HUMAN NEUROANATOMY

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PREFACE TO SECOND EDITION

In the preparation of the second edition, the suggestions received from both students and practitioners were carefully considered, and as a result two main additions have been made to the text. One is the incorporation of a new chapter (Ch. X) on segmental and peripheral innervation, including a clinico-anatomical survey of the cervical, brachial and lumbosacral plexuses and of the main peripheral nerves. The second is an expansion of chapter XXI to give a more complete and fully illustrated account of the arterial supply and venous drainage of the brain. The remainder of the book, though generally revised, has been left substantially the same as in the first edition. Many of the recent advances, especially in the field of neurophysiology, could not be adequately included in a text of this scope, since the interpretation of the available data and their application to human clinical neurology are still in a controversial state. Reference to the newer work has been made wherever possible, and the more important publications have been listed in the enlarged bibliography.

Of the nineteen new illustrations, fifteen were selected from various sources which are duly acknowledged, and special thanks are due to the W. B. Saunders Company for permission to reproduce Figs. 105, 130 and 130A from Haymaker and Woodhall "Peripheral Nerve Injuries." The authors are deeply indebted to Frances H. Elwyn for her careful redrawing and relabeling of the new illustrations, and to the publishers for their unfailing courtesy and cooperation.

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PREFACE

Neurology, more perhaps than any other branch of medicine, is dependent on an accurate knowledge of anatomy as a basis for the intelligent diagnosis and localization of neural disturbances. This book, the result of many years of neuroanatomical teaching, is intended to supply this basic anatomical need, to give the student and physician a thorough and clear presentation of the structural mechanisms of the human nervous system together with some understanding of their functional and clinical significance. It is an attempt to link structure and function into a dynamic pattern without sacrificing anatomical detail.

The book is a human neuroanatomy sufficiently rich in content to obviate the necessity of constantly consulting larger anatomical texts. It may be conveniently divided into two parts. The first part (Chapters I-VIII) is concerned with the general organization and meaning of the nervous system, its embryology and histological structure, and with some fundamental neurological problems as they apply to man. This is followed by a discussion of the organization and segmental distribution of the peripheral nerve elements, including an analysis of the functional components of the spinal nerves and of the various receptors and effectors. If these earlier chapters are perhaps more extensive than in most other texts, it is due to the conviction that the book should be complete in itself, and also that a knowledge of these preliminaries is essential for an understanding of the complex machinery of the spinal cord and brain.

The second and larger part (Chapter IX-XX) is devoted to the architectonics of the central nervous system and may be regarded as "applied neuroanatomy." Special features of this part are the many fine photographs, both gross and microscopic, of the human brain and spinal cord, the great wealth of anatomical detail, and the discussion of the structural mechanisms in the light of clinical experience. While the individual portions of the nervous system are treated separately, an attempt has been made to achieve organic structural continuity by judicious repetition and overlapping and by constant reference to related topics already familiar to the student from previous chapters. The plan of exposition is substantially the same for each topic. The gross structure and relationships are concisely but thoroughly reviewed with the aid of clear and graphic illustrations. The internal structure is then presented in detail, usually based on a carefully graded series of fine and clearly labeled microphotographs of human material. At each level the student is familiarized with the exact location, extent and relationships of the various structures seen in the section. Finally the anatomical features of each part are reviewed more comprehensively as three-dimensional structural mechanisms, with a full discussion of their connections and clinical significance. We believe that this treatment will make the complicated structural details alive and interesting to the student. The illustrations are not segregated in the back of the book in the form of an atlas but are scattered in the text, in proper relation to the levels studied.

Besides the many original illustrations, a number of others selected from various and duly acknowledged sources have been completely redrawn and relabeled for the sake of clarity and simplicity. All the illustrations, whether original or borrowed, have been executed by Frances H. Elwyn to whose skill and patience the authors are deeply indebted. We are also indebted to Dr. H. Alsop Riley for the use of several microphotographs; to Drs. R. C. Truex and Benjamin Salzer for the reading of several chapters; and especially to Dr. Otto Marburg for his many stimulating discussions and suggestions and for his critical

reading of the chapters on the mesencephalon, diencephalon, and cerebral hemispheres. Thanks are also due to Rosette Spoerri for her competent help in preparing the manuscript and bibliography.

The authors cannot express too strongly their obligation to the publishers for their continuous courtesy and coöperation in all matters, and for their infinite patience in waiting for a manuscript long overdue.

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CONTENTS

CHAPTER I

CHAPTER II

CHAPTER III

CHAPTER IV

CHAPTER V

CHAPTER VI

CHAPTER VII

CHAPTER VIII

CHAPTER I

GENERAL ORGANIZATION AND SIGNIFICANCE OF THE NERVOUS SYSTEM

The biological significance of the nervous system, stated in the most general terms, is the coordination of bodily activities in response to both external and internal conditions. The complex vital activities of the human body may be regarded as a series of adjustments effecting harmonious action of the various parts and enabling the individual to respond properly to environmental changes. Many of these adjustments of a physicochemical nature are performed largely through the agency of the hemolymphatic vascular system. Others are brought about by changes passing from one part of the body to another along the conducting units or neurons which form the nervous system. Those adjustments or reactions of the organism to changes in its environment which are performed by the intervention of the nervous system are termed *neural reactions*. However, the vascular and neural mechanisms are by no means independent of each other but are in fact closely interrelated. Substances circulating in blood and lymph, such as metabolites, internal secretions and toxins; the amount, temperature and gaseous content of the blood itself, etc., change the physiological condition of the neural mechanisms and thereby alter neural reactions to various stimuli. In some cases they may even initiate neural reactions. Thus the accumulation of carbon dioxide in the blood directly stimulates the neural respiratory center, and similarly the centers for heat regulation are affected by the heightened temperature of the blood. On the other hand, vascular and glandular activities are in turn more or less definitely regulated by the nervous system.

The nervous mechanism of man, as of any other vertebrate, may be divided into the *central nervous system* consisting of brain and spinal cord, and the *peripheral nervous system* including the *cranial* and *spinal nerves* with their respective ganglia and the peripheral portions of the *autonomic nervous system*. The bundles of long nerve fibers which form the bulk of the peripheral nervous system connect the brain and the spinal cord with the various parts of the body, from which they transmit impulses to the central nervous system or to which they conduct impulses from the central nervous system for the initiation or modification of muscular or glandular activity. On the other hand, the central nervous system with its complicated interconnected neuron groups adjusts the incoming stimuli to the outgoing impulses, determining what parts of the body and to what extent shall be affected by the stimuli it receives. In other words, it is the adjusting or coordinating center of the neural mechanism.

The peripheral nerve fibers which conduct impulses to the central nervous system are called *afferent peripheral fibers* ("sensory" fibers) and the neurons of which these nerve fibers are a part are the *afferent peripheral neurons* ("sensory" neurons). Those peripheral fibers which conduct impulses from the brain and spinal cord constitute the *efferent peripheral fibers* and their neurons the *efferent peripheral neurons*. The various structures which first receive stimuli and which contain the distal endings of the afferent peripheral fibers are known as *receptors* (sensory endings, sense organs). Those structures in which changes or effects are produced by impulses transmitted to them by the efferent peripheral fibers and which contain the distal endings of the latter are termed *effectors*. In man these are principally muscles and glands. The changes brought about by neural impulses may be an initiation or increase of muscular or secretory activity (*excitation*) or a diminution or complete cessation of the same (*inhibition*), the neural impulses themselves being termed excitatory or inhibitory respectively. The vast numbers of neurons, which lie wholly in the central nervous system and have no direct contact with the periphery, constitute the *central, intermediate* or *associative neurons*. The various interactivities of these central neurons may likewise excite or inhibit each other.

It is evident from the above that a complete neural reaction will pursue the following circuit: receptor, afferent peripheral neurons, central neurons, efferent peripheral neurons, effector. Such a circuit may be termed a *neural* or *reflex arc*. While various neural reactions have to some extent their separate neural arcs and one of the purposes of this book is to trace the neural pathways of specific reactions, it must be emphasized that the various portions of the central nervous system are widely interconnected. The nervous system may be regarded as a highly differentiated nerve net in which are laid down the more permeable, more easily accessible pathways which form the neural arcs for specific reactions. But these arcs are never isolated, the excitation may spread from one to another, and the various reactions and their arcs mutually influence each other in many ways.

The general structure and organization of the nervous system is largely determined by two factors: (1) the presence, distribution and relative development of the receptor and effector organs, and (2) the nature and degree of development of the various central neural mechanisms which interrelate the afferent and efferent peripheral neurons. Certain important features of the nervous system showing the influence of these peripheral and central factors may be briefly discussed.

In a general way the body as a whole falls into two great divisions: (a) the outer body wall including the limbs and part of the head, and (b) the inner tube with its appendages comprising the alimentary, respiratory and reproductive tracts and other coelomic viscera. The former is derived embryologically from the somatopleure and, excepting its glands and blood vessels and other smooth muscles (pilomotor), may be termed *somatic*. The coelomic viscera together with the glands and smooth muscles (vascular and pilomotor) lying in the outer body wall may be termed *splanchnic* or *visceral*. Thus glandular epithelium and smooth muscle wherever found are to be regarded as splanchnic. The striped muscle of the heart is likewise splanchnic. The outer body wall is primarily concerned with reactions to changes in the external environment. Such reactions are initiated by external changes acting on the numerous superficial receptors, the *exteroceptors*, and effecting the rapidly contracting striped skeletal musculature, producing a movement of the whole or parts of the body. Most of our conscious volitional reactions and of the deep (kinetic) and superficial reflexes fall under this category and are performed by the somatic part of the nervous system. Reactions initiated by stimuli arising in the muscles and tendons of the body wall itself and effecting the skeletal musculature likewise belong to this type.

The inner tube and other viscera are mainly concerned with the nutritional, metabolic, secretory and vascular activities, the so called *vegetative* or *vital* functions. These reactions are for the most part initiated by internal changes acting upon visceral receptors (*visceroceptors*) and taking effect in the involuntary musculature and glands. Such reactions are under the control of the *visceral* portion of the nervous system, and are to a large extent unconscious and involuntary. Those which are conscious are usually of an instinctive or emotional character, dealing with fundamental imperative bodily needs. The visceral and somatic systems are, however, closely connected both in the central and peripheral nervous systems. While some reactions may be purely somatic or purely visceral, many are mixed. Thus external stimuli, as sight of food or cutaneous pain, may produce secretory or vasomotor effects, and visceral stimuli, as hunger or visceral pain, may produce energetic voluntary movements.

Peripherally, the *autonomic* nervous system innervating the viscera consists of several series of ganglia lying at varying distances from the brain and spinal cord. These are composed of neurons which send their fibers to the visceral effectors. They are connected with the central nervous system by fiber bundles known as *rami communicantes* (See Autonomic System). As will be seen more definitely later this system comprises two divisions: the sympathetic and parasympathetic, each of which innervates the same structures. As a result most of the viscera have a double innervation, the effect of the two being usually antagonistic to each other. For example, impulses from the parasympathetic slow up the activity of the heart, those from the sympathetic accelerate cardiac activity. Of these two, the parasympathetic has more to do with the self-regulation of the visceral organs, i.e. their regulation by stimuli from the organs themselves, while the sympathetic is concerned more with the adjustment of visceral mechanisms to external environmental conditions. In other words, the parasympathetic reactions are primarily viscero-visceral, while those mediated by the sympathetic are often somato-visceral. The external stimuli which produce the latter reactions are usually those which directly affect bodily welfare and are of a specially painful, disagreeable or agreeable character. Stimuli of this type together with visceral stimuli enter into combination with discriminative reactions of the cerebral cortex and form the basis of the emotional or affective side of many cortical actions.

Another important division of the nervous system relates to the neural mechanism involved in the self-regulation of *posture* and *movement*. Movements may be initiated by all kinds of stimuli, but their proper performance requires regulation by stimuli from the locomotor organs themselves, i.e. muscles and tendons, while the movement is being carried out. Similarly, a constant position or posture can only be steadily maintained by stimuli from the organs maintaining posture. The receptors thus stimulated by the tension states of the muscles, whether varying or constant, lie in or near the muscles or tendons themselves and are known as *proprioceptors*. The latter also include the vestibular sense organ of the ear (cristae and maculae) which is stimulated in like manner by the position and movement of the head. This whole self-regulating apparatus, to a large extent unconscious and involuntary, may be termed proprioceptive. The eye plays an important part in these reactions and there may be other neural factors. Naturally the mere physical properties of the locomotor system, such as the rigidity of bone, the respective contractile and tensile strength of muscle and tendon form a non-neural part of the proprioceptive mechanism.

The constant tension state of muscles concerned with maintaining a characteristic posture (primarily against gravity) is known as muscle *tonus* and the neural reactions involved in its maintenance are *tonic* or *static* reactions. "Reflex tonus is postural contraction." Reactions resulting in movement are *kinetic* or *phasic*. A movement may fix into a posture (kineto-static reaction) while steady maintenance of posture by postural stimuli may be termed stato-static or pure static. Any movement will obviously be affected by the tonus of the muscles involved, hence there is a static element in movement itself. "Tonus is the shadow of movement" (J. Ramsay Hunt)

While the most highly developed proprioceptive mechanisms are concerned with the somatic voluntary musclature and the above mainly applies to them, there are similar visceral mechanisms involved in maintaining the positions of the viscera and the adjustment of the walls of hollow organs to their contents, as for instance bladder pressure, etc. The same applies to the heart and blood vessels. All these are usually included in the visceral reactions and are carried out by the involuntary muscles of the organs involved.

Disturbances of the somatic proprioceptive mechanisms, both tonic and kinetic, are largely responsible for the breakdown of normal movement as expressed in the various hypotonias, hypertonias, ataxias, and at times abnormal involuntary movements. Many such phenomena are to be explained as a hyperactivity of certain neural mechanisms due to their being no longer correlated or opposed by influences from other neural mechanisms which have been injured or destroyed ("release phenomena").

The vertebrate is an elongated bilaterally symmetrical animal progressing in a definite direction, primitively perhaps by alternating contractions of a segmented lateral musculature. Corresponding to these characteristics is the bilateral character of the nervous system and its transverse segmentation, shown by its series of nerves, a pair to each muscle segment. The anterior end of the animal which during movement first encounters the new environment becomes highly differentiated. Here are located the mouth and respiratory apparatus. Here also are developed the complicated organs of special sense, such as the nose, eye, ear, lateral line organs and taste buds, which greatly increase the range of stimuli received by the animal and thereby render possible a greater range of responsive activities in obtaining and testing food, in protection and in reproduction. Corresponding to this specialization of the forward end or formation of the *head* (*cephalization*) the highest development of the central nervous system also occurs in this region, leading to the formation of the *brain* or *encephalon*, a process which might be termed *encephalization*. A large part of the brain thus consists of the central coordinating neural mechanisms for the three great sense organs of the head: the nose, eye and ear. These centers are already indicated in early development by the three primary expansions of the brain: the forebrain expansion, from which the pallium or cerebral cortex is later formed, for the nose; the midbrain expansion for the eye; and the hind brain expansion known as the cerebellum for the primitive vestibular part of the ear. These three parts which become greatly enlarged and differentiated also receive stimuli from other parts of the head and from the body, and they constitute the highest coordinating portion of the nervous system. The manner in which they are lifted out of the lower segmental parts of the brain has led to their designation as the *suprasegmental* portions of the nervous system. The *segmental* part of the brain is in a general way that part more closely connected with the peripheral (segmental) nerves and containing the simpler and more fundamental coordinating mechanisms.

In the course of its development to the conditions seen in man, the vertebrate body has undergone many structural changes. Older parts have become modified or reduced; newer ones, often quite complicated, have arisen in response to environmental changes. The distinction between the older and newer parts of the human body is helpful to an understanding of many neural arrangements, since the two have to some extent separate, if interlocking, neural representations. Phylogenetically, the change from a water to a land habitat is expressed in profound structural alterations. The water breathing gills with their neural center in the brain (medulla) have been supplanted by air breathing lungs now directly controlled by the spinal cord, but the medullary centers are still necessary for respiration. There is a loss of certain sense organs receiving stimuli only through a watery medium, such as the lateral line organs and those taste buds lying outside of mouth and pharynx, and the acquisition of a new organ for the reception of aerial sound vibrations (the cochlea of the ear). Limbs adapted for locomotion displace the older locomotion by the axial musculature, with concomitant marked alterations and additions in the nervous system. In many parts of the latter, the neural mechanisms controlling the limbs are quite different from those of the older axial or trunk portions of the body. Later developments of the vertebrate body include the acquisition of separate head movements, of frontal and binocular vision, the development of the hand as an organ for finer sensory discrimination and as a highly differentiated motor apparatus, with its concomitant release from active locomotion. The latter entails locomotion with the lower extremity only and the acquisition of an erect posture introducing new problems of bodily equilibrium and posture maintenance. Other recent changes are the facial musculature of expression and the organization of lips, tongue and larynx into an apparatus of speech.

A most important development of the vertebrate brain, reaching its culmination in man, is the rise of a neural mechanism for the more complex correlation and discrimination of sensory impulses, and the greater utilization in various neural reactions of traces of former reactions. The principal function of this mechanism may be termed *associative memory* and such reactions *mnemonic* (memory) reactions. A reaction elicited by a certain stimulus associated with other stimuli may be subsequently elicited by one of these associated stimuli instead of the primary one. When a piece of meat is placed in the mouth of a newborn dog, salivation immediately occurs. This reaction is an inherited characteristic and has been termed by Pavlov an *unconditioned reflex*. Seeing the meat for the first time will not cause salivation, but after eating a few times just the sight of food will start profuse salivary activity. The animal now *recognizes* the food before he has tasted it. Such reactions which depend on previous experiences Pavlov has called *acquired* or *conditioned* reflexes and these form the most important neural basis of the processes of educability.

The enormous importance of the mnemonic reactions in man is shown by the fact that their neural mechanisms constitute the greater part of the central nervous system. A primary factor in their development is the presence in the head of the receptors of the nose, eye and cochlea. These organs are *teloreceptors* or *teleceptors*, i.e. they receive stimuli from distant objects, permitting identification of such objects before actual contact with them is made. As a result of previous associations (experience), closer relations with distant objects are avoided or sought in accordance with their previously ascertained harmful or beneficial nature. The avoiding or seeking character thereby acquired by teleceptive mnemonic reactions constitutes their emotional or affective side. It is probable that the affective tone of neural activities has other sources than the above. The physiological states attendant upon neural activity, the influence upon neural structures of substances circulating in the hemolymphatic system, etc., all these probably contribute to the totality of feeling tone in affective consciousness.

Another important type of mnemonic reactions, usually termed proprioceptive, relates to the acquisition of skill which involves the increased motor ability to carry out the discriminative mnemonic reactions. Proprioceptive stimuli leave traces which regulate subsequent movement and posture, constantly modifying and perfecting them. This enables that partly unconscious reduction of unessential movements and the increase in speed and accuracy which characterizes the "learned" or skilled reactions. The basis of what is psychologically known as "voluntary" movement is probably the reception by the cerebral cortex of proprioceptive stimuli from the voluntary striped musculature and the resulting presence of proprioceptive traces or memories. On the other hand, the "involuntary" character of smooth muscle may be due in part to the absence of proprioceptive stimuli from them reaching the cortex and consequent absence of proprioceptive memories of their activities.

That part of the brain especially concerned in associative memory is the *pallium* or *cerebral cortex* which arises developmentally as a secondary subdivision of the forebrain expansion (*telencephalon*). In the lowest vertebrates it is small and devoted principally to the reception of olfactory stimuli. As phylogenetic differentiation progresses, stimuli from all parts of the body and from the organs of special sense project into this region forming a newer non-olfactory part, the *neopallium*, which becomes tremendously expanded in the higher vertebrates, reaching its greatest extent and differentiation in man. Coincident with this growth which might be termed *telencephalization*, there is a parallel development in other portions of the nervous system. The cerebellum, which is the highest proprioceptive center for the automatic regulation of movement and posture, the thalamus and other neural mechanisms likewise acquire new parts in immediate connections with the neopallium. These new acquisitions, i.e., the neopallium and other parts in immediate connection with it, are often collectively termed the *neencephalon* as distinguished from the older *palencephalon*. Newer motor mechanisms for the special execution of the most important mnemonic pallial reactions are seen in the development of the hand and speech organs as already mentioned.

The simpler neural reactions which, while influenced by other portions of the nervous system than those necessary for their performance, are not originated or essentially modified by past neural activities or experience of the individual are usually termed *reflexes*. They are thus not "acquired" and their performance in many cases at least does not involve the pallium, though their character may be altered by changes in the higher neural centers. How far, in general, the various fundamental neural mechanisms including reflexes have been altered by their being brought under the control of the pallial ones, is a problem which has not yet received full solution.

Reflexes may be kinetic when resulting in movement, static or tonic when resulting in setting or maintaining posture. In fact the greater part of tonic activities is of a reflex character. When posture is initiated by movement the reflex may be termed kinetostatic. Posture-setting and posture-maintaining impulses from the proprioceptors of muscles and tendons, from the vestibule of the ear and from the eye are correlated in various ways to bring about these adjustments. Some of the highest of these automatic kinetopostural mechanisms are those which bring the body as a whole from an abnormal into a normal position, the so called "righting reactions" ("Stellreflexe" of Magnus and de Kleijn).

Clinically, kinetic reflexes are usually divided into *deep* and *superficial*, according to the source of the stimulus. The deep reflexes are elicited by tapping the tendon of a muscle (tendon reflex) or the bone to which it is attached (periosteal reflex) thereby producing shortening of the muscle itself. Familiar examples of deep reflexes are the bicipital, tricipital, radial, ulnar, patellar (knee jerk), tibial and Achilles (ankle jerk). The superficial reflexes are elicited by stroking or otherwise stimulating the skin (cutaneous reflexes) or mucosal membranes (mucosal reflexes) and thus causing a contraction of the subjacent or other muscles. Examples are the corneal, abdominal and plantar cutaneous reflexes and the mucosal palatal and pharyngeal reflexes. Certain other reflexes obtained by stimulation of the organs of special sense, such as the important pupillary reaction to light, do not fall under the above categories. It is evident that the deep reflexes are proprioceptive kinetic reflexes and the superficial are exteroceptive reflexes. While the reflexes mentioned above are comparatively simple and segmental in character, many others, such as sneezing, coughing, vomiting, etc., and most of the postural reflex adjustments, are extremely complicated and involve large portions of the body.

Those reactions usually called *conscious* are difficult to define but appear in general to represent a heightened activity of various portions of the pallial mechanism of associative memory. The problem of distinguishing what is original or inherited and what is acquired by individual experience in neural reactions is one of great importance and equally great difficulty. The laws of growth and development apply to the brain as well as to other organs and there is every reason to suppose that the nervous system has its given neuronal structure which forms the basis for the acquisition and utilization of experience as well as the performance of reflex acts and thereby constitutes mental and emotional capacity for mnemonic reactions. However, the individual neural acquisitions are built upon previous acquisitions in such a complicated manner that the ascertainment of the non-acquired fundamental reactions upon which the acquired ones are built and of the given capacity for their acquisition still requires much investigation.