20 μm. The range in diameter of the larger fibres is largely due to variations in the thickness of their myelin sheath. These differences in the overall diameter of myelinated fibres are associated with different functional properties; for example thin fibres conduct impulses more

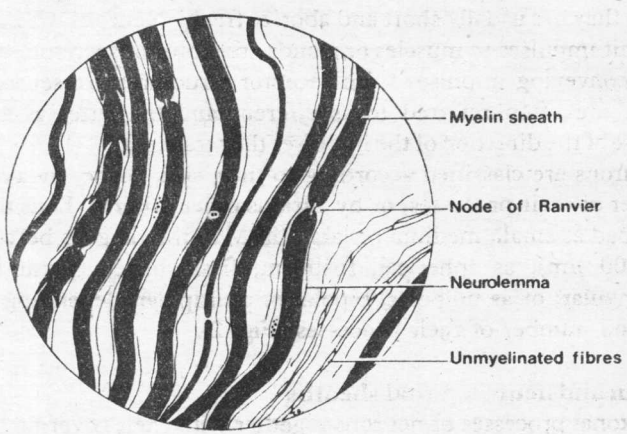

Fig. 3 Longitudinal section of myelinated (medullated) and unmyelinated (non-medullated) nerve fibres (× 210) treated with osmic acid which stains the myelin darkly. This obscures the enclosed axons, except at the nodes where the myelin sheaths are interrupted. Both types of fibres possess delicate nucleated neurolemmal sheaths.

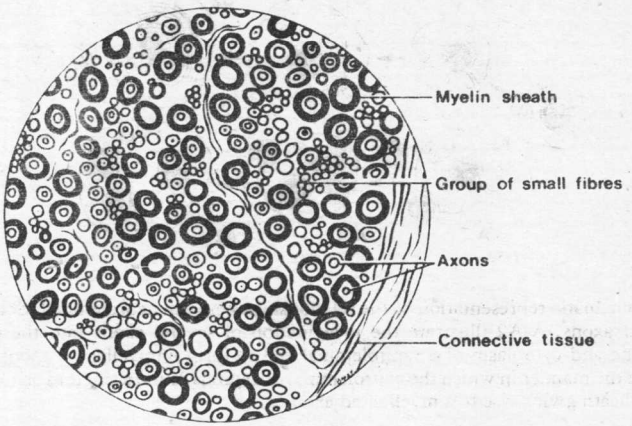

Fig. 4 Transverse section of a nerve (x 280) treated with osmic acid. The myelin (medullary) sheaths are stained black and the contained axons are white or pale grey in colour. The sheaths are very thin or apparently absent in the finest fibres.

slowly than thick ones. Furthermore, these variations in fibre size and conduction velocities exist in both the peripheral and central nervous system.

All nerve fibres are naked in their early stages of development and those constituting the tracts in the white matter of the central nervous system acquire their myelin sheaths at different periods; some do not become myelinated until after birth. Apparently the acquisition of a myelin sheath and functional activity are associated; for example, most nerve tracts concerned with visceral activities become myelinated before those which control the muscles responsible for voluntary movements.

The so-called neurolemmal sheaths are confined to nerve fibres in peripheral nerves. They consist of a series of neurolemmal (Schwann) cells, one for each internode in myelinated fibres, with prominent ovoid or elongated nuclei. Most of the cytoplasm is in the region of the nucleus but elsewhere a thin layer of cytoplasm is wrapped around the internodal myelin sheath. At the nodes of Ranvier the neurolemmal sheath appears to be in close proximity to the axon. In the case of unmyelinated fibres several axons may be enclosed within the same series of neurolemmal (Schwann) cells.

Ultrastructural studies of developing and adult nerve fibres have shown that the myelin sheath and neurolemmal sheath are both derived from the Schwann cell. The myelin is produced by proliferation of the plasma membrane of the Schwann cell which becomes wrapped around the axons. The thin layer of nucleated cytoplasm,

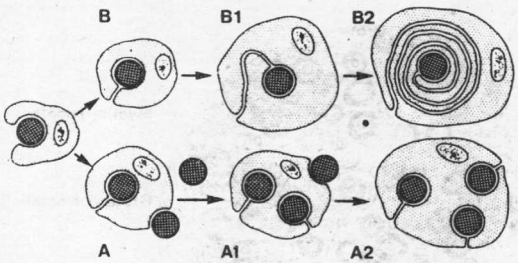

Fig. 5 Schematic representation of the relationships between neurolemmal (Schwann) cells and axons. A-A2 illustrate the invagination of several axons into the plasma membrane and cytoplasm of a neurolemmal cell to form unmyelinated axons. B-B2 illustrate the manner in which the neurolemmal cell spirals round a single axon to form a myelin sheath giving rise to a myelinated axon.

together with the outer plasma membrane of the Schwann cell surrounding the myelin sheath, constitute the so-called neurolemmal sheath (Fig. 5). Unmyelinated nerve fibres are seen to consist of several axons invaginated into the cytoplasm of a single neurolemmal (Schwann) cell (Fig. 5).

In the central nervous system the internodal myelin sheaths are produced by the oligodendrocytes. Unlike the individual neurolemmal cell which produces the internodal myelin around a single axon, different processes from a single oligodendrocyte produce the internodal myelin around several axons. Consequently there is no cytoplasmic sheath surrounding the central myelinated axons comparable to the neurolemmal sheath in peripheral nerves.

Synapses

Within the nervous system impulses are conducted from one part to another along a chain of neurons. The terminal arborizations of the axon of one neuron ramify in close contact with the cytons or dendrites of many others and these areas of contact are termed *synapses*: the axonal terminations are slightly swollen and form 'boutons terminaux' (Fig. 6). These manifold contacts permit an extraordinary degree of integration and correlation. Thus the fibres innervating the voluntary or striated muscles of the body and limbs are the axons of large multipolar nerve cells located anteriorly in the grey matter of the spinal cord. It has been estimated that each of these motor neurons receives synaptic connections from the terminal axonal ramifications of up to 1000 other nerve cells. All of these synapses add their quota of influence to the efferent impulses conducted along the axons of these motor neurons to the muscles; it is therefore appropriate that these

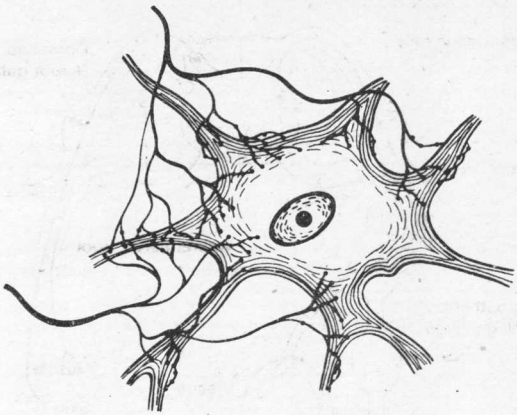

Fig. 6 *Boutons terminaux* on a nerve cell. The nerve fibres forming synaptic relationships with the cell branch and form neurofibrillae which become slightly expanded at their terminations.

neurons are often referred to as *final common pathways*. The relationship at neurons is close, but there is possibly no true continuity between the neurons; the impulse is conducted from one to the other by chemical substances released as a result of nervous activity—a process known as chemical mediation. The concept that each neuron is structurally independent, although it has intimate structural and functional relationships with others, is termed the *neuron theory*. The evidence that there is no real continuity between neurons is based on the findings that (1) some delay in transmission occurs at synapses, (2) normally the impulses travel in one direction only across these junctions as if the synapses acted as one-way valves and (3) degenerative changes in nerve fibres following injury to the cyton or its axon are confined as a rule to that neuron. The proof that there is complete discontinuity at the peripheral terminations of *all* axons is not altogether satisfactory, and some anatomists believe that the peripheral processes of neurons innervating viscera and vessels unite directly to form a very delicate nervous syncytium known as *a terminal network or 'ground plexus'*.

Reflex arcs

The *functional* unit of the nervous system is the *reflex arc*, a linkage of afferent and efferent neurons. The effector mechanism, e.g. a muscle, is supplied by an efferent nerve, and between the afferent and efferent components there may be one or more connector or intercalated neurons. These elements—afferent, intercalated (internuncial) and

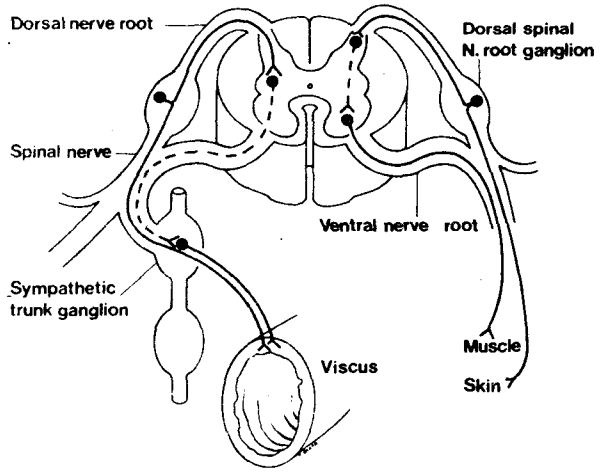

Fig. 7 Typical reflex arcs: somatic (right side) and autonomic (left side).

efferent neurons—are the basis of reflex nervous activities (Fig. 7).

Some sensory endings are specialized and different types exist for the appreciation of different stimuli (Fig. 8). They are found not only in the covering layers of the body and in special sense organs such as the eye and ear, but also in deeper structures such as muscles and joints. The impulses engendered by stimulation of these endings are transmitted to the brain and spinal cord by afferent nerve fibres. Other sensory endings are simple, such as those for the appreciation of pain in the skin and cornea, and consist merely of fine, free, terminal filaments of the afferent fibres.

Impulses produced from sources outside the body are termed exteroceptive (pain, touch, temperature, pressure, visual, auditory, olfactory and gustatory); those arising in the muscles, tendons, bones and joints are termed proprioceptive (sensations of movement and position); and those originating in the organs and vessels are termed interoceptive (visceral sensations of all types).

The efferent neurons convey impulses to muscles, glands and other active tissues, and in the simpler types of animals the reception of a sensory stimulus usually induces an immediate response in the associated efferent neurons, which in turn evokes an appropriate reaction in the effector mechanism. In higher forms the functioning of reflex arcs is less automatic, as they are controlled by brain centres which integrate impulses from both external and internal sources and sift them through the screen of experiences stored in the memory before initiating the appropriate efferent impulses. The presence of

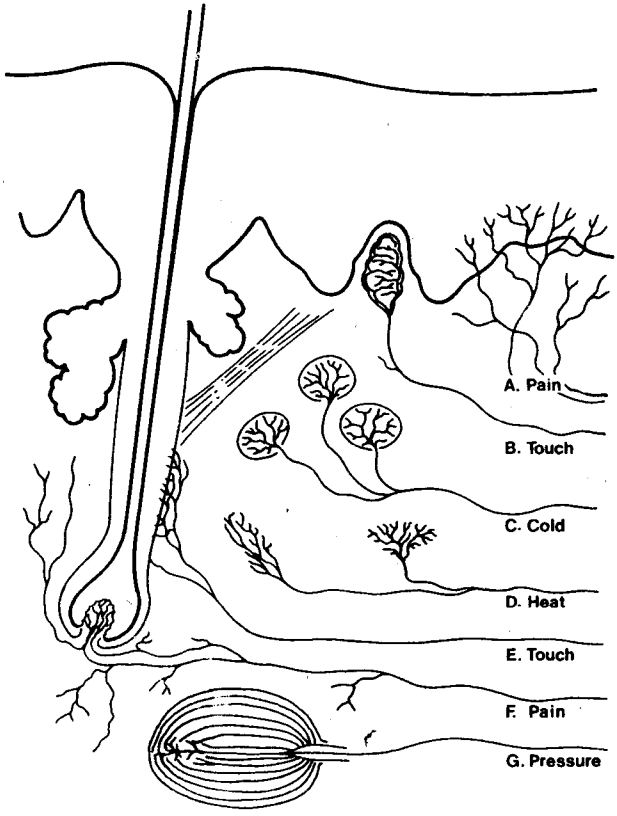

Fig. 8 Schematic representation of sensory nerve endings in the skin.
A. Free nerve endings in the dermis and epidermis.
B. Tactile corpuscle (Meissner) in a dermal papilla.
C. Bulbous corpuscle (Krause) in the dermis
D. End organ (Ruffini) in the dermis.
E. Nerve terminals around hair follicles.
F. Free nerve terminals in a hair papilla and deep layers of dermis.
G. Lamellated corpuscle (Pacinian) in superficial fascia.

intercalated neurons permits both afferent and efferent components to establish functional continuity with many other neurons and an essential step in the evolution of the more elaborate types of nervous system was an increase in the number of intercalary neurons and linkages.

COMPONENTS OF THE NERVOUS SYSTEM

The nervous system is divided into *central* and *peripheral* components and these in turn are sub-divided into *somatic* and *autonomic* parts, but