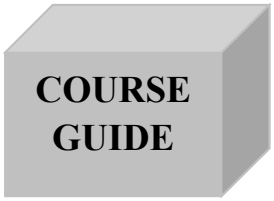
NATIONAL OPEN UNIVERSITY OF NIGERIA

SCHOOL OF SCIENCE AND TECH.

COURSE CODE:-NSS 214

COURSE TITLE:-
PHYSIOLOGY FOR NURSES



NSS 214
HUMAN PHYSIOLOGY FOR NURSES II

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Introduction

Physiology is the scientific discipline that deals with process or the functions of the living things. It also examines how the parts of the body work and the ways in which they cooperate together to maintain life and health of the individual.

One outstanding quality of physiology is that it integrates the individual functions of all the body's different cells and organs into a functional whole, the human or animal body. Indeed, life in the human being relies upon this total function, not on functions of the single parts in isolation from the others.

NSS 214: Human Physiology is a three credit course for students in the BNSc. programme. The course is broken to 4 modules with 12 study units. It will introduce the students to Physiology. At the end of the course, the learner is expected to demonstrate clear understanding of physiology and its application to nursing and holistic patients' care.

This course guide provides you with what to expect in the course, how to work through the course material as a distance learner saddled with the responsibility of studying on your own and your overall responsibilities and expectations. Tutorial sessions are also linked up with the course to provide the needed support you required.

What You Will Learn in this Course

The overall aim of this course NSS 214: Human Physiology is to reveal to us the dynamic nature of the human body. It will also help you to appreciate the functions of the cellular or molecular level in the overall performance of the individual cells and the chemical reactions that goes with it.
As you learnt earlier, physiology is the study of the function of anatomical structures. Human physiology is the study of the functions of the human body. These functions are complex and much more difficult to examine than most anatomical structures. As a result, there are even more specialties in physiology than in anatomy, which includes:

- Cell physiology: This is the cornerstone of human physiology; it is the study of the functions of cells. It deals with events at the chemical and molecular levels.
- Special physiology: this is the study of the physiology of special organs. For example, renal physiology is the study of kidney function.
- Systemic physiology: includes all aspects of the function of specific organ systems; cardiovascular physiology, respiratory physiology and reproductive physiology are examples of systemic physiology.
- Patho-physiology is the study of the effects of diseases on organ or system functions (pathos is the Greek word for "disease"). Modern medicine depends on an understanding of both normal physiology and patho-physiology

Course Aims

This course aims at providing the learners with in depth understanding of physiology so as to understand and predict the body's response to stimuli and also understand how the body maintains conditions within a narrow range of values in the presence of a continually changing environment.

Course Objectives

To achieve the aims set out above, the course sets the overall objective. In addition, each unit has specific objectives stated at the beginning of a unit. Learners are advised to read them carefully before going through the unit. You will have to refer to them during the course of your study to monitor your progress. You are encouraged to always refer to the Unit objectives after completing a Unit. This is the way you can be

certain that you have done what was required of you in the unit**.**

The wider objectives of the course are set below be able to:

7.0 Enhance the nurse with the knowledge of the human body on how the body response to a stimuli
8.0 Equip the nurses with the understanding of how various organs in the body function to maintain life.
9.0 Provide the nurses with the basis of understanding disease conditions
10.0 Help the nurse to know when there is deviation in the body function (homeostasis)

Working through this Course

To complete this course, you are required to study through the units, the recommended textbooks and other relevant materials. Each unit contains some self assessment exercises and tutor marked assignments and at some point in this course, you are required to submit the tutor marked assignments. This will be followed by an end of term examination.

Course Materials

The following are the components of this course:

- The course guide
- Study Units
- Textbooks
- Assignment file
- Presentation schedule

Study Units

This course is made up 4 modules in 12 study units. These are:

Module 1 Physiology of the Nervous System I

Unit 1 Physiology of the Central Nervous System: Brain
Unit 2 The Spinal Cord, Cranial and Spinal Nerves
Unit 3 Neurons and Neuronal Transmission
Unit 4 The Autonomic Nervous System

Unit 5 Receptor Physiology and the General Senses

Module 2 Sensory Physiology I

Unit 1 Taste and Olfaction
Unit 2 The Ears and Hearing
Unit 3 Vestibular Apparatus and Equilibrium

Module 3 Sensory Physiology II

Unit 1 Eyes and Vision
Unit 2 Retina and Neural Processing of Visual Information

Module 4 Skeletal and Muscle Physiology

Unit 1 Bones and Osseous Tissue
Unit 2 Muscle Physiology

Textbooks and References

Carola, R. Harley J.P., and Noback C.R. (1990). *Human Anatomy and Physiology.* New York: McGraw Hill.

Fox, S.I. (1996). *Human Physiology* Boston: Wm. C. Brown Publishers.
Guyton, A.C., Hall J.E. (2000). Textbook of Medical Physiology. Philadelphia: Saunders Co.
Sherwood L. *Human Physiology: From Cells to Systems*. Minneapolis: West Publishing Co.

Sherwood, Lauralee (1993). Human Physiology from Cells to Systems, Minneapolis: West Publishing Co.

Thibodeau G.A. and Kevin T.P. (2000). Anatomy and Physiology. St. Louis Mosby.

Assignment File

The assignment file will contain the Tutor Marked Assignment (TMA) which will constitute part of the continuous assessment (CA) of the course.

Assessment

There are two aspects to the assessment of the course. These are the Tutor marked assignment and written examination. In tackling the

assignments, you are expected to apply information, knowledge and strategies gathered during the course. The assignments must be turned in to your tutor for formal assessment in accordance with the stated presentation schedules. Three out of the four assignments submitted for assessment will count for 30% of your total course work.

At the end of the course you will need to sit for a final written examination of three hour's duration. This examination will also count for 70% of your total course mark.

Tutor-Marked Assignment

There are 4 tutor-marked assignments to be answered for this course. You are advised in your own interest to attempt and submit the assignments at the stipulated time in study centre. You will be able to complete the assignments from the information and materials contained in your reading and study units. There is other self activity contained in the instructional material to facilitate your studies. Try to attempt it all. Feel free to consult any of the references to provide you with broader view and a deeper understanding of the course. Extensions will only be granted for submission after deadline on exceptional cases.

Final Examination and Grading

The final examination of NSS 214 will be of 3 hours duration and have a value of 70% of the total course grade. The examination will consist of questions which have bearings with the attempted self assessment exercises and tutor marked assignments that you have previously encountered. Furthermore, all areas of the course will be evaluated. Make sure you give enough time to revise the entire course.

Course Marking Scheme

The following table includes the course marking scheme
Table 1

Assessment	**Marks**
3 Assignments	3 assignments = 10% x 3 = 30%
Final examination	70% of overall course marks
Total	100% of course marks

Course Overview

This table indicates the units, the number of weeks required to complete the assignments.

Unit	**Title of Work**	**Week**	**Assessment**

		Activity	
	Course Guide	Week 1	
Module 1	**Physiology of the Nervous System I**		
1	Neurons and Neuronal Transmission	Week 2	
2	Physiology of the Central Nervous System: Brain	Week 3	
3	The Spinal Cord, Cranial and Spinal Nerves	Week 4	
4	Functions of the Autonomic Nervous System	Week 5	
5	Receptors Physiology and the General Senses	Week 6	
Module 2	**Sensory Physiology I**		
1	Taste and Olfaction	Week 7	
2	The Ears and Hearing	Week 8	
3	The Vestibular Apparatus and Equilibrium	Week 9	
Module 3	**Sensory Physiology II**		
1	Eye and Vision	Week 10	
2	Retina and Neural Processing of Visual Information	Week 11	
Module 4	**Skeletal and Muscular Physiology**		
1	Skeletal Physiology	Week 12	
2	Muscular Physiology	Week 13	

How to Get the Most Out of the Course

In distance learning, the study units replace the university lecture. This is one of the greatest advantages of distance learning. You can read and work through specially designed study materials at your own pace and at time and place that suit you best. Think of it as reading the lecture notes instead of listening to a lecturer. In the same way that a lecturer might set you some reading task, the study units tell you when to read your other material. Just as a lecturer might give you an in-class exercise, your study units provide exercise for you to do at appropriate points.

The following are practical strategies for working through the course:

- Read the course guide thoroughly.
- Organize a study schedule.
- Stick to your own created study schedule.

- Read the introduction and objectives very well.
- Assemble your study materials.
- Work through the unit.
- Keep in mind that you will learn a lot by doing all your assignment carefully.
- Review the stated objectives.
- Don't proceed to the next unit until you are sure you have understood the previous unit.
- Keep to your schedules of studying and assignments.
- Review the course and prepare yourself for the final examination.

Facilitators/Tutors and Tutorials

There are 12 hours of effective tutorial provided in support of this course. Details will be communicated to you together with the name and phone number of your tutor through the study centre.

Your tutor will mark and comment on your assignments, keep a close watch on your progress and any difficulties you might encounter and also provide assistance to you during the course. You must ensure that you submit your assignment as and at when due. You will get a feedback from your tutor as soon as possible to the assignments.
Do not hesitate to contact your tutor or study centre on phone or email in case of any of the following circumstances:

1. You do not understand any part of the study units or the assigned reading
2. You have difficulty with the self test or exercises.
3. You have questions or problems with an assignment, tutors comments or grading of an assignment.

You are encouraged to attend the tutorials to allow for face to face contact with your tutor and ask questions which you needed answers immediately. It is also an opportunity to discuss any grey area with your tutor. You can equally prepare questions to the tutorial class for meaningful interactions. You are sure to gain a lot from actively participating in the discussion.

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MODULE 1 PHYSIOLOGY OF THE NERVOUS SYSTEM I

UNIT 1 PHYSIOLOGY OF THE CENTRAL NERVOUS SYSTEM: BRAIN

CONTENTS

1.0 INTRODUCTION

The Nervous system is one of the two major control systems of the body in addition to the endocrine system. The central nervous system (CNS) is composed of the brain and spinal cord. These receive input about the external and internal environment from afferent neurons. The CNS sorts, processes and transmits this information to the efferent neurons which carry the instruction to glands or muscles to bring about the desired response. The nervous system acts by means of its electrical signals to

control the rapid responses of the body. The brain, the first part of the central nervous system is arranged in regions and subdivisions. This unit will examine the functions of the various regions of the brain and some higher brain functions.

2.0 OBJECTIVES

At the end of this unit you should be able to:

- describe the structural organization of the brain
- explain the anatomical divisions of the cerebrum and their functions
- explain the lateralization and language function of the cerebral cortex
- explain the functions of the various parts of the encephalon
- explain the neural basis for the control of emotions, motivation and memory
- describe the function of the midbrain
- identify the structures of the hindbrain and explain their functions
- explain the function of the Reticular formation.

3.0 MAIN CONTENT

3.1 Structural Organization of the Brain

The central nervous system (CNS) consists of the brain and spinal cord. They receive input from sensory neurons, and direct the activity of motor neurons. Association neurons are present to "associate" appropriate motor responses with sensory stimuli.

The early embryo contains an embryonic tissue layer known as ectoderm, on its surface that will eventually form the epidermis of the skin and the nervous system. As development continues, a groove appears in the ectoderm along the dorsal midline of the embryo's body. The groove deepens and by the twelfth day after conception has fused to form a neural tube. The part of the ectoderm where the fusion occurs becomes a structure separate from the neural tube and is called the neural crest. The neural tube becomes the CNS later while the neural crest eventually becomes the ganglions of the peripheral nervous system and other structures. By the middle of 4^{th} week three distinct swellings are evident on the anterior end of the neural tube which will form the forebrain, midbrain and hindbrain. In the 5^{th} week those three areas are modified to form five regions. The forebrain divides into the telencephalon and diencephalon. The midbrain is unchanged and the hindbrain divides into the metencephalon and myelencephalon. These regions later become greatly modified but the terms described are still used to indicate the general regions of the brain.

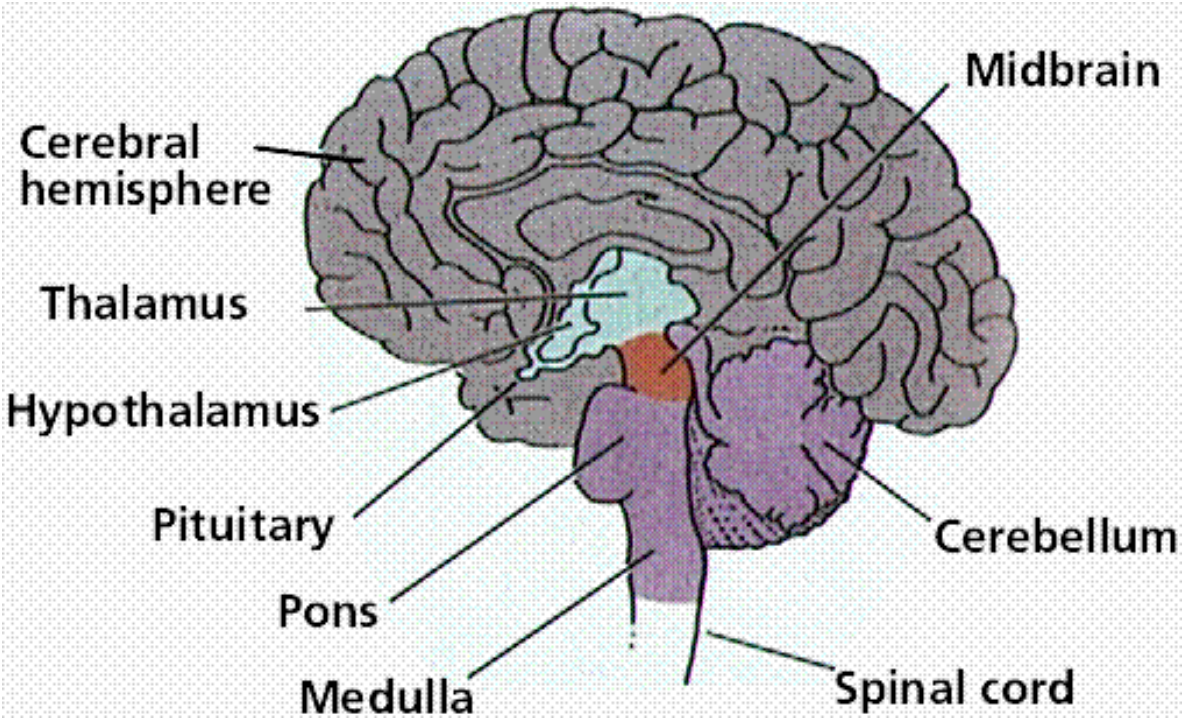

Fig 1. The Human Brain

The telencephalon grows disproportionately in humans forming the two enormous hemispheres of the cerebrum that cover the diencephalon, the mid brain and some portion of the hindbrain. The CNS that began as a hollow tube remains hollow even as the regions are formed. The hollow parts divide into cavities called ventricles in the brain. These become filled with cerebrospinal fluid. These cavities are connected to themselves and are continuous with the central canal of the spinal cord.

The central nervous system is composed of grey and white matter.
Grey matter is composed of high concentration of neuronal cell-bodies and dendrites that do not have myelin sheath. Grey matter is found in the surface layer (cortex) of the brain and deeper within the brain in neuronal aggregations called nuclei. White matter consists of high concentration of axon tracts. Because axons are usually myelinated they acquire the white colour of myelin sheath. White matter lies under the cortex and also surrounds the nuclei.

The adult brain contains about 100 billion neurons, weighs about 1.5kg and receives about 20% of the total blood flow to the body per minute.
The human brain is mostly water (75%) and has the consistency of gelatin. It needs support for its existence. The brain is therefore protected by the scalp, hair etc and by the reinforced bony cranium which is one of the strongest structures in the body. It also floats shock-proof in cerebrospinal

fluid and is encased in three layers of cranial meninges - the dura mater, arachnoid mater and pia mater.

3.2 Functions of the Cerebrum

The cerebrum is the only structure of the telencephalon, and the largest of the brain regions (accounting for about 80% of the brain mass). It is believed to be the centre for higher brain functions and the most sophisticated region of the brain. The cerebrum is divided into two halves the right and left cerebral hemisphere, and these two hemispheres are connected to each other by a thick band of neuronal axons called corpus callosum. The outer layer of the cerebrum is the **cerebral cortex** which caps an inner core of white matter that houses the **basal nuclei**.

3.2.1 The Cerebral Cortex

The cerebral cortex is composed of a thin (2 to 4mm thick) outer covering of grey matter overlying a thick central core of white matter. The cortex characteristically contains numerous folds and grooves called convolutions. The elevated folds are called gyri (singular-gyrus-) and the depressed grooves are called sulci (singular sulcus).

Each cerebral hemisphere is divided by deep sulci or fissures into lobes - 4 major ones and probably an additional minor fifth lobe. The lobes are the frontal, parietal, temporal and occipital lobes, which are visible from the surface and deep and fifth insula lobe.

The **frontal lobe** is the anterior portion of each cerebral hemisphere. It is separated by a deep fissure called the central sulcus from the parietal lobe. The precentral gyrus is located in the frontal lobe just in front of the central sulus. This gyrus is responsible for voluntary motor control. Other functions of the frontal lobe are that it is also responsible for speaking ability and for elaboration of thought. The primary motor cortex in the precentral gyrus on each side of the brain primarily controls muscles on the opposite side of the body.

The **parietal lobes** situated directly on the top of the head behind the frontal lobe and separated from the frontal lobe by the deep central sulcus. The parietal lobes are primarily responsible for receiving and processing sensory input such as touch, pressure, heat, cold and pain from the surface of the body.

The post-central gyrus, directly behind the central sulcus in the parietal lobe is the primary area of the cortex responsible for the perception of these sensations collectively called somaesthetic sensations. (i.e. those

arising from cutaneous, muscle, tendon, and joint receptors).

The **temporal lobes** are located at the sides of the head and contain the auditory centres that receive sensory fibres from the cochlea of the ear. The lobe is also involved in the interpretation and association of auditory and visual information. The occipital lobes are located at the back of the head and they are primarily responsible for vision and coordination of eye movements.

The insula lobe is small and buried deep in the central sulucs. It is supposed to be associated with memory, and visceral activities.

3.2.2 The Basal Nuclei

The basal nuclei is also known as basal ganglia. They are masses of grey matter composed of neuron cell bodies located deep within the white matter of the cerebrum. A nucleus (plural nuclei) refers to a functional aggregation of neuronal cell bodies. The most prominent part of the basal nuclei is the corpus stratum.
The major function of the basal nuclei is a complex role in the control of voluntary movement in the following ways - (i) inhibiting muscle tone throughout the body (to balance excitatory inputs); (ii) selecting and maintaining purposeful motor activity while suppressing useless or unwanted patterns of movement, and (iii) helping to monitor and coordinate slow sustained contractions, especially motor neurons but they modify ongoing activity in motor pathways.
The importance of the basal nuclei in motor control is evident in diseases involving this region; the most common of which is Parkinson's disease. In this condition there is deficiency of dopamine, a neurotransmitter in the basal nuclei. This lack makes the basal nuclei unable to perform normal roles therefore the characteristic features of Parkinson's disease manifest. These are (1) increased muscle tone or rigidity (2) involuntary, useless or unwanted movements like resting tremors and (3) slowness in initiating and carrying out motor behaviours.

3.2.3 Lateralization and Kabgyage Language Function of the Cerebral Cortex

Function of the cerebral cortex. Each cerebral hemisphere controls the movements of the opposite side of the body through motor fibres that originate in the precentral gyrus. In the same way, somaesthetic sensations from each side of the body projects to the opposite side on the post central gyrus due to crossing over (decussation of fibres). However, the two hemispheres can receive information from both sides of the body because they communicate with each other via the corpus callosum.

The cortical areas described so far appear to be equally distributed. However, studies seen to indicate that a task can be successfully performed by one side but not by the other. For example, the left hemisphere has been shown to be the one in which most of the language and analytical abilities reside as well as handedness. Fine motor control seems to be more under the control of the left hemisphere. This is evidenced by the fact that most people are right handed and the left hemisphere controls the right side of the body. It is these findings that led to the concept of cerebral dominance. That is since these various obvious activities are controlled by the left hemisphere, then the left hemisphere must be the dominant one. However, further studies have shown that the right hemisphere is also specialized along different less obvious lines. Therefore, rather than one hemisphere being dominant and the other, being subordinate, the two hemispheres appear to have complimentary functions. The term cerebral lateralization, or specialization of function in one hemisphere or the other, may be preferred, more recently to the term cerebral dominance.

Unlike the sensory and motor regions of the cortex, which are present in both hemispheres, the areas of the brain responsible for language ability are found in the left hemisphere in most people.

Language is a complex form of communication in which written or spoken words symbolize objects and convey ideas. It involves the integration of two distinct capabilities namely, expression and comprehension - each of which is related to a specific area of the cortex. The two areas are the Broca’s area and Wernicke's area. Broca's area is responsible for speaking ability and articulation of speech.

Broca's aphasia is the result of damage to the Broca's area. Common symptoms include weakness of the right arm and right side of the face. People with Broca's aphasia are reluctant to speak, and when they speak, their speech is slow and poorly articulated. Speech comprehension is not affected. They can understand a sentence but have difficulty repeating it.

The Wernicke's area is located in the parietal lobe almost at the junction of the parietal, occipital and temporal lobes. It is concerned with language comprehension. It plays a critical role in understanding both spoken and written messages. It is responsible for formulating coherent patterns of speech that are transferred via a bundle of fibres to the Broca's area for articulation. Wernicke's aphasia results in speech that is rapid but without meaning. People with Wenicke's aphasia produce what has been described as "word salad' e.g. real words chaotically mixed together or made up words. Language comprehension whether written or spoken is destroyed in Wernike's aphasia.

3.3 Diencephalon

Together with the telencephalon (cerebrum) the diencephalon constitutes the forebrain. The diencephalon is almost completely surrounded by the cerebral hemispheres and contains a cavity called the third ventricle. It can be said to be the deep part of the cerebrum connecting the midbrain with the cerebral hemispheres. It is composed of the thalamus, epithalamus and hypothalamus. The pituitary gland is connected to the hypothalamus.

The **thalamus** is composed of two egg-shaped masses of grey matter covered by a thin layer of white matter. It is located in the centre of the cranial cavity directly beneath the cerebrum and above the hypothalamus. It forms the lateral walls of the third ventricle.

The thalamus acts as an intermediate relay point and processing centre for all sensory impulses (except smell) on their way to the cerebral cortex from the spinal cord, brain stem, cerebrum, basal ganglia and other sources. It screens out insignificant sensory impulses to appropriate areas of the somato sensory cortex as well as to other regions of the brain. The thalamus working with the brain stem and cortical association areas is important in our ability to direct attention to stimuli of interest and so forth.

The **epithalamus** is the dorsal portion of the diencephalon that contains a choroid plexus over the third ventricle where cerebrospinal fluid is formed. It also contains the pineal gland or epiphysis.

The **hypothalamus** is a small portion of the diencephalon located below the thalamus, where it forms the floor and part of the central walls of the third ventricle. It is a collection of specific nuclei and associated fibres.

This extremely important brain region is an integrating centre for many important homeostatic functions and serves as an important link between the autonomic nervous system and the endocrine system. Specifically the hypothalamus (1) controls body temperature; (2) controls thirst and urine output; (3) controls hunger and food intake; (4) controls anterior pituitary hormone secretion (5) produces posterior pituitary hormones (6) controls uterine contraction and milk ejection; (7) serves as a major autonomic nervous system coordinating centre which in turn affects all smooth muscle, cardiac muscle and exocrine glands; and (8) plays a role in emotional and behavioural patterns. In addition, centres in the hypothalamus, contribute to the regulation of sleep, wakefulness, sexual arousal and performance, and emotions as such anger, fear, pain and pleasure.

The pituitary gland is located immediately inferior to the hypothalamus. It is said to be derived embryonically from a down growth of the diencephalon by means of a stalk neurons in the supraoptic and paraveneticular nuclei of the hypothalamus produce two hormones - antidiuretic hormone (ADH) and oxytocin. These hormones are transported to the neurohypohypsis and stored and secreted in response to hypothalamic stimulation.

3.4 Emotion and Motivation

The parts of the brain that appear to be of paramount importance in emotional states are the hypothalamus and the limbic system.

The limbic system is not a separate structure but refers to a ring of nuclei and fibre tracts that surround the brain stem and are interconnected by intricate neuronal pathways. The structures of the limbic system include the cingulate gyrus (part of cerebral cortex), amygdala, hippocampus and septal nuclei. This complex interacting network of structures is associated with emotions, basic survival and socio-sexual behavioural patterns motivation and learning. It is the centre for basic emotional drives.

There are few synaptic connections between the cerebral cortex and the structures of the limbic system which may help explain the fact that we have so little control over our emotions. However there is a closed circuit of information between the limbic system and the thalamus and hypothalamus and they cooperate in the neural basis of emotional states. Studies suggest that the hypothalamus and the limbic system are involved in the following feelings and behaviours:

1. Aggression - stimulation of areas of the amygdala and particular areas of the hypothalamus can both produce rage and aggression.
2. Fear - electrical stimulation of the amygdala and hypothalamus produce fear. Removal of the limbic system can result in absence of fear.
3. Feeding - as discussed under hypothalamus.
4. Sex - the hypothalamus and limbic system are involved in the regulation of the sexual drive and behaviour.
5. Goal directed behaviours.

The concept of emotion encompasses subjective emotional feelings and moods (anger, fear and happiness) plus the overt physical responses that occur in association with these feelings. Such responses include specific behavioural patterns (e.g. preparation for attack or defence) and observable emotional responses (e.g. laughing, crying and blushing).
Motivation is the ability to direct behaviour towards specific goals that are

aimed at satisfying specific identifiable needs related to homeostasis. However most human behaviours are shaped in a complex framework of unique personal gratifications blended with cultural expectations.

3.5 Memory

Memory is the storage of acquired knowledge for later retrieval. The neural change responsible for retention or storage is known as neural trace. Concepts and not necessarily verbatim words are stored and so is recall. Storage of acquired information is believed to occur in at least two stages - short-term memory (STM) and long term memory (LTM) **Short Term Memory** lasts for seconds to hours. Long term memory is retained for days to years. When knowledge is first acquired it is stored in the short term memory. In order for it not to be forgotten it has to be consolidated into the long term memory. The capacity of the short term memory to store is very limited but the capacity of the long term memory bank is much larger.

Different informational aspects of long term memory traces seem to be processed and coded, then stored in conjunction with other memories of the same type.

It takes longer time to retrieve information from the LTM because the stores are larger. **Remembering** is the process of retrieving specific information from memory stores. Forgetting is the inability to retrieve stored information. Information in the STM is permanently forgotten while in the LTM forgetting is only traMemory traces are present in multiple regions of the brain. The neurons involved are widely distributed throughout the cortical and sub cortical regions of the brain. The regions of the brain implicated in memory include the temporal lobes, the prefrontal cortex, other regions of the cerebral cortex, the limbic system and the cerebellum.

The temporal lobes and limbic system are essential for transferring new memories into long term storage. The hippocampus plays a vital role in integration of various related stimuli in the STM. It is also crucial for consolidation into LTM. However the hippocampus stores only temporarily new LTM store and then transfers them to other cortical structures. For more permanent storage. Accessing and manipulating these long-term stores; appears, to be carried out by the prefrontal region of cerebral cortex. the cerebellum seems to play a role in **procedural memories** involving motor skills gained through repetitive training. The hippocampus and surrounding regions are responsible for declarative memory.
Amnesia (loss of memory) has been found to result from damage to the temporal lobe of the cerebral cortex, hippocampus, head of the caudate

nucleus, or dorsomedial aspects of the thalamus.

3.6 Midbrain

The mesencephalon or midbrain is located between the diencephalon and the pons. It connects the pons and cerebellum with the cerebrum (forebrain). On the ventral surface of the midbrain is a pair of **cerebral peduncles,** made up of pyramidal tracts (fibres to the motor nuclei of the spinal nerves within the spiral cord) corticobulbar (motor fibres to the cranial-nerve motor nuclei) and corticopontine fibres to the pons. The third cranial nerve (occulomotor) emerges from the fossa between the peduncles on its ventral side.

Passing through the midbrain is the cerebral aqueduct. The dorsal portion of the midbrain situated above the aqueduct is the roof which has 4 little elevations - the colliculi. The colliculi are known collectively as the **corpora quadrigemina**. The superior pair of colliculi are reflex centres that coordinate the movements of the eyeballs and head, regulate the focusing mechanism in the eyes and adjust the size of the pupils in response to visual stimuli. Cranial nerve IV (trochlear) emerges from the roof of the midbrain. The inferior colliculi just posterior are relay nuclei of the auditory pathways going to the thalamus and eventually to the auditory cortex.

The midbrain also contains the red nucleus, an area of grey matter deep in the midbrain. It maintains connections with the cerebrum and cerebellum and is involved in motor coordination. Another nucleus is also present, a heavily black pigmented nucleus called substantial nigra. It is integrated into neural circuits with the basal ganglia and therefore is involved also with motor-coordination (somatic motor activities).The substantial nigra has a role in Parkinson's disease.

3.7 The Hindbrain

The hindbrain (rhombencephalon) is composed of the metencephalon and the myeloencephalon and they will be discussed separately.

3.7.1 Metencephalon

The region is composed of the pons and the cerebellum. The pons can be seen as a bulge on the underside of the brain, between the mid brain and the medulla oblongata. The pons is composed mainly of fibres that connect the hindbrain to the midbrain as a relay station. Surface fibres in the pons connect to the cerebellum, and sensory tracts, that pass from the medulla oblongata, through the pons and onto the midbrain. Within the

pons are several nuclei associated with specific cranial nerves - Trigeminal (V) abducens (VI), facial (VII) and Vestibulocochear (VIII).

Other nuclei in the pons cooperate with nuclei in the medulla oblongata to control breathing. Two respiratory control centres are in the pons - the apneustic and pneumotaxic centres.

The cerebellum occupies the inferior and posterior aspect of the cranial cavity and is the second largest structure of the brain. It contains outer grey matter and inner white matter (like the cerebrum). Fibres from the cerebellum pass through the red nucleus to the thalamus and then to the motor areas of the cerebral cortex. Other fibre tracts connect the cerebellum with the pons, medulla oblongata and spinal cord. The cerebellum receives inputs from proprietors (receptors in joints, tendons and muscles) and working together with the basal ganglia and motor areas of the cortex participate in the coordination of movements.

The cerebellum consists of 3 functionally distinctive parts with different functions:

1. **The Vestibulocerebellum** is important for the maintenance of balance and control of eye movement.

2. **The Spinocerebellum** regulates muscle tone and coordinates skilled, voluntary movements. It receives signals from the cortex concerning specific message to muscles and also receives inputs from peripheral receptors concerning body movement and position. The spinocerebellum essentially acts as "middle management" comparing the "intentions" or "orders" of the higher centres with the "performance" of the muscles and correcting deviations.

3. **The Cerebrocerebellum** plays a role in planning and initiation of voluntary activity by providing input to the cortical motor area. It is also the region involved in procedural memories.

Damage or disease of the cerebellum produces the following range of symptoms which reflect the loss of the aforementioned function. Poor balance, nystagmus, reduced muscle tone but no paralysis, inability to perform rapid movement smoothly and inability to stop and start skeletal muscle action quickly. All these are due to a lack of coordination due to errors in speed, force and direction of movement, a condition called ataxia. The condition is also characterized by intention tremor which occurs only when intentional movements are made. The person may reach for an object and miss it by overshooting or placing the hand too far to the left or right of the object, and then attempt to correct it by repeating the to and from movement. This back and forth movement can result in oscillations

of the limb.

3.7.2 Myeloencephalon

This is made up of only the medulla oblongata. The medulla measures about 3cm long and is continuous with the pons superiorly and the spinal cord inferiorly. The medulla, with the pons and midbrain make up the brain stem.

All the descending and ascending tracts that provide communication between the spinal cord and the brain must pass through the medulla.
The vertical surface of the medulla contains bilateral elevated ridges called the **pyramids**. These pyramids are composed of the fibres of motors tracts from the motor cerebral cortex to the spinal cord. These fibres (pyramids) cross to the contralateral (opposite) side at the lower part of the medulla to the opposite side of the spinal cord, forming an "X". This crossing over of motor nerve fibres is called decussation. The result is that the left side of the brain receives sensory information from the right side of the body and vice versa. Similarly, the right side of the brain controls motor activity in the left side of the body and vice versa.

Many important nuclei are contained in the medulla. Some of them are involved in motor control while some of them form nerve roots for many of the cranial nerves. Cranial nerves IX, X, Xi and XII all have rootlets in parts of the medulla. The vagus nuclei located one on each lateral side of the medulla give rise to the highly important vagus (X) nerve. Other nuclei are there which relay sensory information to the thalamus and them to the cerebral cortex.

The medulla also contains groupings of neurons that make up the vital centres. These include the cardiac (cardioinhibitory centre) for the parasympathetic inhibition of the heart, the vasomotor centre, for control of the autonomic innervations of blood vessels, and the respiratory centre which acts together with centres in the pons to control breathing.

3.8 Reticular Formation

Running throughout the brain stem and into the thalamus and hypothalamus is a widespread and complex network of neurons and fibres called the reticular formation. It is organized into (1) ascending (sensory) pathways from ascending spinal cord tracts and the cerebellum, (2) descending (motor) pathways from the cortex and hypothalamus; and (3) cranial nerves. Ascending fibres from the reticular formation carry signals upwards to arouse and activate the cerebral cortex. These fibres compose the **reticular activating system** (RAS) which controls the overall degree

of cortical alertness and the ability to direct attention. Because of its many interconnections, the RAS is activated in a non-specific fashion by any modality of sensory information. Not surprisingly, general anaesthetics may produce unconsciousness by depressing the RAS. Also the ability to fall asleep may be due to the action of specific neurotransmitters that inhibit activity of the RAS.

4.0 CONCLUSION

The brain is a very important component of the central nervous system which is responsible for controlling and coordinating almost all activities of the human organisms. These functions are carried out by the use of an enormous number of neurons, associating with one another in various regions and subregions of the brain.

5.0 SUMMARY

In this unit we learnt that:

1. The brain is structurally organized through the embryonic neural tube, from where the structures developed upwards moving from the hindbrain up to the forebrain. The direction of sophistication and consciousness also follows the direction of development. By the 5^{th} - 6^{th} week of intrauterine life the brain had differentiated into 5 regions which are still used to indicate the general regions of the brain as follows: (1) telencephalon (cerebral cortex) and (2) diencephalon both of which make up the forebrain. (3) mesencephalon which is the midbrain (4) metencephalon (which consists of the pons and cerebellum) and (5) myeloencephalon which contains the medulla oblongata. These last two make up the hindbrain. The adult brain contains up to 100 billion neurons.

2. The cerebrum consists of two hemispheres connected by a large fibre tract called the corpus callosum. The outer part of the cerebral cortex is grey matter and underneath is white matter; however there are still nuclei of grey matter buried within the white matter of the cerebrum called basal nuclei. The two cerebral hemispheres have a degree of specialization of functions termed cerebral lateralization, but there is cooperation in the functions of the two hemispheres aided by the corpus callosum. Particular regions of the cortex (left hemisphere) appear to be more important in language ability.

3. The limbic system and the hypothalamus are brain regions implicated as centres for various emotions. Memory traces involve numerous brain regions but the hippocampus of the medial

temporal lobes in particular appears to control consolidation of short term memory into long term memory.

4. The diencephalon is the region of the forebrain that includes the epithalamus, thalamus and hypothalamus. These structures control many functions in the body as well as serve as important relay centres for sensory information.

5. The structures of the midbrain and hindbrain make up the brainstem which performs many functions. The brain stem serves as a connecting link between the rest of the brain and the spinal cord. Most of their functions are concerned with incoming and outgoing fibres traversing between the periphery and the higher brain centres with incoming fibres relaying sensory information to the brain and outgoing ones carrying command signals from the brain for efferent output.

6.0 TUTOR-MARKED ASSIGNMENT

Explain the differences in functions of the right and left cerebral hemispheres and list the areas of the brain believed to be involved.

7.0 REFERENCES/FURTHER READINGS

Fox, S.I. (1996). *Human Physiology* Boston: Wm. C. Brown Publishers.

Carola, R. Harley J.P., and Noback C.R. (1990). *Human Anatomy and Physiology.* New York: McGraw Hill.

Sherwood L. *Human Physiology: From Cells to Systems*. Minneapolis: West Publishing Co.

UNIT 2 THE SPINAL CORD, CRANIAL NERVES AND SPINAL NERVES

CONTENTS

1.0 INTRODUCTION

The spinal cord is the second part of the central nervous system that extends through the vertebral canal and is connected to spinal nerves. The spinal cord is strategically located between the brain and the peripheral nervous system; and this location enables it to fulfil its primary functions. One of the primary functions of the spinal cord is that it serves as a link for transmission of information between the brain and the remainder of the body. This unit will examine the physiology of the spinal cord. It will also look at cranial and spinal nerves.

2.0 OBJECTIVES

At the end of this unit, you will be able to:

- review briefly the anatomy of the spinal cord
- discuss the functional roles of the spinal cord in terms of the following:

- White matter
- Gray matter
- The spinal reflex

- describe the 12 cranial nerves and functions
- describe the spinal nerve and their functions

3.0 MAIN CONTENT

3.1 Review of the Functional anatomy of the Spinal Cord

The spinal cord is the part of the central nervous system that extends from the level of the foremen magnum of the skull downward for about 45cm to the level of the first lumber vertebra (L1) in adults. The upper end is continuous with the lowermost part of the brain (medullar). Its lower end tapers off as the cone-shaped conus terminalis; located in the vicinity of the first lumber vertebra.

The spinal cord is encased in the bony vertebral column which serves to protect the cord. The central opening or foramen in the vertebral column has a diameter about the size of your index finger. The cylindrical cord inside the column is about as thick as a pencil, or ones' little finger. Paired spinal nerves emerge from the spinal cord through the spaces formed between the bony, wing like arches of adjacent vertebrae. The nerves are named according to the region of the vertebral column from which they emerge.

There are 31 pairs of spinal nerves and roots out of which there are 8 cervical (C) nerve pairs, 12 thoracic (T), 5 lumber (L), 5 sacral (S) and one coccygeal (Co). Each pair of spinal nerves passes through a pair of inter-vertebral foramina between two successive vertebrae and distributed to a specific pair of segments of the body.

The roots of all nerves passing caudally below the conus resemble flowing coarse strands of hair. Therefore the bundle of fibres from the lumber and sacral roots is called canda equina (horse tail) because of its appearance.

The spinal cord and nerve roots are also protected by the spinal meninges (membranes) and cerebrospinal fluid. 3 layers of meninges cover the brain. The outer layer is called the dura mater and is a tough fibrous membrane. The middle layer is the arachnoid mater delicate and transparent. The innermost layer is the tender pia mater, thin highly vascularized and tightly attached to the spinal cord.

Cerebrospinal fluid (CSF) is a clear watery ultra-filtrate solution formed from blood. In the capillaries of the brain the fluid passes through small openings from the 4^{th} ventricle into the subarachnoid spaces around the brain and spinal cord and returns to the blood. CSF provides a cushion which protects the delicate tissues of the cord. A cross-section for the spinal cord shows that the anatomy is generally the same throughout its length. Unlike in the brain where grey matter forms a cover over the white matter, the grey matter of the spinal cord is located centrally, surrounded by white matter. The inner grey matter is arranged to form a butterfly (or H) shaped region with two dorsal horns and two ventral horns. The white matter is composed of ascending and descending fibre tracts which are arranged into six columns called funiculi.

The spinal cord is divided into more or less symmetrical halves by a deep groove called the anterior median septum and the posterior median septum.

The two primary functions of the spinal cord are:

1) To serve as a link for transmission of information between the brain and the remainder of the body and
2) To integrate reflex activity between afferent input and efferent output without involving the brain.

3.2 Functional Roles of the Spinal Cord (The White Matter)

The white matter of the spinal cord surrounds the inner butterfly shaped region of grey matter. The white matter is composed mainly of myelinated nerve fibres and myelin has whitish colour. The white matter is divided into three pairs of columns (funiculi) of myelinated fibres running the entire length of the cord. The funiculi consists of the anterior (ventral) column, the posterior (dorsal) column and the lateral column. The bundles of fibres within each funiculus are organized as tracts. A tract is a bundle of nerve fibres (axons of long interneuron) with a similar function. Each tract begins or ends in a particular area of the brain (depending on its type). Each transmits a specific type of information. Some types are ascending tracts (cord to brain) while others are descending tracts (brain to cord).

The tracts are named to indicate their location whether they are ascending or descending, and their origin and termination. Ascending tracts usually begin with spine and end with the brain region where the fibres first synapse. E.g. the lateral spinothalamic tract originates in the grey matter of the spinal cord, synapses at the thalamus before being relayed to the cerebral cortex and is located laterally in the spinal cord. Descending tracts begin with a prefix showing the brain region where they originate and end with the suffix-spinal. E.g. corticospinal tracts begin in the cerebral cortex and descend the spinal cord.

3.2.1 Ascending Tracts

Ascending tracts are made up of sensory fibres that carry impulses up the

spinal cord to the brain. They convey sensory information from cutaneous receptors, propioceptors (muscles and joint senses) and visceral receptors. Most of the sensory information that originates in the right side of the body crosses over to eventually reach the region on the left side of the brain for analysis. Similarly the information arising in the left side of the body is analyzed by the right side of the brain. The decussation occurs in the medulla oblongata for some sensory modalities or it can occur in the spinal cord for other modalities of sensation.

Some sensory pathways (tracts) have sequences that are made up of three neurons. In some path ways (tracts) the neurons in the sequence are called first, second and third order neurons. A first order neuron extends from the sensory receptor to the CNS; a second-order neuron extends from the spinal cord or brain stem to a nucleus in the thalamus and a third-order neuron goes from the thalamus to the sensory area of cerebral cortex.
The principal ascending tracts of the spinal cord are summarized as follows:

Track	Origin	Termination	Function
1. Anterior spinothalamic	Posterior horn on one side of cord but crosses over to opposite side	Thalamus then cerebral cortex	Conducts sensory impulses for crude touch and pressure
2. Lateral spinothalamic	Posterior horn on one side of cord but crosses over to opposite side increase this column.	Thalamus then cerebral cortex	Conducts pain and temperature impulses that are interpreted within the cerebral cortex.
3. Fasciculus gracillis and fasciculus cuneatus	Peripheral afferent neurons cell bodies in dorsal root ganglia.	Nucleus grackles and nucleus conatus of medulla of same side. Fibres from here cross over and get to thalamus then cerebral cortex	Conducts sensory impulses from skin, muscles, tendons and joints which are interpreted as sensations of fine touch, precise pressures and body movements.
4.Spinoreticuloth alamic	Posterior horn of grey matter crosses to opposite side in spinal cord	Reticular formation of brain stem then thalamus, then cerebral cortex	Conducts pain sensations
5.Posterior spinocerebellar	Posterior horn; does not cross over	Cerebellum	Conducts propioceptions. Sensory impulses

			from one side of body to same side of cerebellum, for co-ordinated muscular contractions.
6.Anterior spinocerebellar	Posterior horn some fibres cross over others do not	Cerebellum	Conducts sensory impulses from both sides of body to cerebellum; necessary for coordinated muscular contractions

3.2.2 Descending Tracts

Descending tracts of motor fibres transmit impulses from the brain down the spinal cord to the efferent neurons. The motor (descending) tracts and associated neural circuits are grouped into two as **pyramidal (corticospinal)** and **extra pyramidal tracts.**

The pyramidal tracts descend directly to the spinal cord. The cell bodies that have their fibres in these pyramidal tracts are located primarily in the precentral gyrus (motor cortex). Other areas of the cerebral cortex, however also contribute to these tracts.

About 80% of the corticospinal fibres decussate in the pyramids of the medulla oblongata (hence the name) and descend as the lateral corticospinal tracts. The remaining fibres that did not decussate form the anterior possibly ventral corticospinal tracts. These ones decussate in the spinal cord. Because of the crossing over of the pyramidal tract, the right cerebral hemisphere controls the musculature on the left side of the body and the left hemisphere control the right musculature. The corticospinal tracts are primarily concerned with the control of fine movements that require dexterity.

The remaining descending tracts are extra pyramidal motor tracts. They originate in the midbrain and brain stem regions. Many centres, complex circuits within the brain and several descending pathways are involved. The system includes all the pathways that influence and regulate the motor control of the lower motor neurons except those of the pyramidal tracts. The regions of the cerebral cortex, basal nuclei and cerebellum that participate in this motor control have numerous synaptic interconnections and can influence movement only indirectly by means of stimulation or inhibition of the particular nuclei that give rise to the extra pyramidal

tracts. If the pyramidal tract is cut in an experimental animal, stimulation of the cortex, cerebellum and basal ganglia can still produce movements.

The major tracts in the extra pyramidal system are the reticulospinal tracts. They originate in the reticular formation of the brain stem which receives either stimulatory or inhibitory input from the cerebrum and cerebellum. This is because there are no descending tracts from the cerebellum. The cerebellum can only influence motor activity indirectly by affecting the vestibular nuclei, basal nuclei etc.

Summary of Descending Motor Tracts to Spinal Interneuron and Motor Neurons

	Tract	**Category**	**Origin**	**Crossed or Uncrossed**
1.	Lateral corticospinal	Pyramidal	Cerebral cortex	Crossed
2.	Anterior corticospinal	Pyramidal	Cerebral cortex	Uncrossed
3.	Rubrospinal	Extra pyramidal	Red nucleus (midbrain)	Crossed
4.	Tectospinal	Extra pyramidal	Superior culliculus (midbrain)	Crossed
5.	Vestibulospinal	Extra pyramidal	Vestibular nuclei (in medulla oblongata)	Uncrossed
6.	Reticulospinal	Extra pyramidal	Brain stem reticular formation (medulla and pons)	Crossed

3.3 Functional Role of the Spinal Cord: The Gray Matter

The centrally located grey matter is also functionally organized. The central canal filled with CSF lies in the centre of the grey matter.

The butterfly shaped grey matter has two horns, the dorsal (posterior) and the ventral (anterior) horns. The two posterior horns function in afferent input while the anterior horns function in efferent somatic output. The pair that forms the cross bar of the H shape is known as the grey commissure. It functions in cross reflexes. The dorsal horn contains cell bodies of interneurons where afferent neurons with sensory input synapse. The ventral horn contains cell bodies of neurons that supply skeletal muscles.

Spinal nerves connect with each side of the spinal cord by a dorsal root and a ventral root. Afferent fibres carrying in coming signals enter the spinal cord through the dorsal root; efferent fibres carrying outgoing signals leave through the ventral root. Groups of cell bodies whose axons make up the dorsal root lie outside the cord, and are called dorsal root ganglia (A ganglion is a collection of cell bodies outside the CNS; in the CNS they are called centre or nuclei). The cell bodies of the efferent neurons (called anterior horncells) originate in the grey matter of the cord and their axons make up the ventral root.

The dorsal and ventral roots at each level join up to form a spinal nerve that emerges from the vertebral afferent and efferent fibres traversing between a particular region of the body and the spinal cord.

3.4 Functions of the Spinal Cord (The Spinal Reflex)

A reflex is any response that occurs automatically without conscious effort. There are two types of reflexes simple or basic reflexes, which are built in unlearned responses, such as closing the eyes when an object moves towards them; and acquired or conditioned reflexes, which are a result of practice and learning. An example of this is a pianist striking a particular key on seeing a given note on the music staff. The musician does this automatically, but only after considerable conscious training.

The neural pathway involved in accomplishing reflex activity is known as a reflex arc. The reflex arc typically includes five basic components as follows:

1) Receptor
2) Afferent pathway
3) Integrating centre
4) Efferent pathway
5) Effector

The **receptor** detects a stimulus as a physical or chemical change in the environment of the receptor. In response to the stimulus, the receptor produces an action potential that is relayed by the **afferent pathway** to the **integrating centre** which is usually in the CNS. (The spinal cord and brain are responsible for integration of basic reflexes. The integrating centre processes all information available to it from this receptor and all other inputs; then makes a decision about the appropriate response. This instruction is transmitted through the **efferent pathway** to the **effector** (a muscle or a gland which carries out the required response). Unlike conscious behaviour a reflex response is predictable because the pathway between the receptor and effector is always the same.

A basic spinal reflex is one integrated by the spinal cord i.e. all components necessary for linking afferent input to efferent response are present within the spinal cord. An example is the withdrawal reflex. When a person touches a hot object, a reflex is initiated to withdraw the hand from the hot object. Receptors are present in the skin for hot, cold, warmth, light touch etc. The information is sent as action potentials by the afferent system to the CNS. Once the afferent neuron enters the spinal cord, (integrating centre) it diverges to synapse in different ways. One of the ways is to stimulate an excitatory interneuron that will stimulate the efferent motor neuron which supplies the biceps to flex the elbow and therefore withdraw the hand. It may stimulate inhibitory interneuron which would antagonize the desired response e.g. to inhibit the triceps from extending the elbow. The third is to stimulate other interneuron to carry the message up the spinal cord to the brain where the impulse is appropriately interpreted for what it is, its location and where it can be stored as memory and the person can start thinking about what to do about it.

However a spinal reflex can be modified by the brain to override the input from the receptors; actually preventing the biceps from contracting inspite of the painful stimulus.

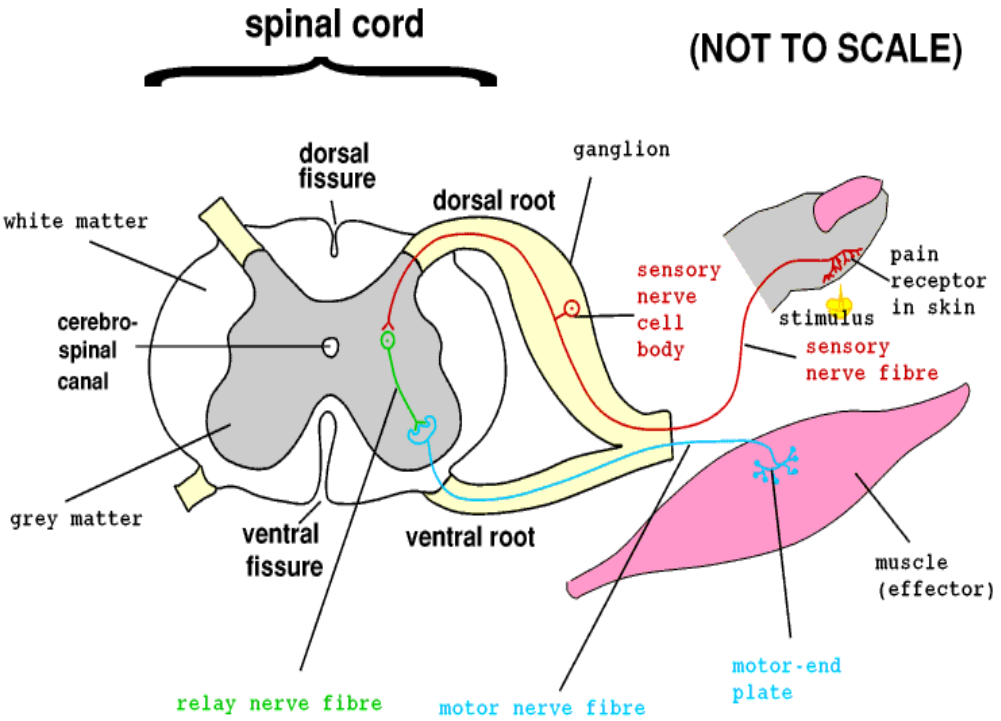

Fig. 2: Spinal reflex

3.5 Cranial Nerves

There are twelve pairs of cranial nerves which are the peripheral nerves of the brain. Two of these pairs arise from the forebrain and ten pairs arise

from the midbrain and hindbrain. The cranial nerves are designated by Roman numerals and by names. The Roman numerals refer to the order in which the nerves are positioned from the front of the brain to the back. The names indicate structures innervated by these nerves (e.g. facial) or the principal function of the nerves (e.g. oculomotor).

Cranial nerves are classified as sensory, motor and mixed. The sensory fibres are afferent fibres associated with the special senses. The cell bodies of these sensory neurons are not located in the brain but are found in ganglia near the sensory organ.

The motor fibres of the cranial nerves emerge from the brainstem. They arise from bundles of neurons called motor nuclei, which are stimulated by nerve impulses from many outside sources; including the cortex of the cerebrum and sense organs. Axons of motor cranial nerves have two roles. They (1) stimulate voluntary muscles or (2) Synapse with ganglia of the autonomic nervous system which then relay nerve impulses to cardiac muscle, smooth muscle and glands.

The rest of the cranial nerves are mixed nerves. This term indicates that the nerves contain both sensory and motor fibres.

The cranial nerves are concerned with the specialized senses of smell, taste, vision, hearing and balance and the general senses and other inputs. They are also involved with the specialized motor activities of eye movement, chewing, swallowing, breathing, speaking and facial expression.

The vagus nerve is an exception projecting fibres to organs in the abdomen and thorax.

Summary of Cranial Nerves

	Nerve	**Type**	**Origin/Distribution**	**Function**
i.	Olfactory	Sensory	Nasal mucous membrane to olfactory	Olfaction

			bulb of cerebrum	
ii.	Optic	Sensory	Retina of the eye terminates in lateral geniculate body of thalamus and superior culliculus of midbrain	Vision, Afferent limb of reflex of focusing and constricting pupil
iii.	Oculomotor	Motor	Midbrain to all extrinsic muscles of eyeball except superior oblique and lateral rectus; also autonomic fibres to ciliary muscles of lens and constrictor muscles	Movement of eyeball, elevation of upper eyelid constriction of pupil focusing of lens
iv.	Trochlear	Motor	Caudal midbrain superior oblique muscle of eye	Eye movements (down and out)
V_1.	Trigeminal (ophthalmic division)	Sensory	Pons to general area of forehead, eyes	Conveys general sense from cornea of eyeball upper nasal cavity front of scalp forehead, upper eyelid conjuctiva, lacrimal gland
V_2.	Maxillary division	Sensory	Pons to general area of maxillary region	Conveys general sense from cheek upper lips upper teeth, mucosa of nasal cavity, palate, parts of pharynx
V_3.	Mandibular	Mixed	Pons sensory branch to area of mandibular region motor: innervates muscles of mastication	Sensory conveys general senses from tongue (not taste) lower teeth skin of lower jaw. motor: chewing
vi.	Abducens	Motor	Caudal Pon innervate lateral rectus muscle of the eye	Abduction of eye. (Lateral movement).
vii.	Facial	Mixed	Pons sensory:	Sensory taste.

			innervates taste buds of tongue motor: innervates muscles of facial expression, autonomic fibres to salivary glands, lacrimal glands	Motor: salivation, lacrimation, movement of facial muscle
viii.	Vestibulocochlear	Sensory	Auditory: medulla, pons to cochlear of inner ear. Vestibular: Medulla, pons to semicircular ducts utricle and saccule of inner ear	Hearing equilibrium
ix.	Glosso-pharyngeal	Mixed	Medulla Sensory: conveys taste from posterior third of tongue, general senses from upper pharynx. Motor: innervates stylo-pharyngeus, muscle autonomic fibres stimulate parotid gland	Secretion of saliva, swallowing
x.	Vagus	Mixed	Medulla to voluntary muscles of soft palate, cardiac muscle, smooth muscle in respiratory, cardiovascular, digestive systems	Swallowing, monitoring oxygen and carbon dioxide level in blood; sense blood pressure, other visceral activities of affected systems.
xi.	Accessory (spinal accessory)	Motor	Medullar, cervical spinal cord to muscles of larynx sternocleido mastoid, trapezius	Voice production (larynx); muscle sense; movement of head, shoulders
xii.	Hypoglossal	Motor	Medulla to tongue muscles	Movements of tongue during. speech, swallowing muscle sense

3.6 Spinal Nerves

There are thirty one (31) pairs of spinal nerves. These nerves are grouped according to the region of the vertebral column as follows:

8 cervical nerves
12 thoracic
5 lumber
5 sacral
1 coccygeal

Each spinal nerve is a mixed nerve composed of sensory and motor fibres. These fibres are packaged together in the nerve, but separate near the attachment of the nerve to the spinal cord. This produces two roots to each nerve. The dorsal root is composed of sensory fibres and the ventral root of motor fibres. The dorsal root contains an enlargement called the dorsal root ganglion where the cell bodies of sensory neurons are located. However the cell bodies of the efferent (motor) fibres that innervate skeletal (somatic) muscles are not in a ganglion but instead in the grey matter of the spinal cord.

The cell bodies for some autonomic motor neurons are located in ganglia outside the spinal cord.

A short distance after the dorsal and ventral roots join together to form the spinal nerve proper, the nerve divides into several branches called rami (singular ramus) as follows the dorsal, ventral, meningeal ramui and the rami communicants. Branches of the dorsal ramus innervate the skin of the back and back of the head and the tissues and deep muscles of the back. Branches of the ventral ramus innervate the skin, tissues and muscles of the neck, chest, abdominal wall, both pairs of limbs and the pelvic area. The meningeal ramus innervates the vertebrae spinal meninges and spinal blood vessels. The rami communicants are composed of sensory (general visceral afferent) and motor fibres associated with the autonomic nervous system.

The ventral rami of the spinal nerves with the exception of T2 to T12 are arranged to form several complex networks of nerves called plexuses. In a plexus the nerve fibres of different spinal nerves are sorted and recombined. Plexuses include

1) The cervical
2) The branchial
3) The lumber
4) The sacral (sometimes the lumber and sacral plexus) and
5) The coccygeal.

The ventral rami of T2 to T12 do not form plexus; each ramus innervates a segment of the thoracic and abdominal walls.

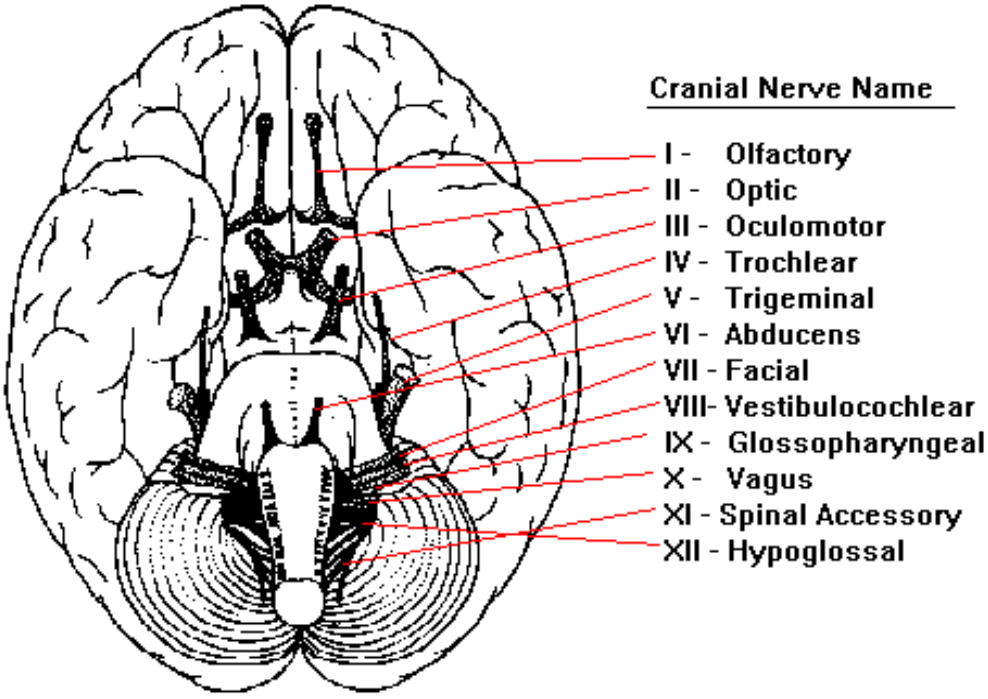

Fig. 3 Diagram of Cranial nerves

Summary of Plexuses of the Spinal Nerves

Plexus	**Components**	**Location**	**Major Nerve branches**	**Region innervated**
Cervical	Ventral rami of C1 to C4	Neck region origin covered by sternocleido mastoid muscle	Cutaneous, muscular communicating phrenic, ansa cervicals	Muscles of the back of head, neck, diaphragm
Brachial	Ventral rami of C5 to C8 and T1 nerves	Lower neck, axilla	Axillary, ulna median, radial, musculo-cutaneous	Muscles and skin of neck, shoulder arm, forearm, wrist, hand
Lumbar	Ventral rami of L1 to L4	Interior of posterior abdominal wall	Femoral obturator	Muscles of skin of abdominal wall.
Sacral	Ventral rami of L4, L5 and S1 to S3	Posterior pelvic wall	Superior gluteal, inferior gluteal; sciatic nerve	Buttock , medial thigh, muscles and skin of posterior thigh posterior leg

			branches: tibial	planta of root
			Common penoneal;	Muscles and skin of lateral posterior thigh, anterior leg, dorsal foot voluntary sphincters of urethra, anus
Coccygeal	Co I nerve, plus communications from S4 and S5 nerves	Coccyx region	A few fine filaments	Skin in coccyx region

4.0 CONCLUSION

The spinal cord is the neuronal link between the brain and spinal cord which serves as the integrative centre for spinal reflexes.

5.0 SUMMARY

1. The spinal cord is the second part of the central nervous system that connects the brain to the peripheral neurons system.
2. A cross-section of the spinal cord show a butterfly-shaped centrally placed grey matter and an outer layer of white matter.
3. The central grey matter of the spinal cord arranged in the form of H-shape has two dorsal horns and two posterior horns which form the dorsal and ventral roots of the spinal nerves.
4. The white-matter of the spinal cord is composed of ascending and descending fibre tracts arranged into six columns.
5. The simple reflex is an unconscious motor response to a sensory stimulus and this reflects a very important function of the spinal cord.
6. Twelve pairs of cranial nerves arise from the forebrain, midbrain and hindbrain and they are concerned with specialized sensory and motor activities.
7. There are 31 pairs of spinal nerves. Each pair contains both sensory and motor fibres. The dorsal root of a spinal nerve contains sensory fibres. The ventral root of a spinal nerve contains motor nerves.

6.0 TUTOR-MARKED ASSIGNMENT

List the tracts of the pyramidal motor system and described the function of the pyramidal system.

7.0 REFERENCES/FURTHER READINGS

Fox, S.I. (1996). **Human Physiology** Dubuque: Wm C. Brown Publishers.

Carola, R. Harley, J.P. of Noback, C.R. (1990) **Human Anatomy & Physiology.** New York: McGraw Hill.

Sherwood L. (1993). Human Physiology from Cells to Systems. Minneapolis:

UNIT 3 NEURONS AND NEURONAL TRANSMISSION

CONTENTS

1.0 INTRODUCTION

The human nervous system contains about a trillion neurons and a lot more gill cells. Neurons are the basic building blocks of the nervous system which is one of the two major regulating systems of the body. The regulatory function of the nervous system is exerted over the body's muscular and glandular activities most of which are directed toward maintaining homeostasis in the body.

Neurons are specialized for rapid integration and transmission of nerve impulses. They are able to initiate, process, code and conduct changes in their membrane potential as a means of transmitting a message rapidly throughout their length. They can also transmit this information through intricate nerve pathways from neuron to neuron, or neuron to muscles and glands through chemical means.

2.0 OBJECTIVES

At the end of this unit, you should be able to:

- describe the neuron and explain structural and functional classification of neurons

- explain the process of impulse transmission
- describe an action potential showing the ionic basis of excitation and conduction
- describe see functional anatomy of a synapse
- explain neuronal transmission across a synapse
- explain the mechanism of action of neurotransmitters, their inactivation, removal and recycling
- explain the action of different neurotransmitters in the nervous system.

3.0 MAIN CONTENT

3.1 Description of Neurons

Neurons are highly specialized cells that transmit impulses within animals to cause a change in a target cell such as a muscle effector cell or glandular cell. Together with neuroglial (glial) cells make up the nervous system. The neuron is the integral element of our five senses and other physical, regulatory and mental faculties including memory and consciousness.

Neurons have three main purposes:

- To gather and send information from the senses such as touch, smell, sight etc.
- To send appropriate signals to effector cells such as muscles, glands etc.
- To process all information gathered and provide a memory and cognitive ability thus allowing us to take action on information received.

The structure of neurons is essentially the same in all animals, although the human nervous system is much more specialized and complicated than that of lower animals. Neurons are divided into different regions each having a different function. A typical neuron has the following parts:

1. A cell body (soma) which contains the cell nucleus and the cytoplasmic organelles which are responsible for maintaining the cell
2. Several short processes called dendrites which are radial extensions of cell membrane of the body which extend to other neurons and increase the surface area available for connecting with other axons from other neurons
3. A long process extending from the soma, called the axon. The axon can sometimes stretch over a very long distance and is responsible for transmitting signals from the neuron to other cells down stream in the chain. The axon divides into terminal branches each ending in a button like structure called synaptic knobs or terminal buttons

4. Specialized cell junctions called synapses between an axon and other cells which allow for direct communication from one cell to another.

Neuroglial or neurilemma cells are associated with axons of neurons. In the central nervous system they are called oligodendrocytes and in the peripheral nervous system, they are the Schwann cells. They associate with the axons by wrapping themselves around portions of the axon. This forms a segmented sheath around the axon called myelin sheath. Myelin is a lipid (fatty) substance which is pale in colour. It is this colour that leads to the term white matter or grey matter within the nervous system. The white matter contains myelinated axons predominantly whereas the grey matter contains mainly neuronal cell bodies which are non-myelinated. The function of the myelin is to increase the electrical capacitance of neurons and to insulate against any leakage of nerve impulse. They also assist in nourishing the axon. The higher the capacitance, and the better the insulation, the faster the nerve impulse will travel along the axon.

The gap of about 1mm between segments of myelin sheath (junctions between adjacent neuroglial cells) is known as nodes of Ranvier. These serve important functions in neural transmission of impulses in a very specialized way.

Neurons display a very high level of metabolic activity for some reasons:

- They have massive surface areas compared to other cells in the body
- They need to generate nerve impulses.
- Their high level of activity reflects on the appearance of the cell-the nucleus is large, with prominent nucleolus representing a high degree of cellular activity.
- There is abundant endoplasmic reticulum for protein synthesis.
- There is a well developed Golgi apparatus to provide secretions especially neurotransmitters.
- There are also large numbers of mitochondria to produce the large amount of energy required by the neuron.

The function of the nervous system as a whole depends very much upon the complexity of the network of connections between the various neurons rather than the specific features of any single neuron.

3.1 Structural and Functional Classification

Neurons exist in many shapes and sizes and their structure affects their functions. The structural classification of neurons depends on the number of processes extending from the soma. Multipolar neurons that have many dendrites and usually have one long axon carrying an impulse away from

the cell body. They also tend to have large cell bodies. Majority of the neurons in the spinal cord are multipolar and they serve principally as motor neurons.

Bipolar neurons have only two main processes similar in length a single dendrite and an axon. Bipolar neurons are generally small simple cells that provide local connections within the central nervous system. They can also be found in some sense organs i.e. retina and olfactory cells. Unipolar neurons possess one major process which subdivides into two branches; one running to the CNS (axon) and the other to a part of the body (dendritic in function). They are usually sensory neurons.

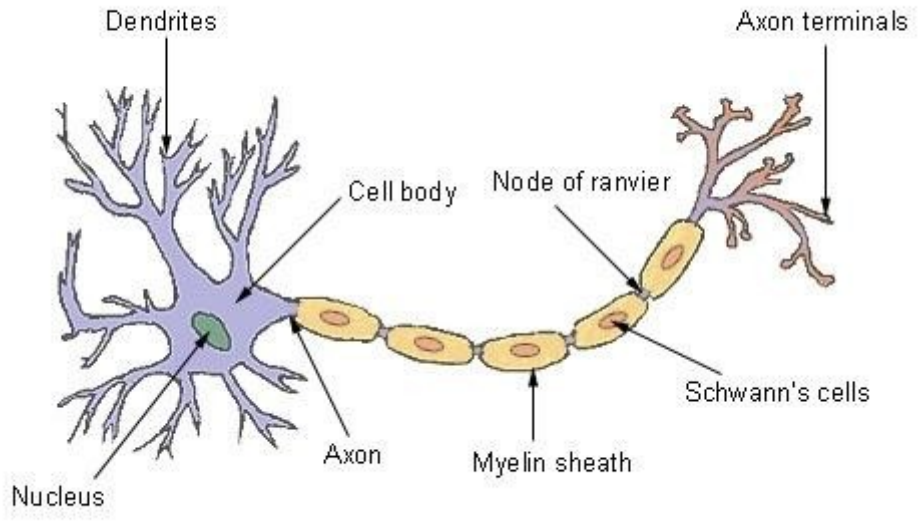

Fig. 4: The diagram of a Neuron

Functionally neurons are classified as sensory neurons, motor neurons or interneurons. Sensory neurons transform physical stimuli (sensations) such as smell, light or sound into action potentials which are then transmitted to the central nervous system. They always have their dendrites in a sensory receptor in the body and the axons end within the central nervous system (either the spinal cord or the brain depending on the part of the body in which the sensory receptor is located). Since they send impulses to the central nervous system, sensory neurons are also called afferent neurons.

Motor neurons transmit nerve impulses away from the brain and spinal cord to muscles or glands and are also called efferent neurons.

Interneurons, also called association neurons provide local connections within the central nervous system. They are mostly found in the central nervous system and are responsible for receiving, relaying integrating and sending nerve impulses within the CNS. All neurons whatever their

structure or function carry nerve impulses in one direction. That is from dendrite to cell body and from cell body to the axon. Dendrites always carry impulses toward the cell body and axons always carry impulses away from the cell body.

3.2 Transmission of Nerve Impulses

The transmission of nerve impulses which is the unique function of nerve cells depends on two properties of nerve cells:

Excitability and Conductivity

Excitability refers to the fact that nerve cells are able to respond to a stimulus, and in fact have a threshold for excitation. The stimulus may be internal or external; electrical, chemical or mechanical. Muscle fibres are also able to demonstrate excitability and this makes them able to contract when stimulated.

Conductivity refers to the property that neurons alone possess which makes them able to transfer their excitability along their length and then on to other neurons or even muscle tissue.

These two properties together allow neurons to deliver appropriate messages to appropriate parts of the body as and when required.

All cells in the body possess a membrane potential which is related to the non-uniform distribution of and differential permeability to Na^+, K^+ and large intra cellular anions (protein ions). Nerve cells and muscle cells have specialized use for this membrane potential. They are able to undergo transient, rapid changes in their membrane potential i.e. they can alter their transmembrane potential reversibly because of the differences in the ionic concentration inside and outside the cell and the selective permeability to Sodium (Na^+) and potassium (K^+). Nerve and muscle cells are therefore said to be excitable tissues because of their ability to produce electrical signals when excited.

In a resting neuron, the concentration of potassium (K^+) inside the cells is up to 30 times greater than it is outside whereas the concentration of sodium is up to 14 times less inside than outside. Even in this state of non-conduction of nerve impulses the neuron continuously maintain a balance of sodium-potassium pump across the membrane i.e. Na^+ are actively transported out and K^+ are actively transported into the cell. The inside of the cell at rest is negatively charged because K^+ are though positively charged and are abundant within the cell; there are a large number of negatively charged (protein) ions within cell which cannot diffuse out through the cell membrane. The K+ is not enough to balance out the

protein anions within the cell and this leads to an overall negative charge within the cell. Outside the cell the larger quantity of Na+ with no protein anion, leads to an overall positive charge in the extracellular fluid. This state of potential difference in polarity across the membrane is known as the resting membrane potential. It is usually about-70mV.

When a nerve cell is stimulated one of two types of physiochemical disturbance is produced: local, non-propagated potentials called electrotonic potentials or a propagated disturbance called action potential or nerve impulses. All excitable tissues exhibit these electrical responses and these are the main language of the nervous system. When an excitable tissue is sufficiently stimulated, the polarity of the membrane is reversed momentarily with the inside becoming more positive compared to the outside. It is this event (shift) that is referred to as the action potential.

3.3 The Action Potential

The stimulation of an excitable tissue represents the delivery of energy to the cell membrane in some way. For example, the energy from sound waves exciting the neurons in the inners ear; heat energy exciting neurons in the skin etc.

Action potentials are brief reversals of membrane potential brought about by rapid changes in membrane permeability occasioned by physiochemical stimulation. Within nerve cells the action potential has an amplitude of approximately +110mv (millivolts) and lasts for about 1 millisecond (MS). Action potentials follow the all-or-none law which means that they are not graded responses but are either full sized or absent depending on the strength of the stimulus. i.e. if the stimulus is strong enough the action potential is fired at its full strength of + 110mv. If the stimulus is not strong enough, there is no action potential at all. The action potential is also able to spread throughout the membrane in non-decemental fashion.

Four terms are normally used to describe the processes that occur during action potentials:
Polarization: This refers to the fact that the membrane has potential (difference) i.e. there is a separation of opposite charges with negative charges inside and positive charges outside. This is the state of the membrane at rest.

Depolarization: The membrane potential is reduced from resting potential; it has decreased or moved toward zero. There is a mix up of opposing charges; only few charges are separated. It is shown as an upward deflection on a recording device.

Hyperpolarization: The potential difference has returned and increased or become even more negative than -70mV. A downward deflection is shown on the measuring device.

Depolarization: The membrane potential returns to its normal resting value.

To initiate an action potential there is a triggering event that causes the membrane to depolarize. Depolarization normally proceeds slowly at first until it reaches a critical level known as threshold potential about 55mv. After this initial 15 mV of depolarization, an explosive increase in depolarization occurs. There is a sharp upward deflection past the zero level to up to +30 to +35mv. This is called the overshoot because the deflection overshoots the zero potential. This is followed again by a rapid decrease towards OmV and a fall rapidly toward the resting level, a process called repolarization. Often the repolarization to resting potential is driven back too far causing a brief period of hyperpolarization (below -70mv). This period lasts about 40ms, before the membrane finally returns to its resting potential (repolarization).

The action potential fails to occur if the stimulus is sub-threshold in magnitude whereas if the stimulus is at threshold or above threshold intensity it occurs with constant amplitude and form regardless of the strength of the stimulus. (The all or none law). Although sub-threshold stimuli do not produce an action potential, they do have an effect on the membrane potential. When there is a triggering event of sub-threshold level, there is localized depolarizing potential charge. This change can rise very sharply but also drops off rapidly as it moves away from the initial source of stimulation. These graded potentials or electrotonic potentials function as signals only for short distances and die out as the distance from the initial source of stimulation increases.

3.3.1 Basis of Excitation and Conduction

The nerve cell membrane as has been discussed is polarized at rest with positive charges lined up along the outside of the membrane and negative changes along the inside. During the action potential this polarity is abolished and for a brief period actually reversed.

The cell membranes of nerves like those of other cells contain different types of ion channels or gates. Some are passive (continually open) and some are voltage-gated (i.e. open or close in response to changes in

membrane potentials) while some are chemical messenger-gated (ligand-gated). These open or close in response to the binding of a specific chemical messenger for example neurotransmitter, hormone, to a membrane receptor. The voltage-gated channels are the ones mostly involved in action potentials.

At rest Na^+ is actively transported out of the cell and K^+ is actively transported into the cell. However K^+ diffuses out of the cell down its concentration gradient and Na^+ diffuses back in through their leak channels (passive). However the permeability of the membrane to K^+ is much greater (because of the leak channels) therefore passive K^+ efflux is much greater than passive Na^+ influx. The resting membrane is 50 to 75 times more permeable to K^+. This in addition to the impermeability of the membranes to most protein anions within the cell maintains the membrane in a polarized state with the outside more positive than the inside (- 70mv). When a membrane starts depolarizing toward threshold as a result of a triggering event, some of the voltage-gated Na^+ channels open. Since the concentration and electrical gradient of Na^+ both favors its movement into the cell, Na^+ starts to move in, carrying its positive charges with it. This depolarizes the membrane further, thereby opening more Na^+ gated channels and allowing more Na^+ to enter. This continues in a positive feedback cycle. There is therefore an explosive increase in Na^+ permeability at threshold potential as the membrane becomes 600 times more permeable to Na^+ than to K^+ Na^+ rushes into the cell rapidly eliminating the internal negativity and making the inside even more positive than the outside. This is represented by the steep upward deflection on a measuring device, past the zero potential level and up to an overshoot level of +30 to +35 mv.

The potential does not however become more positive or rise higher than this level. This is because at this peak level of the action potential the Na^+ channels slam shut and enter a state called inactivate state until the membrane potential has even restored to its negative resting value a period of a few milliseconds. In addition the direction of the electrical gradient for Na^+ reverses and this limits the influx. The cell membrane becomes impermeable again.
At the same time, as the inactivation of the Na^+ channels occurs, K^+ permeability greatly increases i.e. the voltage-gated K^+ channels open and more K^+ move out of the cell the opening of the K^+ channels is slower but more prolonged than the opening of Na^+ channels and can actually be considered a response triggered by the depolarization caused by Na^+ influx. The marked increase in K^+ permeability causes K^+ to rush out of the cell down its concentration and electrical gradients carrying positive charges back to the outside. At the peak of an action potential the very positive inside of the cell also tend to repel the positive K^+ ions so that the electrical gradient for K^+ favours outward movement. The outward

movement of K^+ rapidly restores the internal negatively returning the potential to resting. This completes the repolarization process and is shown by the downward deflection past the zero potential towards the initial resting potential of -70mv on the measuring device. Because the K^+ channels do not close very quickly, more K^+ can actually leave the cell than is necessary. This slightly excessive K^+ efflux makes the interior of the cell more negative than resting potential; and this explains the after hyperpolarization period.

At the end of an action potential, the membrane potential has been restored to its resting condition but the ion distribution had been slightly altered. Sodium has entered the cell during the rising phase while a comparable amount of K^+ has left during the falling phase. It is now left for the Na^+ - K^+ pump to restore these ions to their original locations in the long run.

Depolarization of one part sends an electrical current to neighbouring un-stimulated parts of the membrane, which stimulates adjacent portions of the neuron membrane to also depolarize. This event repeats itself along the membrane of the cell, thereby conveying the nerve impulse along the neuron. This continuous conduction is the way impulses are transmitted down unmyelinated nerve fibres. In myelinated nerves, the myelin sheath forms an insulating layer around the axon therefore depolarization can only occur at the nodes of Ranvier where there are short sections of non-myelination. Impulses are conducted by sequential jumping from one node to another along the nerve.

This form of impulse conduction is usually quicker than continuous conduction. It is known as saltatory conduction.

3.4 Synapses

Impulses are transmitted from one nerve cell to another cell at synapses. A synapse is a junction where the axon of one neuron (the pre-synaptic neuron) meets the dendrite, cell body or even axon of another neuron or in some cases, a muscle or gland cell (the post synaptic neuron or cell).

3.4.1 Functional Anatomy of Synapses

A neuron may terminate at one of three structures; another neuron, a muscle, or a gland specifically the use of the word at this point will be limited to the junction between two neurons. The commonest synapse is formed at the junction between an axon terminal and the dendrites or cell body of a second neuron. Less frequently axon to axon and dendrite to dendrite connections occur. Usually most neuronal cell bodies and their dendrites receive thousands of synaptic input (axon terminals) from many

other neurons

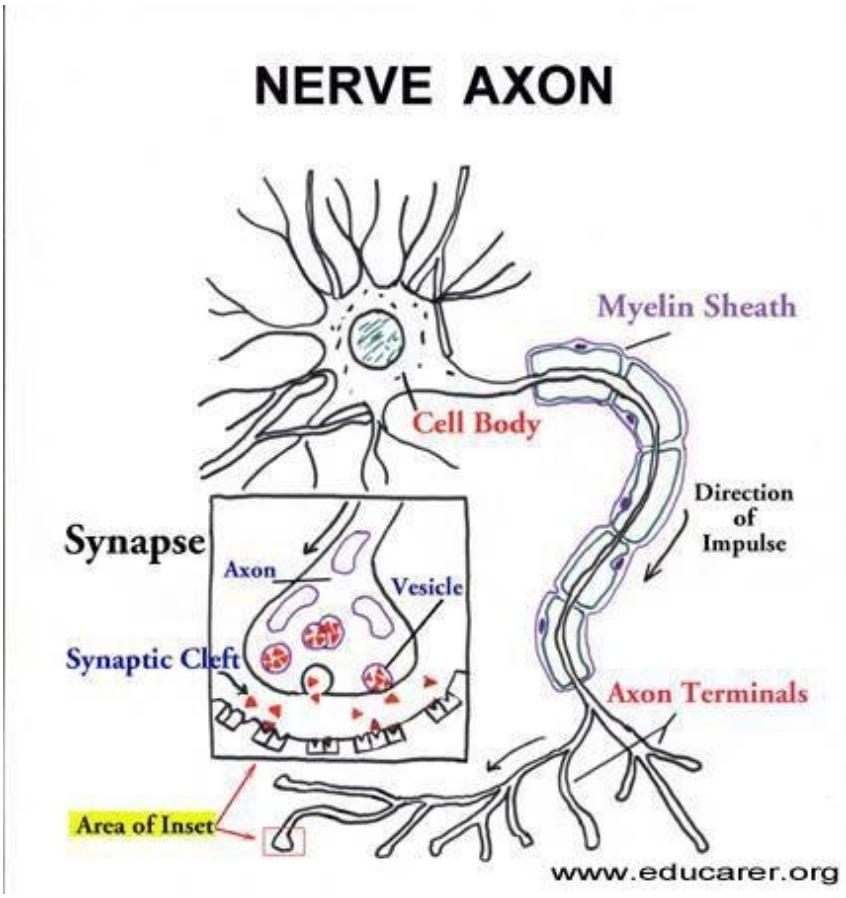

Fig. 5: Diagram of a synapse (inset)

The axon terminal of a pre-synaptic neuron is usually slightly enlarged to form button like structures called the synaptic knobs. The synaptic knobs contain numerous synaptic vesicles which store a specific chemical messenger, called a neurotransmitter. These neurotransmitters have been synthesized by the presynaptic neuron. The membrane of the synaptic knobs (of the presynaptic neuron) does not come into direct physical contact with the membrane of the post-synaptic cell, rather a small gap of about 20 nanometers separate the two. This space is called the synaptic cleft. This space makes it difficult for electrical signals (action potentials) to pass directly between the two cells; the presynaptic and the post synaptic neurons-thereby necessitating the action of a mediator. In most synapses transmission is by chemical means requiring the chemical mediators neurotransmitters. At some synapses however transmission is electrical while in a few synapses it is conjoint i.e. both chemical and electrical being possible. In any case, transmission across a synapse is not a simple jumping of action potentials from the presynaptic to the postsynaptic cell.

Synapses operate in one direction only i.e. the presynaptic neuron brings

in the signal to the synapse and stimulates the postsynaptic neuron which then carries signals away from the synapse.

3.5 Transmission across a Synapse

When an action potential in a presynaptic neuron reaches the synaptic knob, it triggers the opening of the voltage-gated calcium ion (Ca^{++}) channels in the the synaptic knobs. This allows Ca^{++} which is more in the extracellular fluid (outside the cell) to enter inside the cell. The presence of Ca^{++} inside the cell causes the vesicles inside the knob to move towards the cellmembrance at the synaptic cleft. Vesicles fuse with the membrane and release their neurotransmitters by exocytosis into the synaptic cleft. The neurotransmitters diffuse across the space and bind to receptors in the membrane of the post-synaptic cell. The amount of neurotransmitter released is proportionate to Ca++ influx.

The binding of neurotransmitters to receptors in the postsynaptic cell membrane opens ion channels in the post-synaptic cell membrane. This is an example of a chemical messenger-gated channel. With the opening of the channels there is a change in the permeability of the post synaptic membrane, resulting in a change in the membrane potential. If the excitation is strong enough it results in the generation of a nerve impulse.
The neurotransmitter molecules left in the synaptic cleft are usually broken down by enzymes, reabsorbed by pre-synaptic cell where they are resynthesized (using energy from ATP generated by the nearby mitochondria) and packaged once again into vesicles.

3.5.1 Synaptic Excitation and Inhibition

There are two types of synapses depending on the permeability changes induced in the post synaptic neuron by the combination of transmitter substances with receptor sites: excitatory synapses and inhibitory synapses.

At an excitatory synapse, the response to the receptor neurotransmitter combination is an opening of the Na+ and K+ channels in the post synaptic membrane, increasing the permeability to both of these ions. Na+ moves into the cell in large numbers, reducing the potential difference in the cell by making the inside of the cell less negative than at rest. This produces a small depolarization of the post-synaptic neuron. The effect of just one synapse is usually not enough to stimulate the post-synaptic membrane to a firing level (threshold). Before a post-synaptic membrane can fire an action potential, it must be stimulated by several synapses at once. Each synapse produces a small depolarization and each depolarization contributes to bringing the membrane nearer to threshold

and increase the likelihood of firing an action potential. This post synaptic potential change occurring at an excitatory synapse is called an excitatory post-synaptic potential (EPSP). The small rises contributed by depolarizations at each synapse add together, raising the EPSP to a level high enough to trigger a nerve impulse (fire an action potential). It is called spatial summation when stimulation occurring at the same time at several synapses add together to reach threshold level. However if the same synapse supplies impulses to the post-synaptic neuron in quick succession before the previous ones have died out, the stimulations add together in what is called temporal summation.

Certain synapses however have opposite effects. The effect of the neurotransmitter receptor combination instead of opening the Na+ channels rather opens the K^+ or Cl^- channels. The result is that the membrane becomes hyperpolarized and the inside of the post synaptic membrane becomes more negative. What happens is that if it is the K^+ channels that open, more positive charges leave the cell via K^+ efflux, leaving more negative charges behind inside the cell or in the case of increased Cl^- permeability negative charges enter the cell in the form of Cl^- ions because Cl^- concentration is higher outside the cell. The slight hyperpolarization moves the membrane potential even farther away from threshold making it more difficult for excitation to threshold level to occur. The membrane is said to be inhibited under these circumstances, and the small hyperpolarization is called inhibitory post-synaptic potential (IPSP). Both spatial and temporal summation of inhibitory potentials can also occur.

The transmission of an electrical signal across a synapse, for a presynaptic neuron takes time, an interval of at least 0.5ms (0.5 - Ims). This is called synaptic delay, and corresponds to the time it takes for the neurotransmitter to be released and to act on the post-synaptic membrane. Therefore it is faster to transmit electrical signals through a pathway with fewer synapses than a complex pathway with multiple synapses. The more complex (polysynaptic) the pathway, the more synaptic delays and therefore the longer the time required to respond to a particular electrical event.

The generation of an action potential (nerve impulse) in the post-synaptic neuron is therefore the result of a constant interplay of excitatory and inhibitory activity of thousands of presynaptic neurons on the postsynaptic neuron. This produces a flunctuating membrane potential i.e the algebraic sum of the hyperpolarizing and depolarizing activity. The cell body of the neuron performs an integrating function. When the net effect of excitatory and inhibitory activities at synapses produces 10 - 15mv of depolarization, which is sufficient for an action potential to fire, an action potential results i.e an impulse is transmitted.

3.6 Neurotransmitters

Many different chemicals are known or suspected to act as neurotransmitters in the nervous system. Neurotransmitter substances vary from synapse to synapse and the same transmitter is always released at a particular synapse. One particular neurotransmitter will always induce EPSP while another will always induce IPSP. Yet another neurotransmitter may even induce an EPSP in one synapse and an IPSP in another synapse. The response of a given transmitter B receptor combination at a given synapse is always constant. A given synapse is either always excitatory or always inhibitory.

In the human nervous system some neurotransmitters are simple chemical ions such as calcium, others are more complex chemicals such as Dopamine, Serotonin (SHT), gamma-amino-butyric acid (GABA), Acetyloline, etc. Identified neurotransmitters can be divided into broad categories based on their chemical structure. Some are amines e.g. dopamine, Norepinephrine, epinephrine etc, others are amino acids, e.g. glutamate, aspartate, glycine etc, others are purines e.g. adenosine, and many are polypeptides e.g. somatostatin, Endothelins, Endorphins, motilin, Glucagon, Gastrin, angiotensin II etc. Some of these substances in addition to acting locally as neurotransmitters in the synaptic cleft can also function as hormones at other sites distant from where they are produced or act as paracrine regulators. It is also known that many neurons contain more than one transmitter i.e. they contain co transmitters. Often the amines exist with one or more polypeptides.

3.6.1 Neurotransmitter Inactivation, Removal and Recycling

Neurotransmitters are quickly inactivated from the synaptic cleft once it has produced the appropriate response in the post-synaptic neuron so that the post-synaptic neuron can get ready for other presynaptic inputs. As long as neurotransmitters remain bound to their receptors, EPSP or IPSP which they produce continue, thus it is necessary that they are removed and their responses terminated. This removal can be achieved in the following ways:
They may be inactivated by specific enzymes within the membrane of the post-synaptic neuron or they may be actively taken up back into the axon terminal by transport mechanisms in the presynaptic membrane (reuptake). Once the neurotransmitter is inside the synaptic knob, (following reuptake) it can either be (1) Stored and released another time (recycling) or (2) Destroyed by enzymes in the synaptic knob

3.7 Neurotransmitters and Their Receptors

Receptors are protein substances on the surface of the cell or in some instances in the cytoplasm or nucleus which act as binding sites for chemical messengers (hormones, neurotransmitters and other ligands). There are three facts that must be noted about receptor.

1. Every lagans (chemical messenger e.g. neurotransmitter) has many sub types of receptors. For example, nor epinephrine binds to α_1, α_2, $ß_1$ and $ß_2$ receptors. There are also different kinds of α_1 and α_2 receptors. This makes the possible effects of a particular lagans more specific and more selective.

2. Receptors can exist on the presynaptic as well as post-synaptic neurons. The presynaptic receptors usually act to inhibit further secretion of the ligand (by feedback control). For example noradrenaline binding to α_2 presynaptic receptors can inhibit norepinephrine secretion.

3. The subtypes of receptors tend to group in large families as far as structure and function is concerned. Thus some families of receptors in combination with their lagans function by changing the lagan-gated channels thereby altering membrane permeability and ionic fluxes across the postsynaptic membrane. Another mode of synaptic transmission used by the transmitter-receptor complex involves the activation of second messengers within the postsynaptic neuron such as cyclic AMP which can then perform the function of opening the ion channels or other functions as may be necessary.

3.7.1 Acetylcholine as a Neurotransmitter and its Receptors

Acetylcholine is an amine neurotransmitter that exists commonly and in high concentrations in terminal buttons of cholinergic neurons. Neurons which release acetylcholine are known as cholinergic neurons.
Acetylcholine receptors are divided into two main types due to their pharmacologic properties muscarinic and nicotinic receptors depending on the action of acetylcholine on the different parts where they function. Muscarine has stimulatory action on smooth muscles and glands, thus the muscarinic actions of acetylcholine are stimulatory on smooth muscles and glands. The receptors here are called muscarinic receptors. They are blocked by the drug atropine. In autonomic ganglia, large amounts of acetylcholine block transmission of impulses from pre-to post-ganglionic neurons. These are nicotine-like actions. Thus these actions of acetylcholine are nicotinic actions, and the receptors for such actions are called nicotinic receptors.

Acetylcholine nicotinic receptors have 5 sub-units 2 alpha, one beta, one gamma and one delta subunits. Acetylcholine binds on alpha subunits when it does, it opens ionic channels for Na^+ and other cat ions, resulting in the influx of Na^+ and a depolarizing potential Muscarinic receptors also have four types identified and they seem to act through a second messenger system.

Acetylcholine is removed from the synaptic cleft through the catalytic activity of acetylcholinesterase which hydrolyzes acetylcholine to choline and acetate.

3.7.2 Catecholamine and Their Receptors

Norepinephrine is the neurotransmitter found at most sympathetic ganglionic endings. Together with its methylderivative epinephrine they are secreted by the adrenal medulla, however epinephrine is not a mediator at preganglionic sympathetic nerve endings. The neurons secreting norepinephrine are called adrenergic neurons. Sometimes, the termadrenergic is used to refer to both of them. The third catecholamine in the body is dopamine and dopamine secreting neurons are called dopaminergic neurons. The catecholamines are formed by hydroxylation and decarboxylation of the amino acids phenylalanine and tyrosine.

Epinephrine and norepinephrine both act on alpha and ß receptors, with norepinephrine having greater affinity for X adrenergic receptors and epinephrine for ß adrenergireceptors. Both α and ß receptors work through the action of cyclic AMP as second messenger.

Dopamine which is a step in the formation of norepinephrine and epinephrine (catecholamines can be secreted as a neurotransmitter in certain parts of the brain and autonomic ganglia. There are the D_1 and D_2 receptors at sites where dopamine is released. Their action is by activating dopamine sensitive adenylate cyclase (second messenger system).

Catecholamines are recaptured by active reuptake mechanism and inactivated by monoamine oxidase (MAO) and catechol-O-methyltransferase (COMT).

Other classical neurotransmitters of the amine type include serotonin, and histamine.

3.7.3 Amino Acids and Polypeptides as Neurotransmitters

Other transmitters of the amino acid and polypeptide group differ from the classical transmitters in that they are larger molecules containing

sometimes from two to forty amino acids. They also bring about slower and more prolonged responses. Some of these substances released at synapses function as true neurotransmitters but some as neuromodulators. Neuromodulators are chemical messengers that bind to neuronal receptors at non-synaptic sites and by so doing bring about long-term changes that depressesorenhances effective synaptic transmission, often by activating second messenger systems.

For example a neuromodulator may influence the level of an enzyme critical in the synthesis of a neurotransmitter by a presynaptic neuron or alter the sensitivity of a post synaptic neuron to a neurotransmitter.

3.8 Drugs and Synaptic Transmissions

Many drugs are able to interfere with neurotransmitter processes and this has resulted in their use as legitimate drugs for treatment of mental health problems or as illegal or recreational drugs.

The vast majority of drugs that influence the nervous system perform their function by altering synaptic mechanisms. Hence they can be used to block an undesirable effect or to enhance a desirable one. Specifically some of those drugs may act in the following ways:

1. Altering the synthesis, axonal transport, storage or release of a neurotransmitter;
2. Modifying neurotransmitter interaction with the post synaptic receptor,
3. Influencing neurotransmitter reuptake or destruction; or
4. Replacing a deficient neurotransmitter with a substitute transmitter.

For example, the illegal drug cocaine blocks the reuptake of the neurotransmitter dopamine at presynaptic terminals by competitively binding with the dopamine reuptake transporter which picks up released dopamine from the synaptic cleft and shuttles it back to the axon terminal for reuptake. When cocaine occupies the dopamine transporter, dopamine remains longer in the synaptic cleft, and continues to interact with its receptor sites in the post synaptic neuron. This results in prolonged activation of the neural pathways that use dopamine as neurotransmitter, such as those pathways that play a role in emotional responses like feelings of pleasure.

Drugs that alter neurotransmitter functions are called psychoactive drugs. They can be divided into six major pharmacological classes based on their desired behavioural or psychological effect: alcohol, sedative hypnotics, opiate analgesics, stimulant euphoriants, hallucinogens, and psychotropic agents.

Hallucinogens are pscychedelic drugs such as LSD (Lysergic acid diethylamide), mescaline etc. they are serotonin agonists that produce their effects by activating and binding to $5HT_2$ receptors. They are usually taken illegally to alter perception and thinking patterns. They have little known medical use.

Psychotropic drugs like the phenothiazine tranquilizers are effective in the relief of symptoms of schizophrenia. Their antipsychotic activity parallels their ability to blockD_2 dopamine receptors.

3.9 Disease and Synaptic Transmission

Synaptic transmission is also vulnerable to a number of disease processes including defects at presynaptic and post-synaptic sites.

Parkinson's disease for example is attributable to a deficiency of dopamine in a particular region of the brain involved in controlling complex movements called the substantial nigra. The cells have their axons ending in the basal nuclei of the brain. A gradual destruction of the dopamine secreting cells in the substantial nigra and the resultant loss of basal nuclei function are responsible for Parkinson's disease. The basal nuclei is another region of the brain involved in the coordination of slow, sustained movements, inhibition of muscle tone and suppression of useless patterns of movement. As dopamine activity slowly diminishes, symptoms begin with involuntary tremors at rest, such as involuntary rhythmic shaking of hands and head. Symptoms of increasing stiffness and rigidity ensue as disease worsens. Treatment of Parkinson's disease is an example of a deficient neurotransmitter being replaced with a substitute transmitter. Patients with this disease are given Levidopa (L-dopa) a closely related precursor of dopamine. The drug can be taken up by the dopamine deficient synaptic knobs, thereby substituting for the lacking, naturally occurring dopamine. It alleviates the symptoms associated with dopamine deficit.

Strychnine and tetanus toxin act at different synaptic sites to block inhibitory impulses while leaving excitatory inputs untouched. Strychnine competes with the inhibitory transmitter glycine at the post synaptic receptor sites. It takes up receptor sites without affecting the cells potential, making the receptors not available for binding with glycine when it is released. In such nerve pathways that use glycine as neurotransmitter, post-synaptic inhibition is abolished. Unchecked excitatory pathways lead to convulsions and muscle spasticity. Tetanus toxins also prevent the release of another inhibitory transmitter, Gamma aminobutyric acid (GABA) from presynaptic inputs terminating on motor

neurons supplying skeletal muscles. Unchecked excitatory inputs to these neurons result in uncontrolled muscle spasms. The outcomes of the two are similar, but strychnine blocks specific postsynaptic inhibitory receptors whereas tetanus toxin prevents the presynaptic release of a specific inhibitory neurotransmitter. Other drugs and diseases that affect synaptic transmission are too numerous to mention but the examples show that any site along the synaptic pathway can be interfered with pharmacologically or pathologically.

4.0 CONCLUSION

Nerve cells are specialized to receive, process, encode and rapidly transmit information from one part of the body to another. The information is transmitted over intricate nerve pathways by propagating action potentials along the nerve cells length as well as by chemical transmission of the signal from neuron to neuron and later from neuron to muscle or gland through neurotransmitter - receptor interactions at synapses. The specialization of nerve cells depends on their ability to rapidly alter their membrane potential and thus produce electrical signals in response to appropriate triggering event.

5.0 SUMMARY

In this unit, we have learnt about the following:

- Neurons are highly specialized cells which together with neuralgia cells make up the nervous system; and they function mainly to gather and process information from parts of the body to the central nervous system and to bring back appropriate information from the nervous system to relevant parts of the body (usually muscles and glands).

- Structurally neurons are classified as multipolar bipolar and unipolar reflecting the arrangement of its process (axon and dendrites). Functionally, they can be classified as afferent or efferent reflecting the direction of conduction of impulses in relation to the central nervous system. They are also functionally classified into sensory motor, or interneurons.

- The unique function of impulse transmission is made possible in the neurons by their two properties of excitability and conductivity. Nerve cells are excitable tissues because they can alter their trans membrane potential (reversibly) due to selective permeability of their membranes to Na_+ and K_+. This excitation can also be propagated down the entire length of the nerve cell. This is conduction.

- An action potential is an electrical event in a nerve cell characterized by brief reversals of membrane potentials brought about by rapid changes in membrane permeability as a result of physiochemical stimulation.

- Action potentials (excitation and conduction) are made possible because of the existence of ion channels through which electrical charges can flow in and out of the cells. During an AP the permeability of the membrane to Na_+ and K_+ is greatly altered permitting the flow of these cat ions in and out of the cell. The concentration of these cations inside and outside the cell determines the degree of polarization in nerve cells.

- Nerve cells also have to transmit impulses across nerve to nerve junctions called synapses. A neurotransmitter is required to carry the electrical signal across the synapse.

- Some synapses excite the post-synaptic neuron whereas others inhibit it.

- Neurotransmitters are quickly removed from the synaptic cleft; inactivated and recycled in readiness for another use.
- Receptors provide binding sites for neurotransmitters on the post-synaptic membrane. The transmitter receptor complex functions by altering membrane permeability. However some of them function through intracellular second messenger system.

- The effectiveness of synaptic transmission can be modified by drugs and diseases. Any site along the synaptic pathway is vulnerable to interference.

6.0 TUTOR-MARKED ASSIGNMENT

Describe the permeability changes and ionic fluxes that occur during an action potential.

7.0 REFERENCES/FURTHER READINGS

Sherwood, Lauralee (1993). *Human Physiology from Cells to Systems*. Minneapolis: West Publishing Co.

Thibodeau G.A. and Kevin T.P. (2000). *Anatomy and Physiology*. St. Louis Mosby.

Guyton, A.C., Hall J.E. (2000). *Textbook of Medical Physiology*. Philadelphia: Sainders Co.

http://www. jdaross.avc.net/intronerve 3.thitus Nov. 5:2007

http://normaly.sandhills.cc.nc.us/psy150/neuron.html Aug. 30 2005

UNIT 4 THE AUTONOMIC NERVOUS SYSTEM

CONTENTS

1.0 INTRODUCTION

The autonomic nervous system is considered to be the involuntary branch of the peripheral efferent division. Skeletal muscles are innervated by the somatic nervous system while cardiac muscle; smooth muscle most exocrine glands and some endocrine glands are innervated by the autonomic nervous system.

Two neuro transmitters; acetylcholine and nor epinephrine are released at the neuronal terminals and are responsible for bringing about all the changes effected by the autonomic nervous system for example bladder contraction and salivary secretion. The involuntary effects of autonomic innervations contrast with the voluntary control of skeletal muscles through the somatic neurons.

In this unit we shall examine the structures and pathways of the autonomic nervous system, the differences in the autonomic and somatic systems as well as describe the structure and general functions of the sympathetic and parasympathetic divisions of the autonomic system.

2.0 OBJECTIVES

At the end of this unit, you will be able to:

- describe the structures and pathways of the autonomic system
- explain the neural control of involuntary effectors
- describe the sympathetic and parasympathetic divisions of the autonomic nervous system
- explain the functions of the autonomic nervous system
- list the neurotransmitters in the autonomic nervous system and explain their actions
- explain the responses to adrenergic and cholinergic stimulation
- describe the control of autonomic nervous system by higher brain centres
- briefly described the somatic nervous system comparing it with the

autonomic nervous system.

3.0 MAIN CONTENT

3.1 Structures and Pathways of the Autonomic System Compared to Somatic System

The autonomic nervous is the involuntary branch of the peripheral nervous system. It is also known as the visceral efferent motor system because it is concerned with internal organs or viscera. The autonomic nervous system is exclusively a motor system, involved with influencing (innervating) the activity of cardiac muscle, smooth muscle and glands of the body.

The autonomic nervous system consists of two divisions: the sympathetic and the parasympathetic nervous system. Sympathetic nerve fibres originate in the thoracic and lumber regions of the spinal cord. Each autonomic nerve pathway extending from the CNS to an innervated organ consists of a two-neuron chain. The cell body of the first neuron in the series is located in the CNS. Its axon, the pre-ganglionic fibre synapses with the cell body of the second neuron, which the lies within a ganglion outside the CNS. The axon of the second neuron, the post-ganglionic fibre, innervates the effector organ. The involuntary effects of autonomic innervation contrast with the voluntary control of skeletal muscles by way of somatic motor neurons.

3.2 Neural Control of Involuntary Effectors

3.2.1 Autonomic Neurons

Neurons of the peripheral nervous system conduct impulses away from the central nervous. There are two major categories of motor neurons. Somatic motor neurons have their cell bodies within the CNS and send axons to skeletal muscles which are usually under voluntary control.

Unlike somatic motor neurons, which conduct impulses along a single axon from the spinal cord to the neuromuscular junction, autonomic motor control involves two neurons in the grey matter of the brain or spinal cord. The axon of this neuron does not directly reach the effector organ but synapses with a second neuron within an autonomic ganglion. The first neuron is called the preganglionic neuron while the second in this pathway

is called the post-ganglionic neuron and has an axon that extends from the autonomic ganglion and synapses with the cells of an effector organ.

Preganglionic fibres originate in the midbrain, hindbrain and in the upper thoracic to the 4th sacral levels of the spinal cord. Autonomic ganglia are located in the head, neck and abdomen. Chains of autonomic ganglia also parallel both sides of the spinal cord. The origin of the preganglionic fibres and the location of the autonomic ganglia help to differentiate the sympathetic and parasympathetic divisions of the autonomic system.

3.2.2 Visceral Effector Organs

Since autonomic nervous system helps to regulate the activities of glands, smooth muscle and cardiac muscle, autonomic control is an integral aspect of the functioning of most body systems. Autonomic regulation therefore partly explains the functioning of the systems/organs of the body like endocrine regulation, functions of the heart and circulation etc.

Unlike skeletal muscles which enter a state of flaccid paralysis and atrophy when their motor nerves are cut, the involuntary effectors are independent of their innervation. Infact damage to an autonomic nerve makes its target organs more sensitive than normal to stimulating agents. Such compensatory mechanism may explain why the ability of stomach mucosa to secrete acid may be restored after vagotomy. Smooth muscle and cardiac muscle have intrinsic muscle tone. In addition they can contract rhythmically even in the absence of nerve stimulation. This is in response to electrical waves of depolarization initiated by the muscles themselves. Autonomic innervation simply increases or decreases this intrinsic activity. Autonomic nerves also maintain a resting tone in the sense that they maintain a baseline firing rate that can either increase or decrease.

The release of the neurotransmitter, acetylcholine from somatic motor neuron always stimulates the effector organ (skeletal muscle). In contrast some autonomic nerves release transmitters that inhibit the activity of their effectors.

3.3 Divisions of the Autonomic Nervous System

The sympathetic and parasympathetic divisions of the autonomic system have some structural features in common. Both consist of pre-ganglionic neurons, which originate in the CNS, and post ganglionic fibres that originate outside the CNS in ganglia. The specific origin of the prreganglionic fibres and their location are however different in the two divisions.

3.3.1 Sympathetic Division (Thoracolumbar)

It is also called the thoracolumbar division because its preganglionic fibres leave the spinal cord from the first thoracic (TI) to the second lumber (L2) levels. Most sympathetic nerve fibres however separate from the somatic motor fibres and synapse with postganglionic neurons within a double row of sympathetic ganglia or para vertical ganglia located on either side of the spinal cord.

The myelinated preganglionic sympathetic axons exit the spinal cord in the ventral root of spinal nerves, but soon diverge from the spinal nerves within **white rami communicants**. The axons within each ramus enter the sympathetic chain of ganglia where they can travel to ganglia at different levels and synapse with post-ganglionic sympathetic neurons. The axons of the post-ganglionic sympathetic neurons are unmyelinated and form the grey rami communicates as they return spinal nerves to their effector organ. Since sympathetic axons form a component of spinal nerves, they are widely distributed to the skeletal muscles and skin of the body where they innervate blood vessels and other involuntary effectors.

Many preganglionic fibres that exit the spinal cord in the upper thoracic level travel into the neck, where they synapse in cervical sympathetic ganglia. From here post ganglionic fibres innervate the smooth muscles and glands of the head and neck.

Many preganglionic fibres that exit the spinal cord below the diaphragm pass through the sympathetic chain of ganglia without synapsing. Beyond the sympathetic chain of ganglia they form the splanchnic nerves. These preganglionic fibres in the splanchnic nerves synapse in collateral ganglia. These include the coeliac, superior mesenteric and inferior mesenteric ganglia. Post ganglionic fibres that arise from the collateral ganglia innervate organs of the digestive, urinary and reproductive systems.

The adrenal medulla, the inner portion of the adrenal glands is considered a modified sympathetic ganglion, its cells having been derived from the same embryonic tissue as ganglionic sympathetic neurons. It secretes the hormones epinephrine (80%) and norepinephrine when stimulated by the sympathetic system. Like a sympathetic ganglion, the preganglionic sympathetic fibre enervates the adrenal medulla and causes it to secrete epinephrine into the blood. The effect of epinephrine becomes comparable to those of the neurotransmitter norepinephrine which is released at post ganglionic sympathetic nerve endings. No other post ganglionic fibre is needed. For this reason, and because the adrenal medulla is stimulated as part of the mass activation of the sympathetic system, the two are grouped together as a single sympathoadrenal system.

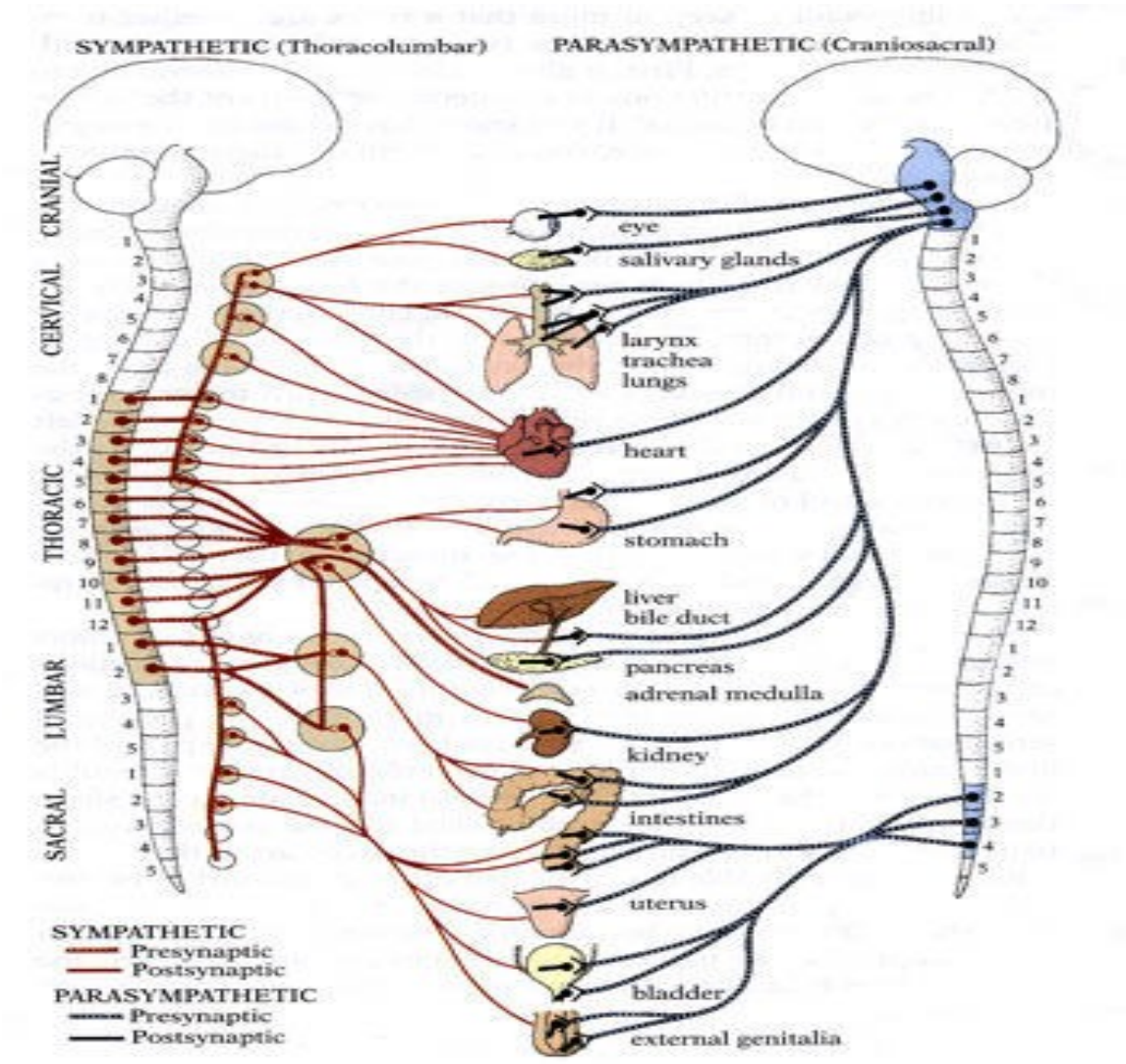

Fig. 7: Diagram of parasympathetic and sympathetic nerves

3.3.2 Parasympathetic (Cranio Sacral) Division

The preganglionic fibres of this division originate in the brain (specifically midbrain, medulla, oblongata and pons) and in the second through 4th

sacral levels of the spinal column. It is therefore also called craniosacral division. These fibres are long in comparison to sympathetic preganglionic fibres because they do not end until they reach the terminal ganglia that lie next to or within the effector organs.

Most parasympathetic fibres do not travel within spinal nerves as do sympathetic fibres. As a result, cutaneous effectors (blood vessels, sweat glands and erector pili muscles) and blood vessels in skeletal muscles receive sympathetic but not parasympathetic innervation.

Four of the twelve pairs of cranial nerves contain preganglionic parasympathetic fibres. These are oculomotor (III) facial (VII) glossopharyngeal (ix) and vagus (x) nerves. Preganglionic fibres from cell bodies located in the midbrain are conveyed by the oculomotor (III) cranial nerve to a synapse in the ciliary ganglion. The post ganglionic axon terminals from there innervate the constrctor muscles in the iris, as well as the ciliary muscles that change the shape of the lens to focus the eyes. Preganglionic fibres originating in the lower pons leave by way of the facial cranial (vii) nerve to either the pterygopalatine or submandibular ganglia where they synapse. Post ganglionic fibres innervate the lacrimal glands, which secrete tears, and the nasal, oral and pharyngeal cavities. Preganglionic fibres of the glosso-pharyngeal nerve from nuclei in upper medulla synapse in the otic ganglion which sends post ganglionic fibres to innervate the parotid salivary glands.

Preganglionic fibres that emerge from cell bodies located in the dorsal vagal nucleus of the medulla are conveyed by the very long vagus (x) nerve. They synapse in terminal ganglia located in many regions of the body. The preganglionic fibres travel through the oesophageal opening in the diaphragm into the abdominal cavity. In each region some of these pre-ganglionic fibres branch from the main trunks of the vagus nerves and synapse with postganglionic neurons located within the effector organs. These very long preganglionic vagus fibres provide parasympathetic innervation to the heart, lungs, oesophagus, stomach pancreas, liver, small intestine and the upper half of the large intestine. Post ganglionic parasympathetic fibres arise from terminal ganglia within these organs and synapse with effector cells (smooth muscles and glands).

From the sacral levels of the spinal cord arise preganglionic parasympathetic innervation to the lower half of the large intestine, rectum and to the urinary and reproductive systems. These fibres like those of the vagus synapse with terminal ganglia located within the effector organs.

3.4 Functions of the Autonomic Nervous System

The sympathetic and parasympathetic divisions of the autonomic system affect the visceral organs in different ways. Mass activation of the

sympathetic system prepares the body for intense physical activity in emergencies or stressful situations, such as a physical threat from the outside environment. This response is typically referred to as the flight or fight response because the sympathetic system readies the body to fight against or flee from the threat. Think about the body resources needed in such circumstances. The heart beats more rapidly and more forcefully, blood pressure, is elevated because of generalized constriction of the blood vessels; the respiratory airways open wide to permit maximal airflow, glycogen (stored sugar) and fat stores are broken down to release extra fuel in the blood; and blood vessels supplying skeletal muscles dilate.

The effects of parasympathetic stimulation are in many ways opposite to the effects of sympathetic stimulation. They dominate in quiet, relaxed situations. Under such non-threatening circumstances the body can be concerned with its own general activities like digestion and emptying of the urinary bladder. The parasympathetic system promotes these kinds of bodily functions while slowing down those activities enhanced by the sympathetic system.

The parasympathetic system however is not normally activated as a whole. Visceral organs respond differently to sympathetic and parasympathetic nerve activity because the postganglionic fibres of these two divisions release different neurotransmitters.

3.5 Neurotransmitters of the Autonomic Nervous System

Sympathetic and parasympathetic preganglionic fibres release the same neurotransmitter, acetylcholine (ACH) but the postganglionic endings of these two systems release different neurotransmitters. Parasympathetic postganglionic fibres release acetylcholine. Accordingly, they, along with all autonomic preganglionic fibres are called cholinergic fibres. In contrast, most sympathetic post ganglionic fibres are called adrenergic fibres because they release norepinephrine (noradrenaline). There are very few exceptions where some sympathetic fibres release ACH. Examples are in the sympathetic supply to blood vessels in skeletal muscles as well as to sweat glands.

3.5.1 Responses to Adrenergic Stimulation

It has been found that both excitatory and inhibitory effects can be produced in different tissues by the same chemical. For example

adrenergic stimulation from sympathetic nerves causes the heart, muscles of the iris and the smooth muscles of many blood vessels to contract. However the same sympathetic stimulation dilates the smooth muscles of the bronchioles and some blood vessels. The possible explanation lies in the biochemistry of the tissue cells, especially differences in the membrane receptor proteins. For example two major classes of these receptor proteins have been designated alpha and beta adrenergic receptors. There are also two subtypes of each class for example alpha 1 and alpha - 2 and beta 1 and beta 2. From this, compounds which selectively bind to one or the other of adrenergic receptor have been developed. As a result of their binding capacity to adrenergic receptors, drugs have been developed which either promote or inhibit adrenergic effect. It has also been possible to determine which sub types are present in each organ.

A drug that binds to receptors for a neurotransmitter and promotes the process stimulated by that neurotransmitter is called an agonist of that neurotransmitter. A drug that blocks the action of a neurotransmitter is said to be an antagonist. The use of drugs that selectively stimulate or block a1, a2, ß1 and ß2 receptors has proved extremely useful in medical application. For example, people with hypertension have been treated with a beta-blocking drug known as propranodol. This drug blocks B1 receptors to produce the desired effect of lowering the cardiac rate and blood pressure etc.

3.5.2 Responses to Cholinergic Stimulation

Somatic motor neurons, all preganglionic autonomic neurons and most postganglionic parasympathetic neurons are cholinergic releasing ACH as a neurotransmitter.

The cholinergic effects of somatic motor neurons are always excitatory. The cholinergic effects of postganglionic parasympathetic fibres are also usually excitatory but there are some notable exceptions. For example the parasympathetic (cholinergic) effect on the heart causes slowing of the heart rate instead of excitation.

Just as adrenergic receptors are divided into alpha and beta subtypes, cholinergic receptors are divided into muscarinic and nicotinic receptor subtypes. The drug muscarine stimulates the cholinergic receptors in the heart, digestive system, however does not stimulate the muscarinic subtypes in autonomic ganglia or at the neuromuscular junction of skeletal muscles. It is rather the drug nicotine that stimulates these cholinergic receptors, therefore the receptors in these places must be nicotinic receptors. The drug used for skeletal muscle relaxation blocks nicotinic receptors but has little effect or muscarinic receptors.

3.6 Dual Innervation of Visceral Organs

Most visceral organs are innervated by both sympathetic and parasympathetic nerve fibres. On a general note the two systems exert opposite effects in a particular organ. One system dominates at one time while the other dominates other times depending on circumstances. Usually both systems are partially active at each point in time until the particular circumstances that will cause the activity of one to dominate the other ensue.

These kinds of effect are called Antagonistic effects in conditions of dual innervation. The best example of antagonism in the two systems is their innervation of the pacemaker region of the heart. Here adrenergic stimulation from sympathetic fibres increases the heart rate while cholinergic stimulation from parasympathetic fibres decreases the heart rate.

In a few cases the effects of sympathetic and parasympathetic nerves are complementary or cooperative. Complementary effects occur when stimulation of both divisions produce similar effects. An example is the sympathetic and parasympathetic stimulation of the salivary glands. The effects are cooperative when sympathetic and parasympathetic stimulation produce two different effects that work together to promote a single action. An example is the parasympathetic effect on the penis causing erection and the sympathetic effect producing ejaculation, they cooperate to promote reproduction.

A few organs in the body however do not have dual innervation. These include the adrenal medulla, erector pili muscles, sweat glands and most blood vessels which receive only sympathetic innervation.

3.7 Control of Autonomic Nervous System by Higher Brain Centres

Visceral functions are mostly regulates by autonomic reflexes, sensory input is transmitted to the brain centres that integrate this information and respond by modifying the activity of preganglionic autonomic neurons. The neural centres that directly control the activity of autonomic nerves are influenced by higher brain centres and by sensory input.

The medulla oblongata in the brain stem is the area that most directly controls the activity of the autonomic system. Almost all autonomic responses can be elicited by experimental stimulation of the medulla. The organ contains centres for the control of cardiovascular, pulmonary, urinary, reproductive and digestive systems.

The medulla oblongata itself is responsive to regulation by higher brain areas. One of these is the hypothalamus which is the brain region that contains centres for the control of body temperature, hunger, thirst, regulation of the pituitary gland and together with the limbic system and cerebral cortex also controls various emotional states.

The limbic system which includes the cingulate gyrus of the cerebral cortex, the hypothalamus, hippocampus and amygdaloidal nucleus is involved in basic emotions like anger, fear, sex and hunger. The involvement of the limbic system with the control of autonomic function is responsible for the visceral responses characteristic of these emotional states. Blushing, fainting, racing heart, cold sweats are examples of the many visceral reactions that accompany emotions as a result of autonomic activation.

3.8 Somatic Nervous System

The somatic nervous system is that part of the motor (efferent) division that supply skeletal muscles. The cell bodies of somatic motor neurons are located within the ventral horn of the spinal cord. Unlike the two neuron chain of the autonomic system, the axon of a somatic motor neuron is continuous from its origin in the spinal cord to its termination on skeletal muscles. Motor neuron axon terminals release acetylcholine which brings about excitation and contraction of the innervated muscles. The effect of motor neuron on skeletal muscles is only stimulation and never inhibition or both. Inhibition of skeletal muscle activity can only be accomplished within the CNS.

Somatic motor neurons are influenced by many converging presynaptic inputs both excitatory and inhibitory but the level of activity in a motor neuron and its subsequent output to the skeletal muscle fibres depend on the balance of EPSPs and IPSPs. The motor neuron is considered to be the final common pathway by which any other parts of the nervous system can influence skeletal muscle activity. The somatic nervous system is considered to be under voluntary control but much of skeletal muscle activity involving posture, balance and stereotypical movements are subconsciously controlled.

4.0 CONCLUSION

The CNS control effector organs (muscles and glands) by transmitting signals from the CNS to these organs through the efferent division of the

peripheral nervous system. The two parts of the efferent system are the autonomic and somatic nervous system. Much of the efferent system output is directed toward maintaining homeostasis in the body.

5.0 SUMMARY

1. The autonomic nervous system is the involuntary branch of the efferent motor system concerned with innervating and controlling the activities of cardiac muscle, smooth muscle and glands.

2. The ANS is made of a two-neuron chain with preganglionic fibres originating in the brain or spinal cord and postganglionic fibres originating in ganglia outside the CNS.

3. The ANS is divided into two systems: the sympathetic and parasympathetic systems. Preganglionic neurons in the sympathetic division originate in the spinal cord, synapse with the postganglionic neurons located in a double chain of paravertebral sympathetic ganglia outside the spinal cord. Others synapse at the collateral ganglia. Some pregnaglionic fibres innervate the adrenal medulla which in turn secretes hormones similar to the chemical transmitters from the sympathetic postganglionic nerve endings.

4. Preganglionic parasympathetic fibres originate in the brain and sacral levels of the spinal cord. They are long nerves synapsing with post ganglionic neurons within the effector organs or very close to them.

5. The functions of the autonomic nervous system is evidenced in the functions of the two major divisions. The sympathetic division exerts their effect through adrenergic stimulation of effector organs. This chemical transmission activates the body to flight or fight reaction necessary in emergences.

6. The parasympathetic division mostly exert antagonistic effects to its counterpart causing more relaxation and quiescence in the body and activating more routine bodily functions like digestion.

7. The body's response to the two neurotransmitters of the ANS noradrenaline and acetylcholine depends a lot on which receptor protein is present in each effect organ.
8. Higher brain centres like the medulla oblongata and the limbic system control the autonomic nervous system.

9. The somatic nervous system is the part of the efferent peripheral nervous system that innervates skeletal muscles.

6.0 TUTOR-MARKED ASSIGNMENT

Define the terms adrenergic and cholinergic and use these terms to describe the autonomic nerve fibres.

7.0 REFERENCES/FURTHER READINGS

Carola *et al* (1990). *Anatomy and Physiology*. New York: McGraw B Hill.

Sherwood L. (1993). *Human Physiology*. West Publishing Company Minneapolis.

UNIT 5 INTRODUCTION TO RECEPTOR PHYSIOLOGY AND GENERAL SENSES

CONTENTS

1.0 INTRODUCTION

Information about the internal and external environment reaches the central nervous system through a variety of sensory receptors. These receptors are transducers that convert various forms of energy in the environment into action potentials in neurons. Each type of sensory receptor responds to a particular modality of environmental stimulus by causing the production of action potentials in a sensory neuron. There are so many more receptor types than the normal ones associated with the five basic senses.

This unit will focus on the characteristics of these receptors and the way they generate impulses in afferent neurons. It will also briefly describe the various general sensations.

2.0 OBJECTIVES

At the end of this unit you will be able to:

- explain what sensory reception means
- describe the four basic features of sensory receptors
- classifying sensory receptors according to their location, type of sensation, type of stimulus or structure
- explain the electrical and ionic basis of events in the sensory receptor with emphasis on the generator potential
- explain the law of specific nerve energies

- describe the sensory modalities classified as general senses
- identify the neural pathways for the general senses.

3.0 MAIN CONTENT

3.1 The Nature of Sensory Reception

The term receptor as it is used in physiology not only to refer to sensory receptors but also to proteins that bind neurotransmitters, hormones and other substances with great affinity and specificity as a first step in initiating specific physiologic responses.

Man is able to cope with changes in his environment because part of our nervous system is specialized to make sure we have a suitable reaction to stimulus. Structures capable of perceiving and changing such stimuli are called receptors. A receptor is associated with the peripheral end of dendrites of afferent neurons. Sensory receptors are stimulated by specific stimuli. The truth about sensations is that they do not exist if they cannot be perceived and interpreted for what they are. All sensory receptors are therefore structures that are capable of converting environmental information (stimuli) into nerve impulses. Thus all receptors are transducers that can convert one form of energy to another. Since all nerve impulses are the same, it is differences in receptors that make it possible for different kinds of stimulus (such as light, sound or heat) to be converted into the same kind of impulse.

The forms of energy converted by the receptors include for example mechanical (touch-pressure) thermal (degrees of heat) electromagnetic (light) and chemical energy (colour, taste, oxygen content of blood). The receptors in each of the sense organs are adapted to respond to one particular form of energy at a much lower threshold than other receptors respond to this form of energy. The particular form of energy to which a receptor is most sensitive is called its adequate stimulus. For example, the adequate stimulus for the rods and cones of the eye is light, not sound. Even though receptors can respond to other forms of energy than their adequate stimulus, the threshold for these non-specific responses is much higher. When a stimulus is strong enough, the receptor cells generate receptor potential or generation potent or which resembles an EPSP. As the stimulus increases, the magnitude of the receptor potential increases. When the magnitude of the receptor potential is up to 10mv an action potential is generated in the sensory nerve. The intensity of stimuli varies with the frequency of the stimulus and the number of receptors stimulated at a time.

3.2 Basic Characteristics of Sensory Receptors

There are several types of sensory receptors and many ways to classify them. There are, however, certain features basic to all sensory receptors:

1. All sensory receptors contain sensitive receptor cells that respond to certain minimum (threshold) levels of intensity. This means that the stimulus must be strong enough to generate a receptor potential and then an action potential.

2. Their structure is designed to receive a specific stimulus. For example, the eye contains light absorbing pigments, an elastic adjustable lens, and other structures suitable for capturing light waves in the visible spectrum.

3. Their primary receptor cells synapse with afferent nerve fibres that travel to the central nervous system along peripheral or cranial nerves. Receptors in the skin for example are connected to neurons with very long fibres that extend to the spinal cord and form a synapse. In contrast, the primary receptor cells in the eye have short axons that synapse with other cells in the retina before projecting to the brain via the optic nerve.

4. After receptor cells synapse with afferent neurons, the nerve impulses are conveyed along neural pathways through the brain stem and diencephalons to the cerebral cortex. In the diencephalon and cerebral cortex the original stimulus and nerve impulse are translated into a recognizable sensation such as sight or sound.

3.3 Classification of Sensory Receptors

Several attempts have been made at classifying sense organs and sensory receptors. Sensory receptors may be classified according to their location, type of sensation, type of stimulus or structure.

A. Location of Receptor

Under this method of classification four kinds of sensory receptors are recognized on the basis of:

1. Exteroceptors

These are concerned with responding to external environmental stimuli that are near at hand i.e. those that affect the skin directly. These stimuli result in sensations of touch, pressure, pain and temperature.

2. Teleceptors (Distance Receivers)

These are exteroceptors located in the eyes, ears and nose. They detect environmental changes or (stimuli) that occur some distance away from the body. These stimuli are ultimately perceived as sight sound and smell.

3. Interoceptors - (Received from Inside)

These are also called visceroceptors. They respond to stimuli from within the body, such as blood pressure, blood carbon dioxide, oxygen and hydrogen ion levels, and the stretching action of smooth muscles in organs and blood vessels. Interoceptors are located within organs that have motor innervation from the autonomic nervous system. They help to maintain homeostasis.

4. Propioceptors (Received from Ones' Own Self)

They respond to stimuli in such deep body structures as joints, tendons, muscles, and the vestibular apparatus of the ear. They are involved with sensing where the parts of the body are in relation to other parts, and the position of the body in space.

B. Type of Sensation

Another way to classify sensory receptors is according to the type of sensations they can detect. The type of sensations here are those associated with the general senses.

Thermal sensations which include cold and warmth. Pain sensations are feelings initiated by harmful stimuli. Light touch and touch-pressure sensations are also produced by mechanical stimuli that come in contact with the body. Light touch involves a finer discrimination than touch pressure. Position sense is elicited by the movement of joints and muscles. It includes both the sense of position when the body is not moving and the sense of body movement called kinesthesia.

C. Type of Stimulus

Sensory receptors can be grouped according to the type of stimulus energy they transduce. Categories include

1. Chemoreceptors

Which sense chemical stimuli in the environment or in the blood. Examples are taste buds, olfactory epithelium and the aortic and carotid bodies which respond to changes in levels of Co_2, O_2 and H_2 in the blood;

2. Thermoreceptors

Respond to temperature changes;

3. Photoreceptor

]
The rods and cones in the retina which respond to visual stimuli of visible light rays.

4. Mechanoreceptors

These are stimulated by mechanical deformation of the receptor cell membrane. These include touch and pressure receptors, and the hair cells within the inner ear. They are the most widespread of all sensory receptors.

5. Nociceptors

Are those that respond to pain stimulus. They normally have a higher threshold for activation than the other cutaneous receptors, so they need a more intense stimulus for their activation.

6. Baroreceptors

Are mechanoreceptors that respond to changes in blood pressure.

D. Sensory Endings of Receptors

This method distinguishes receptors into two according to the type of sensory ending. These include:

1. Naked nerve endings or free nerve endings. Free nerve ending lack schwann cells, myelin or other cellular coverings. Free nerve endings are the naked telodendria in the surface epithelium of the skin, connective tissues, blood vessels and other tissues. They are the sensors for such perceived sensations as pain, light touch and temperature. They are the most widely distributed receptors in the body.

2. Receptors that are covered with various types of capsules, known as encapsulated endings. They are located in the skin, deep fibrous tissues, muscles, tendons, joints and body organs. Pacinian corpuscles, which are involved with vibratory sense and touch pressure (deep pressure) on the skin, and tactile (meissner's) corpuscles that detect light pressure as well as Krause's end bulbs also for touch pressure and position sense are all encapsulated

nerve endings.

E. Sensory Adaptation

When a stimulus of constant strength is applied to some receptor, the frequency of action potentials in its sensory nerve declines. That is, some receptors respond with a burst of activity when a stimulus is first applied, but then quickly decrease their firing rate, when the stimulus is maintained. This phenomenon is known as adaptation.

These are two kinds of receptors based on their speed of adaptation: tonic and phasic receptors. The degree of adaptation varies with the type of sense organ.

Tonic Receptors are those that do not adapt or adapt very slowly. These receptors are important in situations where maintained information about a stimulus is valuable. Examples are pain and muscle stretch receptors. Muscle stretch receptors monitor muscle length and joint propioceptors monitor degree of joint flexion. The CNS must be continually made aware of muscle length and joint position to maintain posture and balance.

Phasic Receptors are rapidly adapting receptors. They even exhibit an off-response. They are useful in situations where it is important to signal a change in stimulus intensity, not just relaying the status quo. Examples include tactile, odour and temperature. Tactile receptors signal change in pressure on the skin surface but they adapt rapidly. Because of this, one is not continually conscious of wearing one=s clothing, watch, rings etc. You only become aware of them again when you put them off.

3.4 Electrical and Ionic Events in Receptors

Stimuli exist in many energy forms or modalities such as heat, light, pressure, sound, chemical changes etc. The only way that afferent neurons can transmit information to the CNS is via action potential propagation, therefore, receptors must convert these other forms of energy into electrical energy. The problem of how receptors convert energy into action potentials in the sensory nerves has been the subject of intensive study. In the complex sense organs, such as those concerned with the special senses, there are separate receptor cells and synaptic functions between receptors and afferent nerves. In most cutaneous sense organs, however, the receptors are specialized histologically modified ends of sensory nerve fibres. Whatever the sensory modality or the receptor type, a stimulus is first converted to a generator potential and then into an action potential with the purpose of stimulating an effector. The role of the brain is to interprete, integrate and coordinate the final impulse to the effector,

with the exception, of course, of the reflex arc.

3.4.1 Generator Potential

The electrical behaviour of sensory nerve endings is similar to that of the dendrites of other neurons. In response to an environmental stimulus the sensory endings produce local graded changes in the membrane potential. In most casesthese potential changes are depolarizations analogous to excitatory postsynaptic potentials (EPSPS). In the sensory endings, the potential stimulation are called receptor or generator potentials; because they serve to generate action potentials in response to sensory stimulation. For example when a light touch is applied to a pacinian corpuscle a small depolarization is produced. Increasing the pressure on the pacinian corpuscle increases the magnitude of the generator potential until it reaches the threshold required to produce an action potential.

As the pressure is increased the generator potential becomes even larger and the nerve fires repetitively. The pacinian corpuscle, therefore, converts mechanical energy into an electrical response, the magnitude of which is proportionate to the intensity of the stimulus.

3.4.2 Ionic Basis of Excitation

In some receptors, mechanical distortion opens channels in the receptor membrane. The resultant influx of Na^+ produces the generator potential and presumably the number of channels opened is proportionate to the intensity of the stimulus. In other receptors like the rods and cones, different mechanisms are responsible and in some instances, the mechanisms are still unknown.

3.5 Coding of Sensory Information

There are variations in the speed of conduction and characteristics of sensory nerve fibres, but action potentials are similar in all nerves. The action potentials in the nerve from a touch receptor for example are essentially identical to those in the nerve from a warmth receptor. This raises the question of why stimulation of a touch receptor causes a sensation of touch and not of warmth.

3.5.1 The Law of Specific Nerve Energies

The sensation evoked by impulses generated in a receptor depends on the specific part of the brain they ultimately activate. The specific sensory pathways are discrete from sense organ to cortex. Therefore, when the nerve pathways from a particular sense organ are stimulated, the sensation

evoked is that for which the receptor is specificialized no matter how or where along the pathway the activity is initiated. This is the doctrine of specific nerve energies put forward by Muller. For example, if the sensory nerve from a pacinian corpuscle in the hand is stimulated by pressure at the elbow, or by irritation from a tumour in the brachial plexus, the sensation evoked is touch. In the same way if it were possible to attach electrodes into appropriate fibres not of the dorsal columns in the spinal cord, the thalamus and the post central gyrus, of the cerebral cortex, the sensation produced by that stimulation would still be touch. The principle of specific nerve energies is one of the cornerstones of sensory physiology.

3.6 General Senses

There are sensory receptors in the skin and elsewhere in the body which the brain interpretes as light touch, touch-pressure, (deep pressure) vibration, heat, cold and pain. They may be referred to as general sensations as well as several others not mentioned.

Light Touch

This is perceived when the skin is touched but not deformed. Receptors for light touch are numerous in the dermis, the tips of the fingers and toes, the tip of the tongue and lips.

Receptors for light touch include nerve endings and tactile (Merkel's) corpuscles in the epidermis, and tactile (Meissners) corpuscles just below in the uppermost (papillary) layers of the dermis. There are many receptors around hair follicles. When hairs are bent, they act as levers and the slight movement stimulates the free nerve endings. For this reason a tiny insect that crawls along a hairy part will be felt through it never touched the skin. Merkel=s corpuscles have free nerve endings. They are found in the deep epidermal layers of the palms and soles. Meissners corpuscles are encapsulated nerve endings found in abundance in palms, soles, lips eyelids, nipples and external genitalia.

Touch Pressure (Deep Pressure)

Touch pressure results from a deformation of the skin, no matter how slight. Sensations of touch pressure last longer than light pressure and are felt over a larger area. Receptors for touch-pressure are pacinian corpuscles which are distributed throughout the dermis and subcutaneous layer especially in fingers, external genitalia, and breasts. They are mechanoreceptors that measure changes in pressure. They are also found in muscles, joint capsules, the wall of the urinary bladder and any other area subjected to pressure. Also abundant in mesenteries.

Heat and Cold (Temperature)

There are two types of temperature receptors cold receptors respond to temperatures below skin temperature and heat receptors respond to temperature above skin temperature. There are discrete cold sensitive and warmth sensitive spots over the surface of the entire body. A spot is associated with several nerve endings. The lips have cold and warmth spots, but the tongue is only slightly sensitive to warmth. Nerve endings that supply the teeth are sensitive to cold, but much less sensitive to heat. The face is less sensitive to cold than other parts of the body usually covered by clothing.

Pain

The subjective sensation called pain is a warning signal that alerts the body of a harmful or unpleasant stimulus. Pain sensation may be initiated by receptors sensitive to mechanical, thermal, electrical and chemical stimuli. Pain receptors are specialized free nerve endings present in most parts of the body (with the exception of the intestines and brain tissue).

Types of pain include:

1. Fast conducted, sharp prickling pain
2. Slow-conducted, burning pain and
3. Deep, aching pain in joints, tendons and viscera.

Other distinctions are sometimes made: superficial somatic pain (from stimulation of skin receptors); deep somatic pain (arising from stimulation of receptors in joints, tendons and muscles) and visceral pain (originating from stimulation of receptors in body organs). Some tissues are more sensitive to pain than others. For example a needle inserted into the skin produces great pain but the same needle probed into a muscle produces little pain. To some extent the perception of pain is a matter of attention as in the case of soldiers wounded in the battle, who may feel little or no pain on the battle field but complain of severe pain when fighting has ceased.

Referred Pain

Pain that originates in a body organ or structure is usually perceived to be on the surface often at a site away from the visceral source. The pain of a coronary heart disease (angina pectoris) felt in the left shoulder, arm and arm pit is a referred pain or an irritation of the gall bladder felt under the

shoulder blades. A possible explanation may be that some neurons may use a common dorsal root to innervate both the visceral and somatic locations involved in referred pain. It is thought that both visceral and somatic sensory fibres discharge into a common pool in the CNS. The brain then interprets the source of visceral pain as a region of the skin, since pain impulses come more frequently from the skin than the viscera. Another explanation is that the area to which the pain is referred is a part that has the same embryonic origin as the real source of the pain. The two areas are therefore supplied by branches of the same peripheral nerves.

Phantom Pain

Is another unusual sensation of pain that is felt in an amputated limb (phantom limb). Sensations of pain, pins and needles, and temperature change are often felt by amputees in their amputated limbs for several months. The pain is felt more in the joints and the distal portions of the amputated (phantom) limb. Phantom pain usually persists longer in those parts that have the largest representation in the cerebral cortex such as the thumb, hand and foot.

The neural mechanism for phantom pain is not known very well. It appears that pools of neurons associated with sensations of the missing limb are somehow activated and results in the perception. Impulses in the pools of neurons may be triggered by the irritation of peripheral nerves in the (proximal) stump.

Proprioception

Receptors in muscles, tendons and joints transmit impulses about our position sense up the dorsal columns of the spinal cord. These impulses help us to be aware of our body and its parts without actually seeing them. This sense is called proprioception or sometimes kinesthetic sense. The receptors are specialized sensory endings in or near joints.

3.7 Other General Senses

Itch and Tickle are produced by relatively mild stimulation especially if the stimulation is produced by something that moves across the skin. Itch is probably produced by repetitive low-key stimulation of slow conducting nerve fibres in the skin. Tickle is caused by a mild stimulation of the same type of fibres especially when the stimulus moves across the skin. Receptors for both sensations are found almost exclusively in the superficial layers of the skin. The sensation may result from the activation of several sensory endings and also conveyed via a combination of pathways. Itch usually occurs where naked endings of unmyelinated fibres are abundant. Itch occurs on the skin, in the eyes, and some mucous

membranes like nose and rectum but not in deep tissues or viscera. Itch is produced both by repetitive technical stimuli as well as chemical stimuli such as histamine released by the body during allergy or inflammation.

Vibration

This refers to the continuous periodic change in displacement with respect to a fixed reference. The change in time is termed the frequency. Most tactile receptors are involved in the detection of vibration; but different receptors detect different frequencies. E.g. lamellated corpuscles can detect vibrations (frequencies) as high as 700 cycles per second (CPS), while Meissners corpuscles can respond to low frequency vibrations up to 100 CPS.

Stereognosis

This is the ability to identify objects by handling them without looking at them (without seeing) them. Normal persons can readily identify objects like keys, and coins. The ability depends on intact touch and pressure sensation as well as on the sensory areas in the parietal lobe of the cerebral cortex. Impaired stereognosis is an early sign of damage to the cerebral cortex. It can occur in the absence of any defect in touch or pressure sensation when there is a lesion of the parietal lobe behind the post central gyrus.

Two Point Discrimination

The minimal distance by which 2 touch stimuli must be separated to be perceived as two separate stimuli. It depends upon the touch component plus the cortical component of identifying two stimuli.
Its magnitude varies from place to place on the body but is smallest where touch receptors are most abundant. Points on the back may be separated by up to 65mm before they can be distinguished as separated points, but on the fingers by as little as 3mm. The two points threshold is a measure of the receptive field of each neuron. It is also an indication of tactile acuity or sharpness of touch perception.

Synthetic Sense: Cutaneous senses which have separate receptors are touch, warmth, cold, pain and possibly itching. Combinations of these sensations, patterns of stimulation and cortical components are synthesized into sensations. Therefore vibration, 2 point discrimination and stereognosis all belong to synthetic sense.

3.8 Neural Pathways for General Senses

The neural pathways involved in relaying data from specific general

sensory receptors to the cerebral cortex include the dorsal column, medial lemniscus tract, the spino thalamic tracts, and the trigemino thalamic tracts.

Sensory fibres from propioceptors and pressure receptors are carried by large myelinated nerve fibres that ascend in the dorsal columns of the spinal cord on the same side to the medulla oblongata; hence some of the fibres are very long. At the medulla, they synapse with second order sensory neurons which later cross over to the contralateral side as it ascends through a fibre tract called medial lemniscus to the thalamus. At the thalamus, third-order sensory neurons receive the input and in turn project them to the post central gyrus (the sensory cortex).

Sensations of hot, cold and pain are carried by thin unmyelinated sensory neurons into the spinal cord where they synapse with second order association neurons. These cross over to the opposite side and ascend to the brain in the lateral spinothalamic tract. Fibres that mediate touch and pressure ascend in the anterior spinothalamic tract. Fibres from these two tracts synapse with third-order neurons in the thalamus which then project to the postcentral gyrus.

Somaesthetic information is always carried in third-order neuron to the post centralgyrus. Also, because of crossing over, somaesthetic information from each side of the body is projected to the post central gyrus of the opposite side. All somaesthetic information from the same area of the body tend to project to the same area of the postcentral gyrus.

4.0 CONCLUSION

Each type of sensory receptor responds to a particular modality of environmental stimulus by causing action potentials in sensory neurons. These impulses are conducted to parts of the brain that provide proper interpretation of sensory perceptions when that particular pathway is activated. Receptor physiology is very important for making meaning out of our world and has a lot to contribute in the maintenance of body homeostasis.

5.0 SUMMARY

1. Receptors may be dendrite nerve endings, specialized neurons or specialized epithelial cells associated with sensory nerve endings.

2. Sensory receptors may be categorized on the basis of their

structure, the type of stimulus energy, the nature of their responses etc.

3. Receptors may be chemoreceptor, nociceptors and propioceptors.

4. According to the law of specific nerve energies each sensory receptor responds with lowest threshold to only modality of sensation; that stimulus is called its adequate stimulus.

5. Generator potentials are graded depolarizations in the membrane potential of the dendritic endings of receptors whose magnitude is directly proportional to the strength of the stimulus applied to the receptor. When the membrane potential change reaches threshold level, an action potential is fired. Subsequently, increases in the magnitude of the depolarization results in increased frequency of action potential in the sensory neuron.

6. The basic general senses include, touch, pressure, cold and warmth and pain. However some of these can be synthesized to form other additional sensations.

7. Somaesthetic information from cutaneous receptors and propioceptors are projected by third order neurons from the thalamus to the postcentral gyrus.
   Propioceptors and pressure receptors ascend the spinal cord on the same side, synapse in the medulla and cross over to the other side and ascend to the thalamus in medial lemniscus tracts from where they project to the sensory cortex. Sensory neurons from other cutaneous receptors synapse and cross over to the opposite side in the spinal cord, ascend in the lateral and anterior (ventral) spinothalamic tracts to the thalamus from where they project again to the sensory cortex.

6.0 TUTOR-MARKED ASSIGNMENT

Describe the receptors for light touch. Touch pressure, pain, temperature and propioception.

7.0 REFERENCES/FURTHER READINGS

Gannong W.F. Review of Medical Physiology Published by Appleton and Lange.

Human Physiology by I.S. Fox Published by Wm C. Brown Publishers.

Guyton=s Textbook of Medical Physiology.

Human Physiology: From Cells to Systems by Sherwood L.

MODULE 2 SENSORY PHYSIOLOGY I

Unit 1 Taste and Olfaction
Unit 2 The Ears and Hearing
Unit 3 Vestibular Apparatus and Equilibrium

UNIT 1 TASTE AND OLFACTION

CONTENTS

1.0 INTRODUCTION

Taste and smell belong to that group of sensory modality called the special sense. However they can both be referred as visceral senses because of the close association they have with gastrointestinal function. The two are physiologically related to each other, infact the flavors of certain foods are to a large extent a combination of their taste and smell. A depressed sense of smell may affect the taste of food, making it to taste differently. Receptors for both taste and smell are chemoreceptors of the enteroceptor and teleceptor variety respectively. Both taste and smell are stimulated by molecules in solution. The two are however anatomically different from each other. Whereas the taste pathways pass through the thalamus and the post central gyrus in the cerebral cortex, the smell pathway has no reference in the thalamus.

This unit will discuss the physiology of gustation and olfaction with emphasis on their neurological control.

2.0 OBJECTIVES

At the end of this unit, you will be able to:

- briefly discuss the anatomy of taste organs
- identify the basic taste sensations
- describe the mechanism of taste
- describe the neural pathway for taste
- describe the structure of olfactory organs/receptors
- explain the mechanism of odour perception (olfaction)
- explain the theory of odour discrimination
- describe the neural pathways for olfaction

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3.0 MAIN CONTENT

3.1 Anatomy of Taste Organs

The surface of the tongue is covered by many small projections called papillae (singular-papilla) which gives the tongue its bumpy appearances. They are also found on the palate (roof of the mouth), throat and posterior surface of the epiglottis. There are three main types of papillae.

- The fungi form papillae (mushroom like): these are scattered singly especially near the tip of the tongue.
- The circumvallated (wall around) papillae: these form two rows parallel to the v-shaped sulcus terminal. It is found near the posterior third of the tongue.
- The filiform papillae (thread like) are pointed structures near the anterior two thirds of the tongue.

Located within the crevices of the papillae are approximately 10,000 receptor organs for the sense of taste called taste buds. Taste buds are barrel shaped clusters of chemoreceptor cells and sustentacular (supporting) cells arranged like alternating segments of an orange. Each taste bud contains about 25 receptor cells. The supporting cells are more numerous and serve as reserve cells to replenish any dead receptor cells. Mature taste receptor cells live for only about 10 days before they die and they can be replaced in about 10 hours. However as one gets older the frequency of replacement decreases. This is one of the reasons why the sense of taste has to diminish with age.

Each taste bud has a tiny outer opening the taste pore which opens into the oral cavity and through which the taste buds make contact with liquid in the mouth. Each taste receptor cell also has short microvilli, called taste hairs projecting through the tiny pores into the surface epithelium of the

mouth. It is through solutions (saliva) that dissolved molecules of the substance to be tasted enter the taste pores and interact with receptor sites on the taste hairs.

3.2 Basic Taste Sensations (Modalities)

Taste cells look structurally identical but each has different types of receptor sites. There are four generally recognized basic taste modalities which are sweet, sour, bitter and salty. Various combinations of the basic taste sensations complemented by an overlay of odours can result to many other flavours which can be tasted. Factors that affect taste perception include texture, temperature, spiciness, odour of food and psychological factors associated with past experiences with the food.

Each taste receptor cell responds to all four primary tastes to varying degrees, but is preferentially responsive to one modality. Hence bitter substances are mostly tasted on the back of the tongue, sour along the edges, sweet at the tip of the tongue and salt almost all over. All four modalities can be tasted on the pharynx and epiglottis. Sour and bitter are also tasted on the palate. Salt taste is usually stimulated by chemical salts B caused by the Na^+ component, the most salty being the Cl^- combination. Sour tastes are usually due to H^+ as in acids, sweet is produced by the particular configuration of glucose, such that other organic substances with similar structure can interact with sweet receptor and produce the same taste e.g. glycol. Bitter taste is caused by the presence of alkaloids e.g. caffeine, nicotine, strychnine morphine, other toxic plant derivatives or even poisonous substances elicit bitter taste (this may serve as a protective mechanism to discourage ingestion of potentially dangerous compounds).

3.3 Mechanism of Taste

The gustatory receptors are chemoreceptors that respond to substances dissolved in oral fluids bathing them. The gustatory receptor cells in the taste buds make synaptic connections to sensory nerve fibres. Substances that are dissolved in oral fluids act on the exposed microvilli in the taste pores to evoke generator potentials in the sensory neurons. The way generator potentials are produced for each taste modality seems to vary from one to the other. For example salt stimuli seem to depolarize salt receptors by influx of Na^+ through passive un-gated apical channels, while sweet seems to work through the action of second messenger (lagans) gated channels.

Whatever the mechanism, generator potentials in the receptors in turn initiates action potentials within the terminal endings of afferent nerves with which the receptor cell synapses.

Variations in the intensity of tastes seem to be produced by differences in the firing frequency of nerve impulses.

3.4 Neural Pathways for Taste

The sensory nerve fibres from the taste buds on the anterior two thirds of the tongue travel to the brain by a branch of the facial nerve (cranial nerve vii). Impulses from the posterior third of the tongue by the glosso-pharyngeal nerve (ix). Impulses from other areas other than the tongue (e.g. palate and pharynx) by the vagus nerve. The taste fibres in these three nerves unite in the medullar oblongata at the nucleus solitarius (nucleus gustatory). They synapse with second order neurons there; their axons cross over and project to the thalamus, ending with the fibres for touch, pain and temperature sensibility. From there impulses are relayed to the taste area of the post-central gyrus in the cerebral cortex.

Taste is represented in the portion of the post central gyrus that serves sensations from the face, adjacent to the tongue area of the somatosensory cortex.

3.5 The Structure of Olfactory Organs

Olfactory cells are located high in the roof of the nasal cavity; in specialized areas of the nasal muscosa called the olfactory epithelium. Each nostril contains a small patch of pseudo stratified, columnar olfactory epithelium about 2.5sq cm.

The olfactory epithelium (mucosa) contains 3 types of cells the olfactory receptors which are the olfactory neurons, the supporting or sustentacular cells and a thin layer of small basal cells. The basal cells are precursors for new olfactory receptor cells, which are replaced every one to two months. They are capable of undergoing mitosis and replacing degenerating receptor and sustentacular cells.

The olfactory receptor cells are not separate cells but are specialized endings of the afferent neurons, having contact with the outside, and with the axon projecting into the brain. The entire neuron can be replaced.

There are about 25 million bipolar olfactory receptors in humans, each surrounded by sustentacular cells. Each olfactory receptor has a short dendrite extending from its superficial end to the surface epithelium ending in a bulbous olfactory vesicle. From this bulbous swelling, 6 to 20 long cilia project through the fluid that covers the mucous membrane. This mucus like fluid is secreted by the sustentacular cells, because substances that stimulate the receptors must be in solution.

The axons of the olfactory receptor neurons pierce the cribriform plate of the ethmoid bone and enter the olfactory bulb. The olfactory bulbs are specialized structures of gray matter, stem like extensions of the olfactory region of the brain. Olfaction is the only sense that does not project fibres into the thalamus before reaching the cerebral cortex.

3.6 Mechanism of Olfaction

The cilia in the olfactory vesicle bulb contain binding sites for attachment of odoriferous molecules. During quiet breathing odorants reach the sensitive receptors by diffusion because the olfactory mucosa is above the normal direction of air flow. Sniffing enhances this process by drawing current upwards within the nasal cavity so that more of the odoriferous molecules in the air come in contact with the olfactory mucosa.

To be smelled a substance must be:

1. Sufficiently volatile that some of its molecules can enter the nose in the inspired air,
2. Sufficiently water soluble that it can dissolve in the layer of mucus coating the epithelium and
3. Lipid soluble to be able to penetrate the lipid barrier of the receptor cell membrane.

The physiology of olfaction may not be too well understood but it seems that odoriferous molecules bind to receptors on the cilia of olfactory receptor neurons. This activates adenylate cyclase via a G protein to increase intracellular cyclic AMP. The cAMP binds to and opens Na^+ channels with resultant Na^+ influx producing a generator potential.

The generator potential depolarizes the initial segment of the axon to firing level opening voltage-gated channels and initiating transmitted impulses in the nerve fibres that synapse in the olfactory bulb.

3.7 Odour Discrimination

The physiological mechanism of smell discrimination is not clearly known. Humans can distinguish several thousands of different odours. Perception of these odours would depend on combinations of various primary odours. There is however no agreement on how many odours are primary and which ones they are. Seven categories have been differentiated in one instance as follows: musky, camphoraceous, floral, pungent, peppermint, ethereal and putrid. Any other odour can then be some combination of two or more of these.

Some researchers believe that there could be receptors for up to a thousand different odours. The leading theory of odour claims that similar odours share a particular configuration in common not a similar chemical composition. Accordingly each type of receptor binding site is expected to have a distinct shape and size that matches the configuration of a particular primary odour.

The olfactory system is highly sensitive and discriminatory even in man (man has one of the poorest sense of olfaction compared to other species); but it is also quickly adaptive. Sensitivity to a new odour rapidly diminishes after a short while. However this type of adaptation has CNS origin and is just specific for the particular smell involved.

Some factors that may affect the perception of smell may include hunger which sharpens the sense of smell. Sense of smell may be inhibited when one has a cold. Females are believed to have a more acute sense of smell than males and in women it may be more acute at certain periods like ovulation.

3.8 Neural Pathways for Olfaction

The unmyelinated axons of the olfactory nerve project directly into the olfactory bulb where they synapse. Fibres leave the olfactory bulb, and travel in two different routes: a subcortical route that goes primarily to the regions of the limbic system especially the lower medial sides of the temporal lobe (the primary olfactory cortex), and (2) a thalamic cortical pathway which, as in other senses is important for conscious perception and fine discrimination of smell. The subcortical route involves the limbic system and especially the hypothalamus and this permits close coordination between smell and behavioural reactions associated with feeding, mating and direction orienting. The association with the limbic system has a role in emotions and memory, and may explain why a particular smell can evoke emotionally charged memories.

3.9 Abnormalities of Taste and Olfaction

Abnormalities of taste include ageusia (absence of the sense of taste), hypogeusia (diminished taste sensitivity) and dysgeusia (disturbed sense of taste). Diseases and drugs like captoril can cause diminished taste sensitivity and temporary loss of taste sensation respectively.

The absence of the sense of smell is called anosmia. Hyposmia refers to diminished olfactory sensitivity while dysosmia refers to distorted sense of smell. Olfactory thresholds increase with advancing age, and more than 75% of humans above 80 years have impairments in their sense of smell.

4.0 CONCLUSION

The senses of taste and smell though physiologically related and quite closely associated are however anatomically quite different as demonstrated in their separate neural pathways.

5.0 SUMMARY

1. The taste buds are the sense organs for taste and there are three different kinds fungiform, circumvallate and filiform, scattered over the tongue, the palate, epiglottis and pharynx**.**

2. Four different basic taste sensations (modalities) are identifiable sweet, sour, salt and bitter. Each of these are dominant in some parts of the tongue, and there are different receptors with predominant tendency to sense the different modalities. Combinations of these basic tastes give rise to many other taste sensations.

3. The four basic tastes seem to follow different mechanisms to produce receptor potentials leading to action potentials. Impulses are however carried in branches of three different cranial nerves (VII, IX and X) to the medulla, then to the thalamus and finally to the cortex in third other neurons.

4. The sense organ for olfaction is the cell body and dendrites of the olfactory nerve (first cranial nerve). The dendrites project some cilia which serve as receptor binding sites for odoriferous molecules. Both taste and olfactory receptors respond only to substances in solution, being chemical senses.

5. Olfaction seems to occur through G protein mediated ligand channels that stimulates increased production/release of cAMP. Impulses from olfactory neurons are carried in their axons to the olfactory bulb where they synapse and go on to the olfactory cortex in the temporal lobe.

6. Many odours can be discriminated but the mechanism is unclear.

7. Drugs and diseases can affect the sense of taste. Age affects the sense of smell as well as diseases.

6.0 TUTOR-MARKED ASSIGNMENT

Trace the various neural pathways, for taste and olfaction.

7.0 REFERENCES/FURTHER READINGS

Gannong, W.F. (1991). *Review of Medical Physiology*. Connecticut: Appleton and Langue.

Carola H., *et al* (1990). *Human Anatomy and Physiology*. New York: McGraw B Hill.

Fox I.S. Human Physiology. Dubuque: Wm.C. Brown.

Sherwood; L. Human Physiology. Minneapohs: West Publishing.

UNIT 2 THE EAR AND HEARING

CONTENTS

1.0 INTRODUCTION

Hearing or audition is a sensation perceived by the auditory or acoustic apparatus of the inner ear. However the external and middle ear all participate in the hearing function. The auditory apparatus is innervated by the cochlear nerve. Auditory apparatus is so closely associated with vestibular apparatus. The nerve that supplies the vestibular apparatus is the vestibular nerve. The two nerves are collectively called the vestibulo cochlear nerve (cranial nerve VIII).

2.0 OBJECTIVES

At the end of this unit you will be able to:

- briefly describe the various structures that participate in hearing
- explain the basic characteristics of sound waves
- explain the ionic basis of Impulse Transmission
- describe the neural auditory pathway
- explain some hearing impairments.

3.0 MAIN CONTENT

3.1 ANATOMY OF HEARING

The auditory system is organized to detect several aspects of sound including pitch, loudness and direction. Anatomically the ear is composed of the external ear, the middle ear and the inner ear.

3.1.1 THE EXTERNAL EAR

The external ear is the visible part of the ear also called the auricle or pinna. It is made up of a thin plate of fibrocartilage covered tightly by skin. The external ear has funnel like curves which are designed to collect sound waves and direct them to the middle ear which is the main function of the external ear in hearing. The deepest depression, (the concha) leads directly to the external auditory meatus.

The external auditory canal (meatus) is a slightly curved canal extending 2.5cm from the floor of the concha to the tympanic membrane which separates the external ear from the middle ear. The canal and tympanic membrane are covered with skin. Fine hairs in the external ear are directed outwards and sebaceous glands and modified sweat glands secrete cerumen. Both hairs and cerumen prevent tiny insects from entering the canal. Cerumen also prevents the skin of the external ear from drying out. The canal also buffers against humidity and temperature changes that can alter the elasticity of the ear drum.

3.1.2 The Middle Ear

The middle ear is an air-filled cavity in the temporal bone between the tympanic membrane and the inner ear. It consists of the tympanic cavity and contains the auditory ossicles (ear bones).

The **tympanic membrane** (ear drum) is a thin layer of fibrous tissue continuous externally with skin and internally with mucous membrane that lines the middle ear. The tympanic membrane is attached to a ring of bone that vibrates in response to sound waves entering the external ear canal. It is well endowed with blood vessels and nerves.

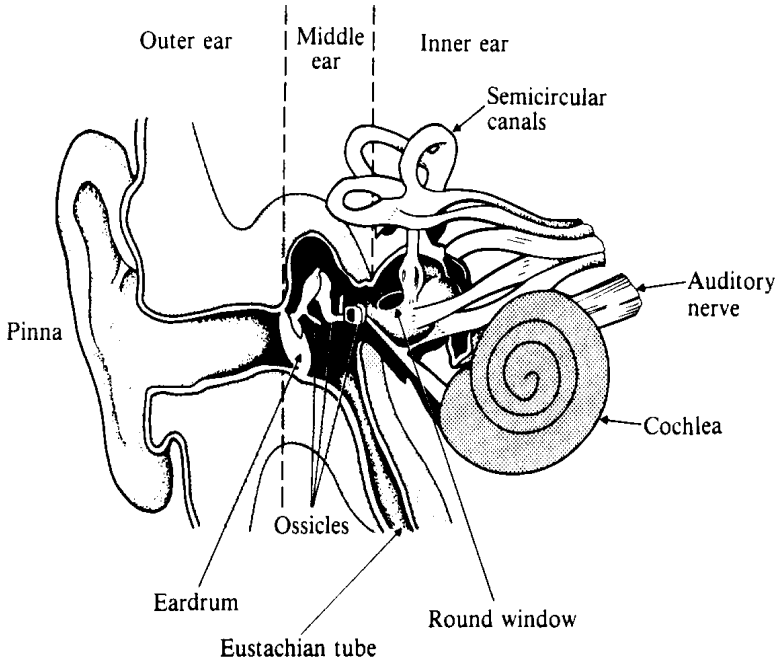


Fig 8: Diagram of Human Ear

The tympanic cavity is the air filled cavity extending from the middle ear to the bony wall that separates it from the inner ear. The bony wall has two openings the oval window and the round window.

In the anterior wall of the tympanic cavity is the auditory (Eustachian) tube that leads from the middle ear to the naso pharynx. The mucous membrane lining of the naso pharynx is continuous with the membrane of the tympanic cavity. As a result an infection may spread from the nose or throat into the middle ear. The function of this auditory tube is to maintain equal air pressure on both sides of the tympanic membrane by permitting air to pass from the nasal cavity into the middle ear.

The three auditory ossicles of the middle ear form a chain of levers extending from the tympanic membrane to the inner ear. This lever system transmits sound waves from the external ear to the inner ear. From the outside in, the tiny movable bones are the malleus (hammer) incus (anvil) and stapes (stirrup). These ear bones are the smallest bones in the body with the stapes being the smallest of all.

The manubrium (handle of the malleus) is attached to the back of the tympanic membrane. Its head is attached to the wall of the middle ear, and its short process is attached to the incus. The incus in turn articulates with the head of the stapes. Its footplate is attached by an annular ligament to the walls of the oval window. Two muscles, the tensor tympanic and the stapedius are also in the middle ear. The tensor tympanic is attached to the handle of the malleus. When it contracts it pulls the malleus in wards

increasing the tension on the tympanic membrane and reducing the amplitude of vibrations transmitted through the chain of auditory ossciles. The stapedius attaches to the neck of the stapes. Its contraction pulls the foot plate of the stapes, decreasing the amplitude of vibrations at the oval window.

In response to a sequence of loud sound the stapedius (acoustic) reflex comes into play to reduce the loudness. In this reflex the stapedius muscle, innervated by the facial nerve, contracts and thereby dampens the amplitude of vibrations of the stapes. In case of a whisper the stapedius can be relaxed thereby enhancing the sound.

3.1.3 Inner Ear

The inner ear is also called the labyrinth because of the intricate structure of interconnecting chambers and passages. The inner ear consists of two main parts:

1. The bony labyrinth is a series of channels hollowed out of the petrous portion of the temporal bone. It is filled with a fluid called perilymph.
2. The membranous labyrinth which is surrounded by the bony labyrinth contains a fluid called endolymph and all the sensory receptors for hearing and equilibrium. There is no communication between the spaces filled with perilymph and those filled with endolymph.

The membranous labyrinth consists of three semicircular ducts as well as the utricle, saccule and cochlea duct all of which are filled with endolymph and contains various sensory receptors. The semicircular ducts are located within the semicircular canals of the bony labyrinth. Perilymph bathe the ducts within the walls of the canals. The membranous labyrinth fits into the bony labyrinth, therefore the two have the same basic shape.

The bony labyrinth consists of the vestible, three semicircular canals and the spirally coiled cochlea. The vestible is the central chamber of the labyrinth. Within it are two endolymph filled sacs of the membranous labyrinth, the utricle and the smaller saccule. Each contains a sensory patch called a macule.

Beyond the semicircular canals and ducts is the spiral cochlea. It is a bony tube, 35mm long and makes 23/4 turns in the form of a spiral. The cochlea is divided into three fluid filled longitudinal compartments throughout most of its length. The upper compartment is called the scala vestibuli and it communicates with the vestible. The lower is the scala tympani. The scala media or cochlear duct is the middle compartment. It tunnels

lengthwise through the centre of the cochlea, but ends blindly a little way before the end (apex) of the cochlea B leaving a small space. The scala media (cochlear duct is continuous with the membranous labyrinth and contains endolymph). The scala vestibuli and the scala tympani contain perilymph. The small space at the end of the cochlear duct (apex of the cochlea) is called the **helicotrema,** where the scala vestibuli and tympani meet themselves and their perilymph meet together. The scala media does not communicate with the other two scalae.

The scala media (cochlear duct) is separated from the scala vestibuli by the vestibular membrane and from the scala tympani by the basilar membrane. Resting on the basilar membrane is the organ of Corti, which is the sense organ of hearing. It also follows the spiral shape of the cochlea ending at the blind end of the cochlear duct. The organ of Corti is an organized complex of supporting cells and hair cells. The hair cells are arranged in 4 rows, 3 rows of outer hair cells lateral to the tunnel about 20,000 in number, and one row of inner hair cells. Both the inner and outer hair cells about 3500 in number have bristle-like sensory hairs or stereocilia which project into the cochlear duct. Covering the rows of hair cells is a thin viscous but elastic tectorial membrane in which the tips of the outer hairs are embedded.

3.1.4 Sound Waves

Hearing is the neural perception of sound energy. Sound waves are traveling vibrations of air that consist of regions of high pressure caused by compression of air molecules alternating with regions of low pressure caused by rarefaction of molecules. Any device capable of producing such a disturbance pattern in air molecules is a source of sound. For example when a tuning fork is struck, its prongs vibrate. As a prong of the fork moves in one direction, air molecules ahead of it are pushed closer together or compressed increasing pressure in that area. At the same time air molecules behind the prong spread out or are rarefied as the prong moves forward. Disturbed air molecules disturb other molecules in adjacent regions setting up new regions of compression and rarefaction and so sound travels. Sound energy is gradually dissipated as sound waves travel from the original sound source, the intensity decreasing until when the last sound wave is too weak to disturb the air around it.

Sound waves can also travel through other media like water but they do so less efficiently. This is because greater pressures are required to overcome the fluids inertia.

Sound is characterized by its pitch (tone), intensity (loudness) and timbre (quality).

The pitch or tone is determined by the frequency of vibrations. The greater the frequency of vibration, the higher the pitch of a sound.

The intensity or loudness of a sound depends on the amplitude of the sound waves, or the pressure difference between a high pressure region of compression and a low pressure region of rarefaction. Within hearing range, the greater the amplitude the louder the sound. Man can detect a wide range of sound intensities from the slightest whisper to the painfully loud take off of a jet. Loudness is expressed in decibels (dB), a logarithmic measure of intensity compared with the faintest possible sound that can be heard. Sounds greater than 100dB can permanently damage the sensory apparatus in the cochlea.

The timbre or quality of sound depends on its overtones, that is, additional frequencies superimposed on top of the fundamental pitch or tone. Overtones are responsible for the characteristic different in voices. Timbre enables the listener to distinguish the source of sound waves because each source produces a difference pattern of overtones. The difference between noise and music, we understand is in the synchronous regularity of music which noise lacks.

3.2 Physiology of Hearing

Sound waves are conducted through air in the external ear, through solids in the middle ear and through liquid in the inner ear. Since sound does not pass readily in water the transition is very important. There is a potential loss of energy but the energy loss is not appreciable in the case of the ear because energy loss is balanced by the levers action of the ossicles in the middle ear. The efficiency of energy transfer from the tympanic membrane (air vibrations) to the oval window (transferring the vibration to the endolymph) is even enhanced because the surface area of the tympanic membrane is up to 20 times greater than that of the foot of the stapes in the oval window. The three phase conduction system is estimated to work at 99.9% transmission efficiency.

The hair cells of the spiral organ (of Corti) are mechanoreceptors in which the mechanical energy of sound is transduced into generator potentials at the cochlea nerve endings. Each hair cell is innervated by several neurons. There are about 23,500 hair cells and about 30,000 neurons and fibres in the cochlear nerve. Sound waves are converted into generator potentials in the following ways:

1. Sound waves enter the external ear. The waves reverberate against the sides of the external auditory canal and create waves of pressure. The waves reach the tympanic membrane.

2. Air molecules under pressure cause the tympanic membrane to vibrate. Low frequency waves produce slow vibrations, and high frequency waves produce rapid vibrations. The vibrations move the malleus on the other side of the membrane.

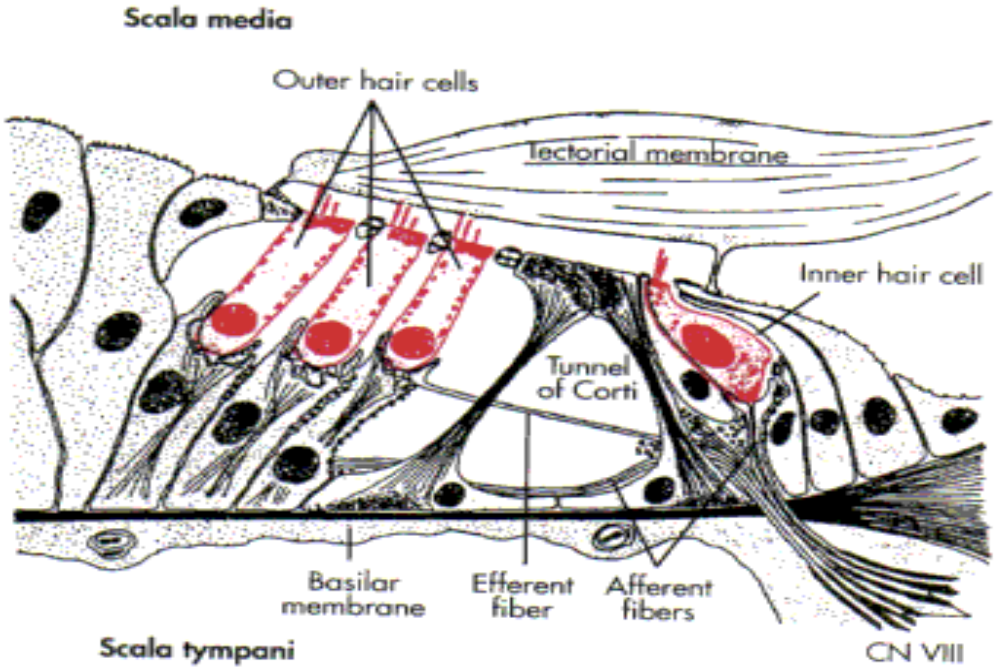


Fig. 9: Cross-section through the Organ of Corti.

3. The handle of the malleus strikes the incus causing it to vibrate.

4. The vibrating incus moves the stapes into and out of the oval window.

5. The sound waves that reach the inner ear through the oval window set up pressure changes that vibrate the perilymph in the scala vestibuli.

6. Vibrations in the perilymph are transmitted across the vestibular membrane to the endolymph of the cochlear duct, and up the scala vestibuli and down the scala tympani. The vibrations are transmitted to the basilar membrane causing the membrane to ripple. The fundamental vibratory ripples result in the perception of pure tones. Overtones such as musical sounds, chords and harmonies result from secondary vibrations superimposed on the fundamental vibration of the organ of Corti.

7. Receptor hair cells of the spiral organ (of Corti) in contact with the overlying tectorial membrane are bent causing them to generate graded generator potentials that excite the cochlear nerve to generate action potentials or nerve impulses. When the hairs are

displaced towards the basal body the hair cells are excited; when the hairs are displaced away from the basal body, the hair cells are inhibited.

8. The nerve impulses are conveyed along the cochlear branch of the vetibulocochlear nerve. The fibres activate the auditory pathways in the CNS and onwards.

9. Vibrations in the scala tympani are dissipated out of the cochlea through the round window into the middle ear.

The nuances of timbre, pitch and intensity of sounds are somehow preserved through each amplifying step from the tympanic membrane through the auditory ossicles, cochlea and spiral organ (of Corti) to the cochlear nerve. As a result, when the sound impulses reach the auditory areas, of the cortex, we can distinguish a saxophones note from a planos, a child's laughter from a dog=s bark etc.

3.3 Ionic Basis of Impulse Transmission

When the cochlear duct is displaced by pressure waves of perilymph, a shearing force is created between the basilar membrane and tectorial membrane. This causes the stereocilia to move and bend. Such movement causes ion channels in the membrane to open, which in turn depolarizes the hair cells. Each depolarized hair cell then releases a transmitter chemical that stimulates an associated sensory neuron.

The membrane potential of the hair cells is about 60mv. When the stereocilia bend in the right direction (towards the basal membrane), the membrane potential is decreased to about 50mv. If the hair processes are pushed in the opposite direction the membrane is hyperpolarized (ihibition). Displacing the processes to a perpendicular axis provides no change in membrane potential and displacing the processes in directions that are intermediate between these two directions produces either depolarization or hyper polarization depending on the location. The mechanism for generating changes depends therefore on the direction of displacement.

The greater the displacement of the basilar membrane and the bending of the processes, the greater the amount of transmitter released by the hair cell and therefore the greater the generator potential released by the sensory neuron.

3.4 Neural Auditory Pathways

From the cochlear nuclei, axons carrying auditory impulses pass via a variety of pathways to the inferior colliculi of the midbrain after synapsing at the medulla. The inferior colliculi are the centres for auditory reflexes. Neurons from here project to the medial geniculate body of the thalamus and from there axons are sent to the auditory cortex of the temporal lobe. By means of this pathway, neurons in different regions of the basilar membrane stimulate neurons in corresponding areas of the auditory cortex. Just as various regions of the basilar membrane are associated with particular tones, so the auditory cortex is tonotopically arranged. Accordingly, specific cortical neurons are activated only by particular tones; each region of the auditory cortex becomes excited only in response to a specific tone detected by a selected portion on the basilar membrane.

3.5 Sound Discrimination

Pitch discrimination depends on the shape and properties of the basilar membrane. Different regions of this membrane vibrate maximally at different frequencies. The narrow end nearest to the oval window vibrates best with high frequency pitches while the wide end nearer the helicotrema vibrates maximally with low frequency pitches. Other pitches in between are sorted out along the length of the membrane for higher to lower frequency. The information is propagated to the CNS which interprets the pattern of stimulation as a sound of a particular frequency.

Overtones of varying frequencies cause many points along the basilar membrane to vibrate simultaneously but less intensely than the fundamental tone, enabling the CNS to distinguish the timbre (quality) of the sound. Intensity discrimination depends on the amplitude of vibration. As sound waves originating from louder sounds strike the eardrum they cause it to vibrate more vigorously. (A softer sound having the pitch will cause less vigorous vibration). The greater ear drum deflection is converted into greater amplitude of the basilar membrane movement in the region of peak responsiveness. The CNS then interprets this greater basilar membrane oscillation as a louder sound.

3.6 Hearing Impairments

Hearing impairments may be due to two major causes:

1. Conductive deafness, which is where there is impairment of sound transmission from air through the middle ear, to the oval window, and
2. Nerve or sensory deafness; in which the transmission of nerve

impulses anywhere from the cochlea to the auditory cortex is impaired (neural pathways).

Conductive deafness can be caused by wax or foreign body in the external ear, destruction of the auditory ossicles in the middle ear thickening of the eardrum following repeated middle ear infections, abnormal rigidity of the attachment of the stapes to the oval window. Also aminoglycoside antibiotics like streptomycin and gentamicin can obstruct the mechanosensitive channels in the stereocilia of the hair cells causing the cells to degenerate. This can produce nerve deafness. Exposure to extremely loud sounds as well as prolonged exposure to noise causes nerve deafness by damaging the hair cells.

Conduction deafness impairs hearing at all sound frequencies. Sensory deafness by contrast impairs ability to hear some pitches more than others (some parts of the basilar membrane may be affected and not others) may be as a result of pathology or aging. Age related hearing loss B presbycusis -- begin after age 20 when ability to hear high frequencies (18,000 to 20,000 Hz) begin to diminish. The progression is variable however, and it occurs more in men than in women. Hearing loss in the higher frequency pitches particularly affects the ability to hear speech. People with such impairments can be helped by hearing aids which amplify sounds and conduct them through the bones to the inner ear.

Audiometry as well as some simple tuning fork tests can be used to detect impairments as well as distinguish between conduction and nerve deafness.

4.0 CONCLUSION

The auditory system is so sensitive and can detect sound as faint as a deflection of only a fraction of a nanometer distance on the basilar membrane. It is therefore no wonder that very loud sounds can set up such violent vibrations as to damage the irreplaceable hair cells.

5.0 SUMMARY

1. The outer ear funnels sound waves of different frequencies (measured in hertz) and intensity (measured in decibels) to the tympanic membrane causing it to vibrate.

2. Vibrations of the tympanic membrane cause movement of the ossicles, malleus, incus and stapes in the middle ear and this movement in turn produces vibrations in the oval window of the cochlea.

3. Vibrations of the oval window set up traveling wave of perilymph in the scala vestibuli. The waves can pass around the helicotrema to the scala tympani or can pass through the scala media to the scala tympani.

4. The scala media (cochlear duct) is filled with endolymph and is bounded by vestibular membrane to the side of the scalar vestibule and the basilar membrane on the side that faces the scala tympani.

5. The organ of Corti or spiral organ of the cochlea, is the sensory structure for hearing. It lies directly on the basilar membrane and consists of sensory hair cells. The stereocilia (hairs) of the hair cells project up into the overhanging tectorial membrane.The hair cells for hearing are innervated by the cochlear branch of the vestibulocochlear (8^{th} cranial) nerve.

6. Sounds of different frequencies produce maximum displacement of different parts of the basilar membrane, with the highest frequencies closer to the oval window end. Displacement of the basilar membrane causes the hairs to bend against the tectorial membrane and stimulate the production of nerve impulses.

7. Pitch discrimination depends on the region of the basilar membrane that vibrates maximally to sounds of different frequencies. Intensity discrimination depends on the amplitude of vibration (how vigorous the vibration).

8. Hearing impairment can be due to conduction impairments or nerve impairments.

6.0 TUTOR-MARKED ASSIGNMENT

Explain how movements of the basilar membrane affect hair cells, and how hair cells can stimulate associated sensory neurons.

7.0 REFERENCES/FURTHER READINGS

Guyton, A.C. (1991). *Textbook of Medical Physiology*. Philadelphia: WB. Saunders.

Gannong W.F. (1991). *Review of Medical Physiology*. Connecticut: Appleton and Langue.

UNIT 3 VESTIBULAR APPARATUS AND EQUILIBRIUM

CONTENTS

1.0 INTRODUCTION

The second functional unit of the ear is the vestibular apparatus which is concerned with posture and balance. This is the sense of equilibrium. The structures that provide for this sense are located in the inner ear and they include the utricle and saccule, and the semi circular canals. As in hearing the receptors for equilibrium are hair cells. These receptors are proprioceptors and they detect rotational and linear accelerations. The vestibular apparatus is innervated by the vestibular nerves which together with the cochlear nerve from the auditory apparatus make up the vestibulo cochlear (8^{th} cranial) nerve.

In this unit we shall examine the functions of the vestibular apparatus in the maintenance of equilibrium.

2.0 OBJECTIVES

At the end of this unit you will be able to:

- explain the structures that make up the vestibular apparatus
- describe the functions of the vestibular apparatus in equilibrium
- explain the occurrence of nystagmus and vertigo
- explain the involvement of the vestibular apparatus in some clinical situations.

3.0 MAIN CONTENT

3.1 Anatomical Considerations

The vestibular apparatus and the snail like cochlea involved in hearing form the inner ear within the temporal bones of the skull. The vestibular apparatus consists of two parts the otolith organs which are the utricle and saccule, and the semi circular canals. The sensory structures of the vestibular apparatus and cochlea are located with in a tubular structure called the membranous labyrinth which is filled with a fluid that is like intracellular fluid in composition; called endolymph. The membranous labyrinth is also located within a tubular bony cavity of the same shape the bony labyrinth. Within the bony cavity, between the membranous labyrinth and the bone is a fluid called perilymph, which is similar in composition to cerebrospinal fluids.

The Semi Circular Canals

The three Semi circular ducts and canals are perpendicular to each allowing each other one to be oriented in one of the three planes of space. The ducts are lined by the membranous labyrinth which is suspended in perilymph within the bony labyrinth while the canals are lined by bone. The semi circular ducts contain endolymph. On the basis of their locations the semi circular canals and ducts are called superior (anterior) lateral and posterior. Each duct has an expanded end called an ampulla which contains a receptor structure called the crista ampullaris. Each crista consists of hair cells and sustentacular cells surmounted by a gelatinous material that closes off the ampulla.

The Utricle and Saccule

Within the vestibule which is the central chamber of the labyrinth are two endolymph filled sacs called the utricle and saccule housed within their bony chambers between the semi circular canals and the cochlea. Each sac also contains a sensory patch called macula. The maculas contain sustentacular and hair cells also surmounted by an otolithic membrane in which is an embedded crystal of calcium carbonate the otoliths.

Sensory hair cells of the vestibular apparatus. The receptors for next line equilibrium are modified epithelial cells known as hair cells because they contain twenty to fifty hair like extensions stereocilia i.e. processes that contain filaments of protein surrounded by part of the cell membrane. One of the extensions is larger and has the structure of a true cilium with a clubbed end. That one is known as kinocilium. Each hair cell is oriented so that it depolarizes when its stereocilia are bent toward the kinocilium. Bending in the opposite direction hyperpolarizes the cell.

3.2 Functions of the Vestibular Apparatus

The vestibular apparatus provides information essential for the sense of equilibrium and for coordinating head movements with eye and postural movements. It detects changes in position and motion of the head. All the components of the vestibular apparatus contain endolymph and are surrounded by perilymph. The main components of the vestibular apparatus are the utricle, saccule and the fluid filled semi circular ducts of the membranous labyrinth. The receptors of the utricle and saccule regulate static equilibrium and the receptors in the ampullae of the semi circular ducts respond to movements of the head. The equilibrium system also receives input from the eyes and from some propioceptors in the body especially the joints. The movement of hairs of a hair cell, in the axis of sensitivity makes the hair cell to generate a receptor potential in the nerve ending, synapsing with the hair cells.

3.2.1 Functions of the Utricle and Saccule Static Equilibrium

The receptor region of the utricle and saccule called the macula contains hair cells embedded in a jelly like otolith membrane. Loosely attached to the membrane, and piled on top of it are hundreds of thousands of calcium carbonate crystals called otoliths (ear stones). These stones make the membrane heavier resulting in a higher inertia than the surrounding fluid (resistance to change in position). Hair cells in the utricle respond to motion changes that occur during the straight-line acceleration and deceleration of the head (back and forth). The hair cells also monitor the position of the head in space, controlling posture. It actually tells you automatically the position of your head in relation to gravity. The utricles are also responsible for initiating the righting reflex which is seen when a cat is dropped upside down and it lands on its feet. This is because the maculas discharge tonically in the absence of head movement because of the pull of gravity on otoliths. The saccule generally responds more to vertical acceleration.

The mechanism of static equilibrium response depends on the difference in density between the otoliths (otoconia) and the endolymph inside each utricle and saccule. Otoliths have greater density than endolymph. As a result when the head moves in a change of posture, the otoliths resist the external force and lag behind the motion of the endolymph. The otolith and membrane remain relatively still and bend the hairs of the hair cell. Each macula hair cell responds to the gravitational force exerted upon the hairs by the dense otoliths. When the head is held horizontally, the gravitational force is directed downward upon the hair bundle. When the head is tilted to the side, the hair bundle of each hair cell is displaced towards the axis of sensitivity, and can excite the afferent nerve fibre. A

tilt of the head that bends the hair against the axis of sensitivity has the opposite effect (inhibition of afferent neuron).

Bending of the hair cells changes the permeability of the cells to Na^+ and K^+. The resulting graded generator potential stimulates nerve endings of the vestibular nerve fibres to generate another graded generator potential and subsequently an action potential in the vestibular nerve.

3.2.2 Dynamic Equilibrium Semicircular Ducts

Each duct of the three semicircular ducts contains a bulge, the ampulla where the sensory hair cells are located which is the crista ampullaris. The hair is embedded within a gelatinous membrane called cupula that projects into the end lymph. The hair cells respond to changes in rotational acceleration i.e. angular movements. Because of the situation of the three ducts in different planes at right angles to each other, at least one duct is affected by each head movement the one in the same plane as the head movement. The endolymph of the semicircular ducts serves a function analogous to the otoliths membrane. It provides inertia so that the sensory processes will be bent in direct opposite to that of the angular acceleration. As the head rotates to the right for example, the endolymph causes the cupula to bend towards the left thereby stimulating the hair cells. This is similar to our body's jerking backwards, when the car in which we are suddenly jerks forward. If the head continues to rotate, the endolymph catches up and moves in unison (same rate and direction) with the head, so that the hairs return to their unbent position. When the head slows down and stops, reverse situation occurs. The endolymph continues to move in the direction of the rotation while the head decelerates to a stop. The result is that the cupula and its hair are bent in the direction of the preceding rotation. When the endolymph gradually comes to a halt, the hairs straighten again. This way the semicircular ducts detect changes in rotational movement. They do not respond when the head is motionless or during circular motion at a constant speed. Linear acceleration probably fails to displace the cupula and therefore does not stimulate the cristae. When the hairs bend in the direction of the axis of sensitivity, nerve endings are stimulated to produce a graded generator potential followed by an action potential in each nerve fibre. The brain receives the impulse and signals appropriate muscles to contract in order to maintain the body's equilibrium.

3.3 Neural Pathways for Equilibrium

Stimulation of hair cells in the vestibular apparatus activates sensory neurons of the vestibulocochlear (8^{th} cranial) nerve. The vestibular tracts consist of pathways to the brainstem, spinal cord, cerebellum and cerebral

cortex. The primary vestibular fibres from the vestibular nerve pass into the vestibular nuclei in the medulla oblongata and from their fibres are sent to the oculomotor centre of the brain stem and to the spinal cord. Neurons in the oculomotor centre control eye movements and those in the spinal cord stimulate movements of the head, neck and limbs.

The sensory signals from the vestibular sensors of the labyrinth are indicators of the position and movements of the head. These inputs from the vestibular receptors are critical in

1. Generating compensatory mechanism to maintain balance and an erect posture in response to gravity.
2. Producing the conjugate movements of the eyes that compensate for changes in the position of the constantly moving head, and
3. Supplying information for conscious awareness of position, acceleration, deceleration and rotation. The vestibular functions are supplemented by proprioceptive inputs from the muscles and joints as well as the visual system.

3.4 Nystagmus and Vertigo

When a person first begins to spin, the inertia of endolymph within the semicircular canals causes the cupula to bend in the opposite direction. As the spin continues however, the inertia of the endolymph is overcome and the cupula and hair cells straighten up. This time the endolymph and cupula move in the same direction and at the same speed. If the movement is suddenly stopped, the greater inertia of the endolymph causes it to continue moving in the previous direction of spin and to bend the cupula in that direction (the way your body moves forward when your car stops suddenly).

Bending the cupula after the movement has stopped affects the muscular control of the eyes and body through the neural pathways. The eyes slowly drift in the direction of the previous spin and then are rapidly jerked back to the midline position producing involuntary oscillations. These movements are called vestibular nystagmus and people experiencing this effect may feel that they or the room are spinning. The loss of equilibrium that results is called vertigo. If the vertigo is severe or in persons who are particularly susceptible the autonomic nervous system may be involved and this produces dizziness, pallor, sweating and nausea.

3.5 Clinical Application/Abnormalities

Vestibular nystagmus is one of the symptoms of an inner ear disease called Meniere's disease. The disease may occur as a result of fluid

imbalances within the inner ear. The early symptoms of the disease are ringing in the ears or tinnitus. Since the endolymph of the cochlea and the endolymph of the vestibular apparatus are continuous, vestibular symptoms of nystagmus and vertigo are often accompanied by hearing problems in this disease.

Some individuals, for incompletely understood reasons, are especially sensitive to particular motions that activate the vestibular apparatus and cause symptoms of dizziness and nausea; this sensitivity is called motion sickness.

Because the inner ears of deaf mutes are not functioning, they are immune to dizziness and motion sickness. These ones have to rely on visual cues for the maintenance of normal movement and posture. Without visual cues, someone who has lost the use of the inner ear may navigate down instead of up when he wants to move up, because there is no sense of position in space (equilibrium).

4.0 CONCLUSION

Orientation in space and maintenance of equilibrium generally depends in large part on input from the vestibular receptors but visual cues are also important as well as those supplied by propioceptors in the joints capsules about the relative position of various parts of the body. Impulses from coetaneous exteroceptors especially for touch and pressure are also required. It is these four inputs that are synthesized at the cortical level into a continuous picture of a person's orientation in space and state of equilibrium.

5.0 SUMMARY

In this unit, we learnt the following:

- The structures for equilibrium are located in the membranous labyrinths which are housed in the body labyrinth of the inner ear. The structures include the semicircular ducts and the otolith organs (utricle and saccule). The utricle and saccule respond to linear acceleration while the semicircular ducts provide information about rotational acceleration.

- The sensory receptors for equilibrium are hair cells that have numerous hair like processes called stereocilia and one kinocilium. When the stereocilia bend in the direction of the kinocilium the cell membrane depolarizes, when they are bent in the opposite direction, the membranes become hyperpolarized.

- In the utricle and saccule, during linear acceleration, the inertia provided by the otolith membrane causes a shearing force between the hairs of the otolith membrane thereby bending the stereocilia and stimulating sensory nerve endings.

- In the semicircular canals, the inertia of the endolymph causes the cupula and hairs to bend in directions opposite that of the head rotation, to stimulate sensory nerve endings.

- Stimulation of hair cells in the vestibular apparatus activates the sensory neuron of the vestibulocochlear nerve, which projects into the cerebellum and vestibular nuclei of the medulla. From the medulla, fibres are sent to the oculomotor centre which controls eye movement.

- Continuous spinning and abrupt stopping can cause oscillatory eye movements called nystagmus.

6.0 TUTOR-MARKED ASSIGNMENT

Describe the structure of the utricle and saccule and explain how linear acceleration results in stimulation of the hair cells within these organs.

11.0 REFERENCES/FURTHER READINGS

Guyton, A.C. (1991). *Textbook of Medical Physiology*. Philadelphia: WB. Saunders.

Gannong W.F. (1991). *Review of Medical Physiology*. Connecticut: Appleton and Langue.

Unit 1 Eyes and Vision
Unit 2 Retina and Neural Processing of Visual Information

UNIT 1 THE EYES AND VISION

CONTENTS

1.0 INTRODUCTION

The eye is the organ for sight. The two eyes have the function of transducing electromagnetic energy into nerve impulses. We see those objects that are illuminated by light waves in our receptive range. Light from an observed object is focused through certain structures in the eyeball onto to the photoreceptive "film" the retina at the back of the eye. A system of nerves conducts impulses generated by the receptors to the brain for proper interpretation.

In the next two units we shall consider the processes through which vision is achieved. We shall examine briefly the structures of the eye as a basis for better understanding of the physiology of vision. The aspects of the physiology of vision that occurs from the entry of light into the eye till the focusing of image on the retina shall also be considered.

2.0 OBJECTIVES

At the end of this unit you will be able to:

- present a summary description of the structures that make up the eye as well as
- explain basic concepts in light and vision
- explain the process of refraction
- discuss accommodation as one of the mechanisms of image formation
- explain visual acuity
- highlight some common defects of image formation and visual acuity.

3.0 MAIN CONTENT

3.1 Brief Description of the Structure of the Eye

The human eyeball is a spherical fluid filled structure about 2.5cm diameter enclosed by three layers of tissue. From outside inwards they are: the outer supporting layer, the middle vascular middle layer and the inner retina layer.

The outer supporting layer consists of the tough outer layer of connective tissue that covers most of eyeball - the **sclera**. This forms the visible white part of the eye covering about $5/6^{th}$ of the eyeball posteriorly and giving shape to the eyeball. The anterior $1/6^{th}$ of the outermost layer is the cornea which is transparent and through which light rays pass into the eye. The middle vascular layer is the choroid which contains many blood vessels that nourish the retina, the anterior portion of the choroid layer has the ciliary body and iris.

The innermost coat under the choroid is the **retina** which has an outer pigment layer and an inner nervous tissue layer. The inner nervous layer contains **rods** and **cones** which are the photoreceptors that convert light energy to nerve impulses. The pigment in the choroid and retina absorbs light after it strikes the retina to prevent reflection or the scattering of light within the eyes.

The interior of the eye consists of two fluid filled cavities separated by a **lens** all of which are transparent to permit light to pass through from the cornea to the retina.

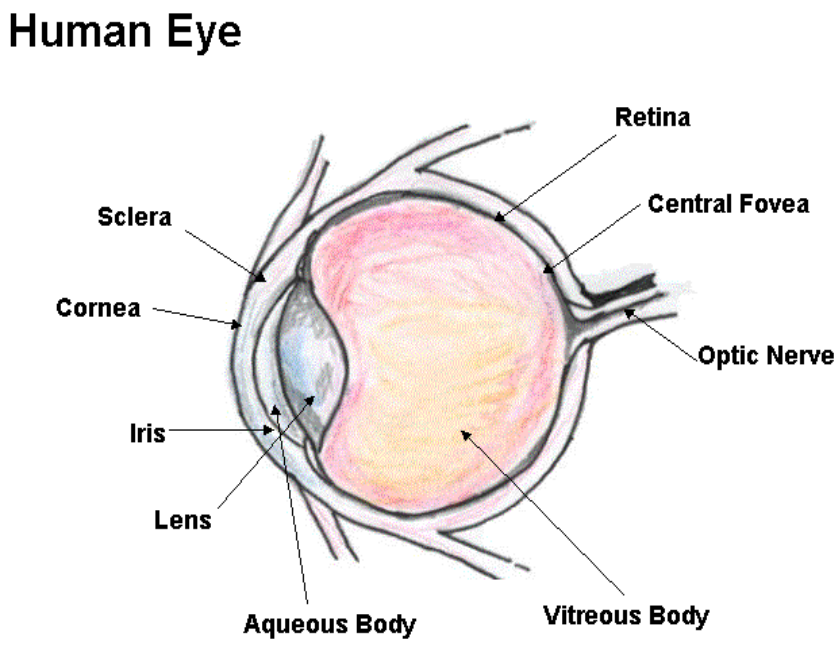


Fig. 10: Diagram of a human eye

The anterior cavity between the cornea and lens contains a clear watery fluid called the **aqueous humour**; and the larger posterior cavity between the lens and retina contains a semi-fluid, jellylike substance, the **vitreous humour**.

The vitreous humour maintains the spherical shape of the eyeball. The aqueous humour carries nutrients for the cornea and lens both of which lack blood supply. Aqueous humour is produced by a capillary network within the ciliary body at a rate of about 5ml/day.

The **ciliary body** is a specialized anterior derivative of the choroid layer. Aqueous humour drains into a canal at the edge to the cornea and eventually enters back into the blood. A problem of drainage of the aqueous humour, may result in accumulation of the fluid in the anterior chamber, causing the intraocular pressure to rise. The condition of raised intraocular pressure is known as **glaucoma**. The excess aqueous humour pushes the lens backward into the vitreous humour which in turn is pushed against the inner neural layer of the retina. This compression can cause retinal and optic nerve damage that can lead to blindness if not promptly treated.

Not all light passing through the cornea reaches the light sensitive photoreceptors because of the presence of the **iris**. The iris is the anterior extension of the choroid layer. It is a thin muscular layer that is seen as a

coloured part of the eyeball. In the centre of the iris is on adjustable circular aperture the **pupil** through which light enters the inner parts of the eye. The size of this opening can be adjusted by variable contraction of the iris to admit more or less light as needed.

3.2 Accessory Structures of the Eye

The accessory structures of the eye are either protective devices or muscles. They include the bony orbit, eyelids, eyelashes, eyebrows, conjunctiva, lacrimal (tear) apparatus and muscles that move the eyeball and eye lid.

The conjunctiva is a thin transparent mucous membrane that lines the eyelids and bends back over the surface of the eyeball, terminating at the transparent cornea, which is uncovered.

The lacrimal apparatus is made up of the lacrimal gland, lacrimal sac, lacrimal ducts and naso-lacrimal duct. The eye is kept moist by secretions of the lacrimal gland (tear) located under the upper lateral eyelid and extending inward from the outer canthus of the eye.

Muscles of the eye and eyelid: A set of six muscles move the eye ball in the socket. The muscles are four rectus muscles and superior and inferior oblique muscles. One end of each muscle is attached to a skull bone and the other end is attached to the sclera of the eyeball. These extraocular muscles are coordinated and synchronized so that both eyes move together to centre on a single image.

Other muscles move the eyelids and they include the orbicularis oris, and the levator palpebrae superioris. These muscles lower and raise the eyelids respectively. There is a smooth muscle that helps to raise the upper eyelid called the superior tarsal muscle.

Inside the eyes are several smooth intrinsic muscles. For example, the **ciliary muscle** which eases tension on the suspensory ligament of the lens and allows the lens to change its shape in order for the eye to focus (accommodate) properly. The **circular** muscle of the iris contracts the pupils, while the **radial muscle** dilates it.

3.3 Light and Vision

Light is a form of electromagnetic radiation composed of particle like individual packets of energy called **photons** that travel in wave like fashion. The distance between two wave peaks is known as the **wavelength**. The photoreceptors in the eye are sensitive only to

wavelengths between 400 and 700 nanometers (nm: billionth of a meter). The **visible light** is only a small portion of the electro-magnetic spectrum. Light of different wavelengths in visible band is perceived as different colour sensations. For example, visible light of shorter wavelengths are sensed as violet and blue and those of longer wavelengths are perceived as orange and red.

Lights of shorter wavelengths beyond the visible spectrum for example ultraviolet light have more energy than visible light and are filtered out by the yellow colour of the eye's lens. Lights of longer wavelengths beyond the visible spectrum do not have sufficient energy to excite the photoreceptors but are felt as heat for example infrared.

In addition to having variable wavelengths, light energy also varies in intensity that is the amplitude or height of the wave.

Light waves also diverge (radiate outward). The forward movement of a light wave in a particular direction is known as a light ray. Divergent light rays reaching the eye must be bent inward to be focused back into a point on the light sensitive retina to provide an accurate image of the light source.

3.4 Refraction

When light passes from a medium of one density into medium of a different density it is bent, except when such rays strike perpendicularly the interface. Such bending is called refraction. Light rays entering the eye have to be refracted so that they can converge at the retina as a sharp focused point (focal point). Before light reaches the retina it passes through the cornea, the aqueous humour of the anterior chamber, the lens, and the gelatinous vitreous humour behind the lens.

Refraction takes place as light passes through both surfaces of the cornea, (a convex non adjustable lens) and again as it passes through the anterior and posterior surfaces of the lens (a convex adjustable lens).

The degree of refraction depends on the comparative densities of the two media, as indicated by their refractive indices. The refractive index of air is set at 1.00, the refractive index of the cornea, is 1.38; the aqueous homour, 1.33 and the lens 1.44. Since the greatest difference in refractive index occurs at the air-cornea interface, the light is refracted most at the cornea. The degree of refraction also depends on the interface between the two media. The curvature of the cornea is constant while that of the lens can be varied. The refractive properties of the lens can therefore provide fine control for focusing light on the retina. As a result of light refraction, the image formed on retina is upside down and right to left.

The reflective structures of the eye must bring images into focus before it reaches the retina, or if not yet focused before it reaches the retina, it will be blurred. Light rays originating from near objects are more divergent when they reach the eye than rays from distant sources.

For a given refractive ability of the eye, a near source of light may require a greater distance behind the lens for focusing on the retina than a far source of light does because the near source rays are still divergent when they reach the eye.

In a particular eye, the distance between the lens and the retina always remains the same. To bring both near and far light sources into focus, on the retina, a stronger lens must be used for the near source. The strength of the lens can be adjusted through the process of accommodation.

3.5 Accommodation

Accommodation is the ability to adjust the strength of the lens so that both near and far sources can be focused on the retina. That is the ability of the eye to keep the image focused on the retina even as the distance between the object and eye is changed.

Images from an object less than 20ft (6m) away would normally be focused behind the retina. The converse is also true, images from an object more than 20ft away would focus before the retina. It is now the function of the adjustable lens to bring images into perfect focus on the retina. This is accomplished by this reflex process called accommodation.

The ciliary muscle, a circular ring of smooth muscle attached to the lens by suspensory ligaments, through its contraction and relaxation can adjust the lens appropriately to ensure that a clear image is focused on the retina. In the normal eye, the ciliary muscle is relaxed and the suspensory ligament pulled taut for a far object. The tense suspensory ligaments pull the lens to become thinner (flattened). But for near vision, the muscle contracts, relaxing the ligament allowing the lens to assume a more convex, stronger quality. This now converges the rays from a near object which ordinarily would still have been parallel/or even divergent as it enters the eye. The more rounded (the greater the curvature) of the lens the greater the strength and the more the bending of light rays.

This elastic property of the lens makes it adjustable and therefore possible to see both near and far objects without difficulty and without blurring. When the lens starts losing its elasticity as age advances, it starts losing the ability to get more spherical in shape required to accommodate for near vision.

The ciliary muscle is controlled by the autonomic nervous system. Sympathetic fibres induce relaxation of the ciliary muscles for far vision and parasympathetic nerves cause the muscles to contract for near vision.

3.5.1 Near Point

Accommodation is an active process that requires muscular effort and can be tiring. Infact, the ciliary muscle is one of the most used muscles in the body. The degree to which the lens curvature can be increased is, of course limited and light rays from a very near object cannot be brought to focus on the retina even with the greatest effort. The nearest point to the eye at which an object can be brought into clear focus by accommodation is called the **near point of vision**. The near point recedes throughout life, slowly at first and then rapidly with advancing age, from approximately 90cm at age 10 to approximately 83cm at age 60. Thus recession is due to increasing hardness of the lens with resulting loss of accommodation. The loss of accommodation is due to the steady decrease in the degree to which the curvature of lens can be increased. By the time a normal individual reaches age 40, the loss of accommodation is usually sufficient to make reading and close work difficult - a condition known as presbyopia. The ability of a person's eyes to accommodate can be measured by the near point of vision test.

3.6 Visual Acuity

Visual acuity is the degree to which the details and contours of objects are perceived. It is usually defined in terms of the **minimum separable** i.e., the shortest distance by which two lines can be separated and shall be perceived as two lines. Clinically it is determined by the Snellen Charts viewed at a distance of 20ft (6m). The individual being tested reads aloud the smallest line distinguishable. The results are expressed as a fraction. The numerator of the fraction is 20ft (or 6m), the distance at which the subject reads the chart. The denominator is the greatest distance from the chart at which the normal individual can read the smallest line the individual can read. Normal visual activity is 20/20 which means that one's eyes can see at 20ft what the normal eye can see at that distance. Hence a person with a visual acuity of 20/15 has a more than normal vision while 10/100 has a subnormal vision. The larger the denominator the worse the acuity (sharpness) legal blindness is 20/200 or less in both eyes with or without corrective eye glasses.

Visual acuity is a complex phenomenon influenced by many factors. Some of them are optical factors such as the state of the image forming mechanism of the eye, retinal factors, such as the state of the cones; and stimulus factors including illumination, brightness of the stimulus, contrast between stimulus and background etc.

3.7 Common Defects of Image Formation Process

When a person with normal visual acuity stands 20ft from a Snellen eye chart (no accommodation required). The line of letters marked "20/20" can be read. If a person has **myopia** (near sightedness), this line will be blurred because the image is brought to focus in front of the retina (i.e. before they reach the retina). This is usually because the eyeball (diameter) is too long. When the light rays do reach the retina, they form an unfocused circle instead of a sharp point and distant objects appear blurred. Myopia is corrected by glasses with concave lenses that cause the light rays to diverge further, so that the point of focus is shifted farther from the lens and thus pushed back to the retina.

In **hyperopia (hypermetropia or farsightedness)**, the eye balls (diameter) are rather too short, the "20/20" line will still appear blurred because the focal length of the lens is longer than the distance to the retina. The image will thus be brought to a focus behind the retina, and the object will have to be placed farther from the eyes to be seen clearly. (near objects appear blurred). Hyperopia is corrected by glasses with convex lens that increase the convergence of light, so that the focus is brought closer to the lens and falls on the retina.

Astigmatism is a condition in which the curvature of the cornea and/or lens is significantly not uniform or symmetrical. Light passing through some parts of these structures may be refracted to a different degree than light passing through other parts. As a result the image formed on the retina is unfocused. If a person with astigmatism for example views a circle of lines radiating from the centre like the spokes of a wheel, the image of these lines will not appear clear in all 360 degrees. Some parts will appear blurred. This condition is corrected by glasses that have greater bending power in one axis than in other.

Presbyopia is a condition associated with loss of accommodation that occurs as a result of progressive loss of the elastic quality of the lens. The problem is associated with advancing age. With loss of elasticity, the lens is no longer able to assume the more spherical (convex) shape required for more refraction to accommodate for near vision. This age related reduction in accommodative ability, affects most people by middle age (45 - 50) requiring them to resort to corrective lens for near vision (e.g. reading).

4.0 CONCLUSION

Light from an object is focused by the cornea and lens onto the photoreceptive retina at the back of the eye. The focus is maintained on the retina at different distances between the eyes and the object by variations in the curvature of the lens.

5.0 SUMMARY

In this unit, we learnt that light enters the cornea of the eye, passes through the pupils and then through the lens from which it is projected to the retina at the back of the eyeball. Before getting to the retina, light rays are refracted by the cornea and lens. The image is upside down on the retina because of refraction and right to left. Accommodation is the ability to maintain a focus on the retina as the distance between the object and the eye is changed. Accommodation is achieved by changes in the shape and reactive power of lens, and this is brought about the activity of the ciliary muscles. Visual acuity refers to the sharpness of the image and depends in part on the ability of the lens to bring the image to a focus on the retina. Some defects can occur in the process of formation of image on the retina. People with myopia have very long eyeball diameter and therefore the image is brought to a focus before the rays reach the retina. It can be corrected with a concave lens. In hyperopia, there is too short an eyeball making the image to focus behind the retina. Correction is with a convex lens. Astigmatism has to do with uneven refraction of light around the 360 circle which is as a result of uneven curvature of the cornea and/or lens.

6.0 TUTOR-MARKED ASSIGNMENT

Explain why a blurred image is produced in each of the following conditions - presbyopia, myopia, hyperopia and astigmatism.

7.0 REFERENCES/FURTHER READINGS

Carola, R. *et al* (1991). *Human Anatomy and Physiology.* New York McGraw Hill.

Gannong, W.F. (1991). *Review of Medical Physiology.* London: Prentice-Hall.

Sherwood, L. (1993). *Human Physiology.* Minneapolis: West Publishing.

Fox, S.I. (1996). *Human Physiology*. Dubuque: Wm C. Brown.

UNIT 2 THE RETINA AND NEURAL PROCESSING OF VISUAL INFORMATION

CONTENTS

1.0 INTRODUCTION

The retina is the inner most of the three layers of the eyeball. It is an egg-shaped, multilayered, light sensitive membrane containing a network of specialized cells.

Two types of photoreceptor cells are present in the retina both of which contain pigment molecules. These molecules undergo dissociation in response to light; called photochemical reactions that will eventually result in the production of action potentials in the optic nerve. The rods and cones provide black and white, and colour vision respectively at different light intensities.

In response to light electrical activity is evoked in ganglion cells of the retina and in neurons of other parts of the neural pathway. The brain interprets visual information in various ways in response to and as a result of the way each neuron type responds to light.

In this unit we shall study the photochemical reactions that take place in the rods and cones and other layers of the retina to generate impulses, as well as the way impulses are channeled and interpreted by the visual components of the nervous system.

2.0 OBJECTIVES

At the end of this unit you should be able to:

- explain the structures involved with photochemical reactions at the retina and the neural processing of visual information
- describe the photoreceptor mechanism in retinal cells (rods and cones)
- describe the electrical activity in retinal cells
- explain visual activity and sensitivity of the retina with reference to the arrangement of the neural pathways for visual information
- describe the neural pathways for visual information
- explain how processing of visual information occurs in ganglion cells
- explain the neural processing of visual information in lateral geniculate bodies and cerebral cortex.

3.0 MAIN CONTENT

3.1 Anatomical Considerations

The Retina

The retina, the inner most layer of the eyeball extends anteriorly almost to the ciliary body and covers the entire posterior aspect of the eyeball. It is organized in several layers and consists of a pigment epithelium, photoreceptor neurons called rods and cones, and layers of other neurons. These other neurons are of four types - bipolar cells, ganglion cells, horizontal cells and amacrine cells.

The first layer of the retina next to the choroid layer is pigment epithelium that prevents reflection from the back of the retina. The pigmented layer along with the choroid prevents reflection back to the retina. The other layers of retina collectively make up the neuroretina which is a thick layer with several layers of cells.

The neuroretina, is actually an extension of the CNS and not a separate peripheral organ. The retinal cells are said to have actually "backed out" of the nervous system during embryonic development. The cells are surprisingly facing backward i.e. the light sensitive ends face the choroid away from incoming light while the neural layers face outward toward incoming light.

The outermost layer of the neural part of the retina contains rods and cones which are the actual photoreceptor cells of the retina. This is followed by the layer of bipolar neurons and then the layer of ganglion cells. The rods and cones synapse with the bipolar cells and bipolar cells synapse with

ganglion cells. Axons of the ganglion cells join together to form the **optic nerve** that leaves the retina. The horizontal cells connect the receptor cells and the amacrine cells connect ganglion cells to one another. All these other cells of the neuroretina form complex neuronal circuitry for the processing of light waves within the retina.

The point on the retina at which the optic nerve leaves and through which blood vessels enter, is the **optic disc.** No visual receptors overlie this area so no image can be detected there. The region is therefore called the **blind spot**.

Light must pass through the neuronal cell layers before reaching the rods and cones on all parts the retina except at the fovea. The fovea is a pin-head sized depression located exactly at the centre of the retina. At this point the cell layers (ganglion and bipolar) are pulled aside so that light directly falls on the photoreceptors. Also only cones, which have greater acuity are found there. This makes the fovea the point of most distinct vision and greatest acuity. Therefore we tend to turn our eyes so that the object we are looking at is focused on the fovea. The area immediately surrounding the fovea is called the macula (lutea which also has a high concentration of cones and fairly high acuity. The other areas of the retina contain rods and cones.

Rods and Cones

The photoreceptors, rods and cones, consist of three parts; an outer segment that lies closest to the choroid detects light stimulus, an inner segment in the middle which contains metabolic apparatus of the cell and a synaptic terminal which lies close to the eye's interior facing the bipolar neurons.

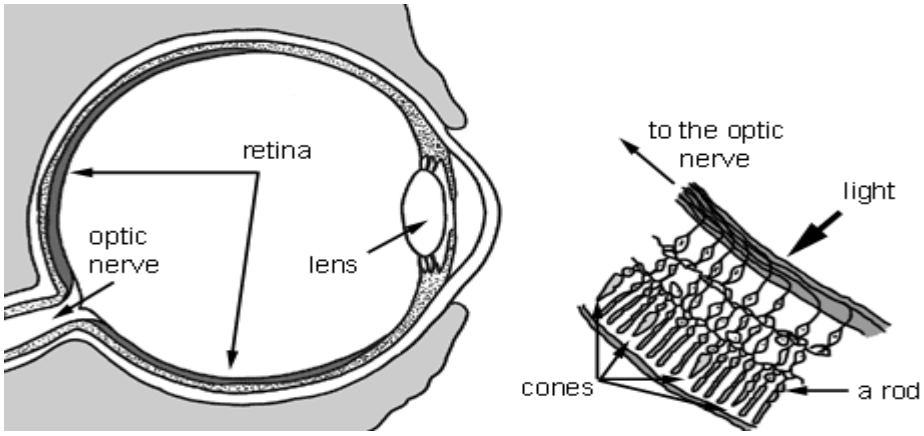


Fig. 11: The Rods and Cones

This transmits the signal generated in the photoreceptors to the next cells in the visual pathway. The outer segment is rod-shaped in rods and cone

shaped in cones, and is composed of stacks of flattened membranous discs containing an abundance of photo pigment molecules. Over a billion of these molecules may be packed into the outer segment of each photo receptor.

The rods are extremely sensitive to light and are the receptors for night vision. The visual apparatus for night vision is not capable of resolving the details and boundaries of objects or determining their colour. The rods have lower visual acuity and this makes it difficult to recognize small objects. The cone system has a rather higher threshold for light (lower sensitivity) but has greater acuity. The system is responsible for vision in bright light and for colour vision. There are therefore two kinds of input from the eye into the nervous system, each one working maximally under different conditions.

3.2 Photoreceptor Mechanism in Retinal Cells

The photopigments undergo chemical reaction, when activated by light. When they absorb light their structures change. A photopigment consists of an enzymatic protein opsin and retinene, a derivative of Vitamin A.

3.2.1 Photochemical Activity in Rods

Each eye contains about 120 million rods which are located in most areas of the retina except the fovea and the blindspot. Rods contain only one photopigment called Rhodopsin - a purple pigment.

In response to absorbed light, rhodopsin dissociates into its two components - opsin and retinene. The reaction is known as the **bleaching reaction.** Retinene has two configurations (isomers) the 11-cis Isomer and the all-trans. The 11-cis form is the one attached to opsin in rhodopsin. The effect of light is to cause dissociation of the rhodopsin by converting the 11-cis isomer to the all-trans isomer. This dissociation initiates changes in the ionic permeability of the rod cell membrane and ultimately results in the production of action potentials. Specifically in the rods and cones hyperpolarization occurs.

Dark Adaptation

The bleaching reaction that occurs in the light results in a lowered amount of rhodopsin in the rods and lowered amounts of visual pigments in the cones. When a light adapted person first enters a darkened room, therefore sensitivity to light is low and vision is poor. A gradual increase in photoreceptor sensitivity called dark adaptation then occurs reaching maximal sensitivity in about 20 minutes. The increased sensitivity is due

partly to increased amounts of visual pigments produced in the dark. Increased pigments in the cones produce a slight dark adaptation in the first five minutes. Increased rhodopsin in the rods produces a much greater increase in sensitivity to low light levels and is even partly responsible for the first adaptation that occurs after five minutes in the dark. In addition to the increased rhodopsin, it is probable that other less well understood, subtle changes occur in the rods that result in a 100,000 - fold increase in light sensitivity in the dark - adapted as compared to light adapted eyes.

3.2.2 Photochemical Activity in Cones

Cones are less sensitive to light but provide colour vision and greater visual acuity. The events of visual excitation are similar in rods and cones. The major difference is that there are three types of cones each with one separate photopigment that responds to red, green and blue light.

Our perception of colour vision depends on the stimulation of only these three types of cones. Each cone contains retinene as in rhodopsin, but there seems to be other proteins associated with retinene other than opsin; or the photopsins of cones are slightly different from the scotopsin of rods. The protein is also different for each of the three cone pigments. As a result each of the pigments absorb light of a given wavelength (colour) to a different degree. The perception of colour depends on which cones are stimulated. The final colour we perceive is produced by the relative degree to which each cone is stimulated by any given wavelength (any colour) of visible light. That is it is determined by the combination of different levels of stimulation of each type of cone. It is the proper mix of the three basic colours of the cone pigments - that produces the perception of white and the absence of all three that produces the perception of black.

Light adaptation can conversely occur as one moves from a dark environment to a lighted one. The eyes at first are very sensitive to the dazzling light. However within five minutes adjustment can take place and this is known as light adaptation. As the bright light rapidly breaks down some photopigments especially the rods, the sensitivity of the eye to the bright light decreases. An explanation therefore is that the rods which are so sensitive to light have their photopigments bleached out, so much that they are actually burned out in bright light, leaving only the slower reacting less sensitive cones.

3.3 Electrical Activity in Retinal Cells

In the retina all the cells including the photoreceptors produce only graded depolarizations and hyperpolarizations analogous to EPSPs and IPSPs with the exception of the ganglion cells and probably the amacrine cells. These ones produce the all or non action potentials. Rods and cones and horizontal cells are all hyperpolarizing. Bipolar cells respond in depolarizing or hyperpolarizing manner. Amacrine cells produce depolarizing generator potentials that may contribute to spikes produced in the ganglion cells.

In the dark Na^+ channels in the photoreceptors are open so that current flows between the inside and the outside of the cell membrane and this is maintained by the Na^+ K^+ pump - with Na^+ moving into the cell and potassium moving out. These sodium channels are kept open in the dark by cyclic GMP that binds to pores in the cell membranae. These cGMP is abundant in the dark. This makes the resting membrane potential to be less negative (a bit depolarized) in the dark.

However when light is absorbed by the outer segments of the rods and cones, some of the Na^+ channels are closed and the result is a hyperpolarizing receptor potential. The hyperpolarization reduces the release of synaptic transmitters, and this generates a signal that will eventually lead to action potentials in the ganglion cells. The hyperpolarization controls the flow of neural information across synapses to other neuronal cells.

A series of steps are involved from the dissociation of a photopigment to opsin and 11-cis retinene through conversion to trans-retinene and so forth till the reduction in cGMP which brings about closure of Na^+ channels. The closure of the Na^+ channels stops the depolarizing Na^+ inward leak and causes membrane hyperpolarization. The hyperpolarization passively spreads to the synaptic terminal of the photoreceptor. Here the potential change leads to a reduction in transmitter release from the synaptic terminal. Thus light (their adequate stimulus) inhibits the photoreceptors while darkness excite them. Put in another way, light causes photoreceptors to become hyperpolarized (inhibition) in comparison to what it was in the dark. This is surprising since ultimately light will have a stimulatory effect on the optic nerve.

The translation of the effect of light on the photoreceptors may be explained this way. The transmitters being released at the synaptic terminals during the dark with photoreceptors in their resting state may be inhibitory on bipolar cells. If the transmitter is inhibitory, their reduction following light induced receptor hyperpolarization decreases the inhibitory action on the bipolar cells. Removal of inhibition actually results in excitation of the bipolar cells. These cells in turn activate the ganglion cells and action potentials will thus be produced in fibres of the optic

nerve.

3.4 Visual Acuity and Sensitivity of the Retina

While focusing visual attention on an object in daylight, each eye is oriented so that the image falls within a tiny area of the retina called the fovea centralis, a small pinheadsized pit. The fovea is within a yellow area of the retina called macula lutea. The pit is formed by the displacement of neural areas around the periphery; therefore light falls directly on photoreceptors at that centre. On the other hand light falling on other areas of the retina must pass through the several neuron cell layers of the retina already described.

There are approximately 120 million rods and 6 million cones in each retina but only about 1.2 million nerve fibres enter the optic nerve of each eye. Each optic nerve is supplied by one ganglion cell. This means that many photoreceptors have to converge on one ganglion cell, through their bipolar cells. This gives an overall convergence ratio of photoreceptors to ganglion cell of 105:1.

However this is not the case for all photoreceptors. The convergence is much lower for cones and higher for rods. On the fovea the ratio is 1:1. The fovea has only cones while the areas peripheral to it have a mixture of both. There are about 4,000 cones in the fovea providing input to about 4,000 ganglion cells, meaning that the ganglion cells in this region have direct lines to the visual field.

Each of these direct line ganglion cells thus receive their input from a very small area of the retina corresponding to the diameter of one cone (about 2 micrometer). Peripheral to the fovea however many rods over larger areas synapse with a single bipolar cell and many bipolar cells converge on a single ganglion cell. A single ganglion cell outside the fovea may therefore receive input from large numbers of rods over an area of up to $1mm^2$ on the retina. Since each cone in the fovea has a private line to a ganglion cell and such ganglion cell covers input from a tiny region of the retina, visual acuity is greatest when light falls on the fovea. On the other hand sensitivity to low light is poorest at the fovea. In dim lights, only rods are activated and vision is best at the corners of the eye when the image falls away from the fovea. Under these conditions, the convergence of large numbers of rods on a single bipolar cell and the convergence of large numbers of bipolar cells on a single ganglion cell increase sensitivity to dim light at the expense of visual acuity. Night vision is therefore less distinct.

The difference in visual sensitivity between cones in the fovea and rods in the periphery can be demonstrated easily. If one goes out on a clear night

and stares hard at a very dim star, the star will disappear. This is because its light falling on the fovea is not bright enough to activate the cones. If he looks lightly off to the side, the star will reappear because the light now falls on the rods.

3.5 Neural Pathways in for Vision

As a result of light refraction by the cornea and lens the right half of the visual field is projected to the left half of the retina of both eyes (temporal half of the left retina and the nasal half of the right retina). The left half of the usual field is projected to the right half of the retina of both eyes. The temporal half of the left retina and the nasal half of the right retina see the same image. Axons from ganglion cells in the left (temporal) half of the left retina pass to the left lateral geniculate body in the thalamus.

Axons from ganglion cells of the nasal half of the right retina cross in the optic chiasma also to synapse in the left lateral geniculate body. The geniculate body therefore receives input from both eyes that relate to the right half of the visual field.

The right lateral geniculate body similarly receives input from both eyes relating to the left half of the visual field. Neurons in both lateral geniculate bodies in turn project to the striate cortex of the occipital lobe in the cerebral cortex. This area is called Broadman Area I79. Neurons in area 17 synapse with those in area 18 and 19.

About 70% to 80% of the axons from the retina pass through this geniculate striate system in the perception of the visual field. 20% to 30% of the fibres from the retina however follow a different part to the superior colliculus of the mid brain (also called the optic tectum). Axons from the superior colliculus activate motor pathways leading to eye and body movements.

Neural pathways that pass from the superior colliculus to motor neurons in the spinal cord help mediate the startle response to the sight of an unexpected intruder. Other nerve fibres from the superior colliculus stimulate extrinsic eye muscles that move the eyes.
The tectal system is also involved in the control of intrinsic muscles of the eye - the iris and ciliary body. The reflex constriction of the pupils when light is shone into one eye is caused by the activation of the parasympathetic neurons by fibres from the superior colliculus. Contraction of the ciliary body during accommodation also involves stimulation of the superior colliculus.

3.6 Processing of Visual Information in Ganglion Cells

Before any visual information reaches the brain, the retinal neuronal layers beyond the rods and cones have affected it somehow by reinforcing selected information and suppressing other information to enhance contrast (between different colours or intensities of light). This means that the neural signals which are generated by the photoreceptors are processed by other retinal cells and stimulate the ganglion cell to produce action potentials. The five different types of cells of the retina interact with one another in definite ways that processing of visual information from photoreceptors begin.

In the direct pathway information passes from the receptors to bipolar cells and to ganglion cells and this is achieved by convergence of signals from many photoreceptors to a ganglion cell except of course for the cones in the fovea. Horizontal and amacrine cells act laterally, connecting adjacent cells and allowing them to modify the signals as they go.

The photoreceptors that converge on a single ganglion cell and influence its activity are said to be the **receptive field** of that ganglion cell. Since each cone on the fovea has a private line to a ganglion cell, the receptive field of that ganglion cell is just the diameter of that cone (2 micrometer). While for the ganglion cells in more peripheral areas of the retina which receive input from hundreds of rods, their receptive field is a larger area of the retina (up to $1mm^2$).

Studies have shown that there are certain points on the receptive field of a ganglion cell where if light falls, it stimulates a large increase in the firing rate of that ganglion cell. Thus a small spot of light on that point may be a more effective stimulus than large areas of light on other points. When this spot of light is moved, only a short distance away from that point of greatest stimulation, (centre of the receptive field) the ganglion cell may respond in an opposite manner (may be inhibited). From this, it was deduced that the receptive field of a ganglion cell is organized into two zones - a small circular zone called the **centre** and a surrounding area around the centre called the **surround**. The centre may be likened to a hole in the doughnut and the surround like the doughnut itself.

Receptive fields may therefore be classified as on-centre or off-centre fields, the ganglion cell that is stimulated with light at the centre of its receptive field may be inhibited by light in the periphery of its field. The responses produced by light in the centre and by light at the periphery of the receptive field are antagonistic. The ganglion cells that are stimulated by light in the centre of their receptive field are said to have **on-centre fields**. (i. on centre, off surround). Those ganglion cells that are inhibited by light in the centre and stimulated by light on the periphery are said to have off-centre fields (i.e. off centre, on surround).
This explains why sometimes a wide illumination has less effect than pin-point illumination. Diffuse illumination may be giving conflicting orders,

illuminating both on and off areas on the receptive field. Because of the antagonism that may exist between the centre and surround, of ganglion cell receptive fields, the activity of each ganglion cell is a result of the interaction among inhibitory and excitatory signals. This is a form of lateral inhibitation that helps to sharpen the colours and contours of images and improve acuity. This is the type of function performed by horizontal and amacrine cells.

3.7 Neural Processing of Visual Information in Lateral Geniculate Bodies and the Cerebral Cortex

The lateral geniculate bodies in the thalamus receive input from ganglion cells of both eyes. The right lateral geniculate body receives input from the right half of each retina (corresponding to the left half of the visual field) and vice versa. Each neuron in the lateral geniculate body however is only activated by input from one eye. Neurons activated by ganglion cells from the left eye are in separate layers from those that are activated by the right eye within the lateral geniculate.

The lateral geniculate bodies have receptive fields much like the ganglion cells. The receptive field of their neurons is the part of the retina that "sees" through its ganglion cell input. They have also been shown to have antagonistic centre and surround like the ganglion cell. This means that when a field is stimulated, the response of the geniculate body is the result of the interaction among inhibitory and excitatory inputs from the photoreceptors through their specific ganglion cells.

Projections of fibres from the lateral geniculate bodies to area 17 of the occipital lobe form the optic radiations. Because the fibre projections give area 17 a striped or striated appearance, this area is known also as the striate cortex. Neurons in area 17 project to area 18 and 19 of the occipital lobe. Cortical neurons in areas 17, 18 and 19 are thus stimulated indirectly by light on the retina.

4.0 CONCLUSION

Electrical activity in ganglion cells of the retina and in neurons of the lateral geniculate nucleus and cerebral cortex is evoked in response to light on the retina. The way in which each neuron type responds to light at a particular point on the retina provides information about the way the brain interpretes visual information.

5.0 SUMMARY

In this unit we learnt that the retina contains photoreceptor neurons called rods and cones and these synapse with bipolar cells and other cell layers till the ganglion cells. Each of the ganglion cells connect to a fibre of the optic nerve. When light strikes on the photoreceptors they dissociate into their components - retinene and opsin. .All the activities of the rods including their distribution on the retina favors vision in the dark or under dim light. The rods therefore provide black and white vision under conditions of low light intensity, At higher light intensity, the rods are bleached out and the cones provide colour vision. There are three types of cones each of which responds to red, green and blue lights - different wavelengths of light. The fovea centralis contain only cones, and more peripheral parts of the retina contain both rods and cones. Each cone on the fovea has a private line to a ganglion cell through a bipolar cell, but in other regions many receptors converge on a bipolar cell and many bipolar cells provide input to a ganglion cell. This impairs visual acuity but improves sensitivity to low lights. The reverse occurs in the cones of the fovea. The right half of the visual field is projected to the left half of the retina. The left half of the left eye and left half of the right eye send fibers to the lateral geniculate bodies of the thalamus. The left lateral geniculate body therefore receives inputs from the left half of both eyes and vice versa. From the lateral geniculate bodies, fibres are sent to the striate cortex of the occipital lobe where meaning is attached to images formed on the retina. Some fibres from the ganglion cells of the retina synapse in the superior colliculus of the midbrain and this aspect controls eye movement both by extraocular and intrinsic eye muscles. The area of the retina that provides input to a ganglion cell is called its receptive field. The receptive field of a ganglion cell is roughly circular with an "on" or "off" centre and an antagonistic surround. Wide illumination that stimulates both centre and surround of a receptive field affects a ganglion cell to a lesser degree than a pin point of light that illuminates either the centre or the surround. Each lateral geniculate body receives input from both eyes but the neurons from each eye are arranged in separate layers in the lateral geniculate. The receptive fields of neurons in the lateral geniculate are circular also having antagonistic centre and surround.

6.0 TUTOR-MARKED ASSIGNMENT

Describe the photochemical reaction in rods and explain how dark adaptation occurs.

7.0 REFERENCES/FURTHER READINGS

Carola, R. *et al* (1991). *Human Anatomy and Physiology.* N.Y. McGraw Hill.

Gannong, W.F. (1991). *Review of Medical Physiology.* London: Prentice-Hall.

Sherwood, L. (1993). *Human Physiology.* Minneapolis: West Publishing.

Fox, S.I. (1996). *Human Physiology.* Dubuque: Win C. Brown.

PHYSIOLOGY

Unit 1 Bones and Osseous Tissue
Unit 2 Muscle Physiology

UNIT 1 BONES AND OSSEOUS TISSUE

CONTENTS

1.0 INTRODUCTION

The skeletal system includes bones of the skeleton and the cartilages, ligaments and other connective tissues that stabilize or connect the bones. Bones are therefore rigid organs that form part of the endoskeleton of vertebrates. There are 206 bones in the adult body and about 300 bones in the foetal body. Bones support the body, work with muscles to maintain body posture and produce controlled precise movements. Without the skeleton to pull against, contracting muscle fibres would not be able to make us sit, walk or run. This unit will discuss the basic characteristics, structure and functions of the bone tissue, as well as discuss in detail the metabolism of calcium and bone physiology.

2.0 OBJECTIVES

At the end of this unit xxii, you will be able to:

- explain the characteristics and functions of bone
- describe the structure of the bone
- describe the various types of bones
- discuss formation/development and growth of bone tissue
- explain the process of bone remodeling
- explain the role of various aspects of bone physiology in maintenance of homeostasis
- discuss the hormonal control of bone physiology
- explain some disease conditions affecting the bone.

3.0 MAIN CONTENT

3.1 Bone Characteristics and Functions

Bone is a special type of connective tissue made up of a collagenous matrix that has been impregnated with minerals especially calcium and phosphorus.

The primary bone tissue - osseous tissue is a relatively lightweight composite material, formed mostly of calcium phosphate in the chemical arrangement called hydroxylapatite. (This is the osseous tissue that gives bones their rigidity).

Bones have relatively high compressive strength but poor tensile strength, meaning that it resists pushing forces well, but not pulling forces. Bone is essentially brittle but it does have a significant degree of elasticity, which is contributed by collagen.

The bone is a living tissue; constantly being resorted and new ones formed; permitting it to respond to the stresses and strains that are put upon it. It is well vascularized with a total blood flow of 200 - 400ml/min in adult humans.

All bones consist of living cells embedded in the mineralized organic matrix that makes up the osseus tissue.

Functions

Bones play several significant functions in the body some of which are:

Shape and Support

The entire skeletal system provides a frame to keep the body supported. Individual bones or groups of bones provide a framework for the attachment of soft tissues and organs.

Protection of Body Organs

Bones serve to protect many internal organs and soft tissues by surrounding them. For example; the skull protects the brain; the ribcage protects the heart and lungs; the vertebrae protect the spinal cord and the pelvis protects the delicate reproductive organs.

Storage of Minerals and Lipids

Bones serve as reserves of minerals most notably calcium and phosphorus. Calcium is the most abundant mineral in the body and 99% of calcium are in the skeleton. The calcium salts of bones are a valuable reserve that maintain the normal concentration of calcium ions and phosphates in body fluids.

Bones of the skeleton also store energy reserves as lipids in areas filled with yellow marrow.

Production of Blood Cells

Red blood cells, white blood cells and other blood elements are produced in the red marrow which fills the internal cavities of many bones in a process known as haematopoiesis.

Leverage and Movement

Many bones function as levers and can change the magnitude and direction of forces generated by muscles. Bones, skeletal muscles, tendons, ligaments and joints function together to generate and transfer forces so that individual parts of the whole body can be manipulated in three dimensional space.

Other functions include:

Acid-Base Balance

Bones buffer the blood against excessive pH changes by absorbing and releasing alkaline salts.

Detoxification

Bone tissues can also store heavy metals and other foreign elements, removing them from the blood and reducing their effects on other tissues. These can later be gradually released for excretion.

Sound Transduction

Bones are important in the mechanical transmission of sounds for hearing.

3.2 Bone Structure

Bone is not a uniformly solid material. Each bone contains two forms of tissue: Compact (dense) bone and spongy or trabecular bone.

Compact Bone is the hard outer layer of compact bone tissue, so called due to its minimal gaps and spaces. It is much denser and less metabolically active. This tissue is what gives bones their smooth, white and solid appearance. It accounts for 75 - 80% of the total bone mass though it can vary with the shape of the bone. Compact bone is thickest where stresses arrive from a limited range of directions. Nutrients are provided to the compact bone through Haversian canals which contain blood vessels. Collagen of compact bones is arranged in concentric layers forming cylinders called osseous or Haversian systems.

Trabecular Bone forms the inner layer of open cell porous network also called spongy or chancellor's bone. It is composed of a network of rod and plate-like elements that make the overall organ lighter, allowing room for blood vessels and marrow. Spongy bone is located where bones are not heavily stressed or where stresses arrive from many different directions.

Trabecular bone accounts for the remaining 20 - 25% of total bone mass, but has nearly ten times the surface area of compact bone. Nutrients diffuse from bone ECF into the trabeculae.

Bone is composed of tough organic matrix greatly strengthened by calcium salts. Average compact bone contains by weight, approximately 30% matrix and 70% salts. The organic matrix of bone is 90 - 95% collagen fibres. The rest is ground substance which is composed of extracellular fluid plus proteoglycans like chondroitin,

glycosaminoglycans, hyaluronic acid etc. The collagen fibres are mostly type I in tendons and skin.

Macroscopically, a typical (long) bone consists of the following structures visible to the naked eye; diaphysis, epiphyses, articular cartilage, periosteum, medullary cavity (marrow) and endosteum.

The diaphysis is the main shaft like portion. It consists of a hollow cylinderical cavity of compact bone tissue with marrow (medullary cavity). This composition adapts the diaphysis well for its function of providing strong support without cumbersome weight. The Epiphysis located at the extremities of long bones, is roughly spherical (bulbous) in shape. It is composed of spongy or cancellous bone and only a thin outer layer of dense compact bone. Marrow fills the spaces of cancellous bone - which can be yellow marrow in most adults, but red marrow in the proximal epiphysis of the humerus and femur. Separating these two main sections at either end of the bone is the metaphysis. It is made up of the epiphyseal (growth) plate.

The growth plate is a thick plate of hyaline cartilage. The epiphyseal plates and metaphysis are the only places where long bones continue to grow in length after birth.

Articular cartilage is a thin layer of hyaline cartilage that covers articular or joint surfaces of epiphyses. This material cushions jars and blows by its resiliency.

Covering the outer surface of a bone (except at joint surfaces) is the periosteum, a fibrous dense white membrane that has the potential to form bone during growth periods and in fractures healing. The periosteum contains nerves, lymphatic vessels and many capillaries that provide nutrients to the bone and give the pink colour to living bones. Its blood vessels send branches into the bone, therefore the periosteum, is essential for the nutrition and therefore survival of the bone cells.

The medullary cavity is a hollow tube-like cavity that runs through the length of the diaphysis. It contains yellow marrow (fatty marrow). Lining the medullary cavity of compact bone tissue, and covering the trabeculae of spongy bone tissue is the endosteum - the membrane that lines the internal cavity of bones.

3.3 Bone Cells

There are several types of cells that make up the bone and these are capable of changing their roles as the needs of the body change.

1. Osterogenic Cells

These are found mostly in deep layers of the periosteum and in bone marrow. These cells are capable of being transformed into borne-forming cells or bone destroying cells during times of stress and healing.

2. Osteoblasts

These are mononucleate bone-forming cells which descend from osteoprogenitor cells. They synthesize a protein (an unmineralized ground substance) called osteoids which mineralizes to become bone. Osteoid is composed of type I collagen. Osteoblasts act to move calcium and phosphates into and out of bone tissue thereby calcifying or decalcifying them. Osteoblasts also manufacture hormones like prostaglandins, to act on the bone itself. They also produce alkaline phosphates, an enzyme that plays a role in the mineralization of bones as well as many matrix. Osteoblasts are the immature bone cells.

3. Osteocytes

These are the main cells of the fully developed bones. They are surrounded by calcified matrix and take on the shape of their individual lacunae within the matrix Osteocytes originate from osteoblasts which have migrated into and become trapped and surrounded by bone matrix which they themselves produce. The spaces which they occupy are known as lacunae. Osteocytes have many processes which reach out to meet other osteoblasts and osteocytes. The function of osteocytes include the following, to varying degrees; formation of bone, matrix maintenance and calcium homeostasis. They help in the release of calcium from bone tissue into the blood thereby regulating the concentration of calcium in body fluids.

4. Osteoclasts

These are large, multinucleated cells located on bone surfaces in what are called resorption pits. These resorption pits are left behind after the breakdown of bone and often present as scalloped surfaces on the bone. Osteoclasts are derived for haematopoietic stem-cells via monocytes. Therefore they can phagocytose bone, digesting it in their cytoplasm just like circulating macrophages can engulf and phagocytose invading organisms.

5. Bone Lining Cells

These are essentially inactive osteoblasts i.e. those that cease their physiological activity and flatten out on the bone surface. Some of their functions include serving as barrier for movement of calcium and phosphates into and out of the bone matrix. They may also serve as osteogenic cells that can divide and differentiate into osteoblasts.

3.4 Types of Bones

The types of bones include: long, short, flat, irregular and sesamoid bones.
Long Bones are characterized by a shaft, (the diaphysis) that is much greater in length than width. They are composed mostly of compact bone and lesser amounts of marrow, which is located within the medullary cavity and spongy bone. Most bones of the limbs, including those of the fingers and toes are long bones except those of the wrist, ankle and knee cap.

Short Bones are roughly cube-shaped and have only a thin layer of compact bone surrounding a spongy interior. The bones of the wrist and ankle are short bones, and the sesamoid bones.

Flat Bones are thin and generally curved, with two parallel layers of compact bones sandwiching a layer of spongy bone. Most of the bones of the skull are flat bones as well as the sternum.

Irregular Bones do not fit into any of the above categories. They consist of thin layers of compact bone surrounding a spongy interior. Their shapes are irregular and complicated. The bones of the spine and hips are irregular bones.

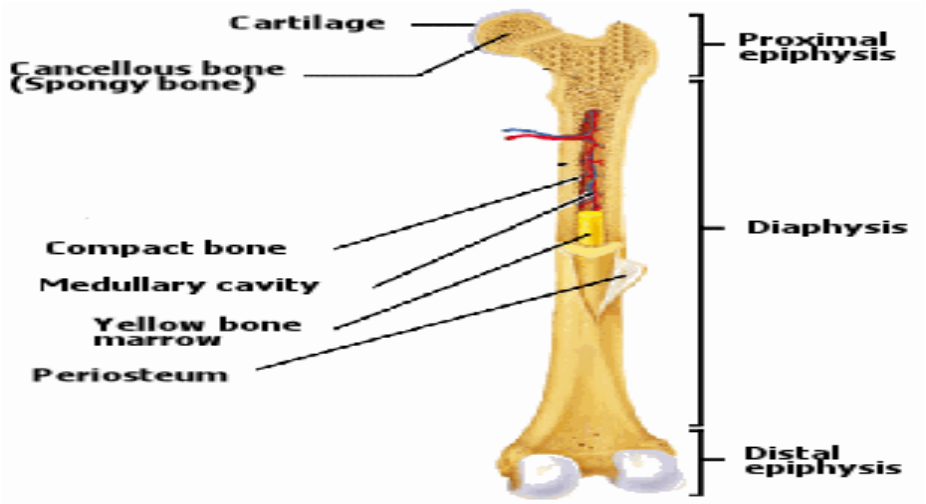


Fig. 12: Diagram of a Long Bone
Sesamoid Bones are bones embedded in tendons. They act to hold the

tendon further away from the joint. Examples of sesamoid bones are the patella and the pisiform.

3.5 Bone Development and Growth

The growth of the skeleton determines the size and proportion of the body. Bones begin to form in a mother's womb about six weeks following fertilization and portions of the skeleton continue to grow till about the age of 25. Most bones originate as hyaline cartilage or some fibrous membrane structure shaped like bones. The cartilage or membrane is gradually converted to bone through a process of ossification or osteogenesis.

Bones develop in the embryo (during foetal development) by two processes: intramembranous ossification and endochondral ossification. In both cases bones are formed from pre-existing connective tissue skeleton. Note that bone is the same no matter how it develops.

3.5.1 Intramembranous Ossification

This occurs where bone tissue develops directly from mesenchymal tissue. For example the flat bones of the skull and face, including those lining the oral and nasal cavities and part of the clavicle are formed this way. It occurs in the following steps.

1. Development of ossification centre
2. Calcification
3. Formation of trabeculae
4. Development of periosteum

From the time of initial bone development, intramembranous ossification spreads rapidly from its centre until large areas of the skull are covered with protecting and supporting bone.

Bone tissue development begins when thin strands that will eventually become branching trabelucae appear in the matrix. At about the same time, the mesenchymal cells become larger and more numerous and their processes thicken and connect with other embryonic connective tissue cells forming a ring of cells around a blood vessel. The site of this ring formation is a centre of ossification. It begins about the second month of prenatal life.

The messenchymal cells differentiate into osteoid secreting osteoblasts which begin to cause calcium salt deposits that form the spongy bone matrix. (From the spongy matrix the trabeculae of cancellous bone will later form).

As the process of calcification continues, some osteoblasts become trapped inside lacunae of the developing matrix and lose their ability to form bone tissue. These are now called osteocytes. As bone forming osteoblasts change into osteocytes, they are replaced by new osteoblasts which develop from the osteogenic cells in the surrounding connective tissue. This way bones continue to grow.

At the same time that osteoblasts are synthesizing and mineralizing the matrix, osteoclasts play a role in bone resorption by removing small areas of bone from the wall of the lacunae.

The trabeculae continue to thicken into the dense network that is typical of cancellous bone tissue. The collagenous fibrils deposited on the trabeculae crowd blood vessels which eventually condense into blood forming marrow.

The osteoblasts on the surface of the spongy bone tissue then form the Periosteum - the membrane covering the outer surface of the bone. The Periosteum is made up of an inner osteogenic layer (with osteoblasts) and a thick fibrous outer layer. The inner layer eventually creates a protective layer of compact bone tissue over the cancellous tissue interior. When this intramembranous ossification has stopped, the osteogenic layer becomes inactive at least temporarily. It becomes active again when necessary for example, to repair a bone fracture.

3.5.2 Endochondral Ossification

This is the kind of bone tissue development that occurs by the replacement of hyaline cartilage. Here the initial model is made of hyaline cartilage and it then becomes eroded. Endochodral ossification produces long bones and all other bones not formed by intramembranous ossification. It must be noted that cartilage is not converted into bone but rather the cartilage model is completely destroyed and replaced by newly formed bone.

Endochondral ossification is a slower process that begins with points in the cartilage called the "primary ossification centres" which appear during fetel development. It continues after birth through the occurrence of the secondary ossification centre still the period of skeletal maturity (18 - 25 years of age).

About 6 to 8 weeks after fertilization, mesenchymal cells multiply rapidly and bunch together in a dense central core of precartilage tissue that eventually forms the cartilage model. This is followed by the appearance of the primitive perichondrium that covers the surface of the cartilage. The cartilage model is then invaded by capillaries which trigger the

transformation of the perichondrium into (bone producing periosteum the fibrous membrane that covers bones).

An intramembranous ossification occurs in the periosteum forming a hollow cylinder of trabecular bone called bone collar around the cartilage of the diaphysis.

By the second to third month of prenatal life the primary centre of ossification is formed around the middle of what will become the diaphysis Bone cells develop rapidly in the diaphyseal area and blood vessels develop in the periosteum and branch into the diaphysis. The diaphysis now has a layer of bone tissue just under the periosteum and an increasing amount of marrow in the centre of the shaft. The ends still consist of cartilage.

After birth the chondrocytes (cartilage cells) in the epiphysis begin the process of dying as in the diaphysis. Blood vessels and osteogenic cells from the periosteum enter the epiphyses where they develop into osteoblasts. The centres of this activity in the epiphyses are called the secondary centres of ossification.

Some cartilage remains on the outer, joint edge of each epiphysis to form the articular cartilage for the smooth operation of the joint. Also a layer of cartilage known as the epiphyseal cartilage or epiphyseal plate remains between each epiphysis and the diaphysis until bone growth in length is complete. The growth of bone length occurs in small spaces in the epiphyseal plate. During growth cartilage cells proliferate and cause thickening of the layer. Osteoblasts then synthesize organic bone matrix and this undergoes calcification, as a result the bone grows longer. This continues till sometime between adolescence and early twenties depending on which bone.

As growth in length slows down, the distal epiphyseal plate disappears first leading to fusion or closure of the epiphysis. The proximal plate disappears a bit later. As growth in length ends the epiphyseal cartilage is completely replaced by osseus tissue.

3.6 Remodeling of Bones

No new growth in bone length continues after age 25,however the diameter of bones may continue to increase throughout most of our lives. Through intramembranous ossification, osteogenic cells in the periosteum deposit new bone tissue beneath the periosteum while most of the old bone tissue erodes away. The combination of cell deposition and erosion widens the bone without thickening its walls. The width of the marrow cavity may increase too.

Bones can thicken or become denser to keep up with any physical changes in the body that may increase stress or load on the bones. For example, in athletes who greatly increase their muscles, the bones can also be strengthened at the same time. If not, the increased pull of the stronger muscles may have to fracture them. The same thing can happen in people who are overweight with resultant increase in the load on their skeleton. On the other hand, inactivity will lead to decalcification - loss of minerals and resultant weakening in a bone. For example a leg that is put in a cast for a month thins out. This is because the muscles of the leg have atrophied and the bones have decalcified by about 30%.

Remodeling of bones (that process of resorption followed by replacement of bone with little or no change in shape) is a local process that is carried out in small areas sometimes called remodeling units. The cycle takes about 100 days and up to 20% of the adult skeleton is remodeled each year. There are about 2 million remodeling units that are active at any one time in the human skeleton. The remodeling is related in part to the stresses and strains imposed on the skeleton by gravity (as already discussed). This is regulated by hormones in the systemic circulation and by growth factors, most of which act locally. Prostaglandins seem to play a part. Infact steoblasts and osteoclasts coupled together via paracrine cell signalling is what is called remodeling units.

The overall purpose of remodeling is to regulate calcium metabolism, repair micro-damaged bone (from daily stress) and also to shape and sculpture the skeleton during growth.

3.7 Homeostasis and the Physiological Functions of Bones

The bone performs many physiological functions which though may not be apparent but they help in maintenance of homeostasis in the body. Some of these functions which are not obvious include the production of blood cells, maintenance of calcium, phosphate and magnesium salts balance in the body and so for the highlight.

Calcium Storage and Release

The functions of calcium are numerous in the body. In the first place bones consist mainly of calcium, so without calcium, there would be no bones. Calcium also plays important roles in many chemical and electrical activities in the body. Without calcium, some enzymes could not function, cells would come apart, the permeability of cell membranes would be affected, muscles (including the heart) could not contract, nerve functions would be hampered and blood would not cloth and so forth.
When the diet does not provide enough calcium the bones release it and if

there is too much calcium, in the body, the bones store it. In order to maintain homeostasis bones help regulate the amount and consistency of extracellular fluid by either adding calcium to it or by taking calcium out of it. Small decreases of calcium in extracellular fluid and plasma can cause the nervous system to become more excitable because of increased neuronal membrane permeability with resultant muscular spasms (tetany). On the other hand, too much calcium (hypercalcaemia) in body fluids depress the nervous system.

Phosphate Storage and Release

Bones also help to regulate the amount of phosphates in the body. Under hormonal control bones can release phosphate salts when needed by the body. Though changing the level of phosphate in the extracellular fluid or blood does not have immediate significant effects on the body, the proper amount, of phosphate is vital to the body's acid-base balance.

Production of Blood cells

The marrow within bones contribute to homeostasis by manufacturing some blood cells. The adult red bone marrow is the main blood-making tissue of the body. It produces all the red blood cells, platelets, and some white blood cells (e.g. granular leukocytes and immature lympocytes and monocytes). All the bone marrow at birth is red marrow. By adolescence, most of it is replaced by yellow fat cells which form the yellow marrow. In the adult, red marrow is found only in the proximal epiphyses of bones such as the femur and humerus, in some short bones and in the vertebrae, sternum, ribs and cranium. The continued production of red blood cells is very important because the cells live only for about 120 days and need to be replaced as they die. About 2.5 million red cells are produced per second and 200 billion daily.

In addition, some of the macrophages and white blood cells from the red marrow help to protect the body from disease.

3.8 Hormonal Control of Calcium and Bone Physiology

Several hormones have a direct effect on bones, and bones also have an effect on hormone secretion. (See relevant sections of the endocrine system).

Several hormones and vitamins are important in bone maturation and in the regulation of calcium in the body.

1. Parathyroid hormone (PTH) acts directly on bones to increase bone reabsorption and mobilize Ca^{++} leading to increase in plasma

calcium levels. It also depresses plasma phosphate and increases the excretion of phosphate in the urine. The latter is as a result of a decrease in reabsorption of phosphates in the proximal tubules. PTH also increases the reabsorption of calcium in the distal tubules. PTH increases Ca^{++} reabsorption from the intestine but this action is due to the fact that it stimulates the formation of 1, 25 - dihydroxy-cholecalciferol, the active metabolite of vitamin D.

The secretion of PTH appears to be stimulated by low calcium levels in the blood. Its secretion raises blood calcium levels by the actions enumerated above. When levels of calcium rise sufficiently to normal, in the ECF and plasma, the secretion of PTH is inhibited by a negative feedback loop.

2. 1, 25 - dihydroxycholecalciferol the physiologically active form of vitamin D^3 dictates the formation of a calcium - binding protein. It also increases the pumping of Ca++ out of the bsolateral membranes of intestinal epithelial cells. It facilitates the reabsorption of Ca++ in the kidney. It also acts on bone where it mobilizes Ca++ and Po_4^{3-} probably by an initial action to release osteoblast factors that activate osteoclasts and subsequently by increasing the number of osteoclasts. All these are aimed towards increasing the level of Ca++ in plasma, and ECF.

3. Calcitonin is a hormone secreted by the thyroid gland whose action balances the action of parathyroid hormone. Calcitonin receptors are found in bones and the kidney. Calcitonin lowers the circulating calcium and phosphorus levels. It exerts its calcium lowering effect by directly inhibiting bone resorption. It inhibits the activity of osteoclasts. It also increase Ca++ excretion in the urine.

4. Other hormones include growth hormone, thyroxin adrenal cortical hormones, plus vitamins A and D. These are important in bone maturation. Growth hormones and thyroxine stimulate the endochondral ossification process. Growth hormone increases intestinal absorption of calcium, thyroxine causes hypercalcaemia. Both male and female sex hormones (from the gonads) regulate growth rates by controlling the appearance of centres of ossification and the rate of bone maturation. Oestrogens prevent osteoporosis probably by direct effect on osteoblasts. Insulin increases bone formation and there is significant bone loss in untreated diabetes. Glucocorticoids lower plasma Ca^{2+} levels by inhibiting osteoclast formation and activity. Over long periods, they cause osteopeorosis by decreasing bone formation and increasing bone resorption. They decrease bone formation by inhibiting cellular replication and protein synthesis in bone and

they inhibit the function of osteoblasts. They also decrease the absorption of Ca^{2+} and Po_4^{3-} from the intestine by an anti - vitamin D action.

3.9 Bone Diseases

The diseases that affect the bone occur as a result of the interplay of factors that maintain normal bone function.

Osteogenesis Imperfecta (brittle bone disease) is an inherited condition in which the bones are abnormally brittle and subject to fractures. The basic cause of this disorder is a decrease in the activity of osteoblasts during bone formation (osteogenesis). In some cases the fractures occur during prenatal life and so the child is born with deformities. In order cases the fractures occur as the child begins to walk.

Osteomalacia and **Rickets** are skeletal defects caused by a deficiency of vitamin D which leads to a widening of the epiphyseal growth plates, an increased number of cartilage cells, a decrease in linear growth etc.

Rickets is the childhood form of the disease. Skeletal deformities manifest as bowed legs; knock knees and bulging forehead. Leg deformities occur if the child is old enough to attempt to walk, resulting in excessive pressure being put upon the soft legs.

Osteomalacia (adult rickets) leads to demineralization and an excessive loss of calcium and phosphorus. Although the skeletal deformities of rickets may be permanent, the similar skeletal abnormalities of osteomalacia may disappear with proper treatment with large doses of vitamin D.

In Osteoporosis, both matrix and mineral are cost from the bone, and there is a loss of bone mass and strength, with an increased incidence of fractures. This disease is almost an opposite of osteopetrosis in that it is characterized over time by a net excess of bone resorption over bone formation. It has multiple causes but is associated mostly with advancing age and the menopause. The WHO defines osteoporosis in women as a bone mineral density (BMD) 2.5 standard deviations in below peak bone mass (20 year - old sex - matched healthy person average).

Osteopetrosis is a rare and severe disease in which the osteoclasts are defective and are unable to resorb bone in their usual fashion. The result is a steady increase in bone density. Neurologic defects occur due to narrowing and distortion of foramina through which nerves normally pass Haematologic defects occur due to crowding out of the marrow cavities.

4.0 CONCLUSION

The bones of the body function to move, support and protect the various delicate organs of the body, produce red and white blood cells and store minerals. Bones come in a variety of shapes and have complex internal and external structures they are hard and strong, but surprisingly they are lightweight. This unique combination of characteristics gives the bone high compressive strength and a somewhat significant degree of elasticity.

5.0 SUMMARY

1. Bones are rigid organs that form part of the endoskeleton in vertebrates; that serve the function of moving, supporting and protecting body organs as well as production of blood cells and storage of minerals.

2. Each individual bone is not uniformly solid but the tissue is made up of a hard outer layer called compact bone and a spongy inner layer called trabecular or spongy or cancellous bone. Macroscopically a long bone consists of the following structures - diaphysis epiphysis, articular cartilage, periosteum, medullary and an endosteum.

3. There are several types of cells constituting the above such as osteoblasts, osteoclasts, osteogenic cells, bone lining cells etc.

4. The various types of bones are long bones, short bones, flat bones, irregular and sesamoid bones.

5. Bone formation begin during intrauterine life and occurs by two processes - intramembranous and endochondral ossification. Intramembranous ossification occurs in places where the basic skeletal model is membranous while endochondral ossification occurs where the model is cartilage. Ossification accounts for linear growth in bows.

6. Bone remodeling or bone turnover is the process of resorption followed by replacement of bone with little change in shape that occurs throughout life. Its purpose is repair and regulation of calcium homeostasis. Bone can also grow in diameter through this turnover.

7. The various physiological functions of bone helps to maintain homeostasis in the body for example calcium and phosphate balance.

8. Three hormones - PTH, 1, 25, dihydroxycholecalciferol and calcitonin are mostly responsible for the control of bone physiology. Some of the diseases that affect the bone are osteogenesis imperfecta, osteoporosis osteomalacia and rickets.

6.0 TUTOR-MARKED ASSIGNMENT

List the various types of bone cells and explain their functions.

7.0 REFERENCES/FURTHER READINGS

More current edition of:

Gannong's Review of Medical Physiology.

Guyton's Textbook of Medical Physiology.

htt/p://en.eikipedia.org/wiki/bone.

www.clevelandclinic.org/health/health info. NY: Mcgraw Hill. 8th May, 2008.

Carola, R. *et al* (1991) *Human Anatomy and Rhysiology.* NY: McGraw Hill.

UNIT 2 PHYSIOLOGY OF MUSCULAR TISSUES

CONTENTS

1.0 INTRODUCTION

The muscle tissue is the driving force or power behind movement. The muscle tissue has properties that are intrinsic to it and each of these has to do with some movement. One of these properties is its contractility. Work is done each time a muscle contracts. For example food is moved along the digestive tract by a series of rhythmic waves of smooth muscle contraction. Contractions of skeletal muscles make the lower limbs to move at the ankle, knee and hip. Muscular contractions help to maintain body posture in sitting and standing positions. Therefore the general function of the muscle tissue is movement, posture and heat production.
In this unit we shall look at the functions of specific muscle tissues in relation to their specific type, structure and characteristics.

2.0 OBJECTIVES

At the end of this unit, you should be able to:

- identify the important physiological properties, general functions and types of muscle tissue
- describe the structure and organization of skeletal muscle tissue
- explain the various types of muscle contraction
- discuss the nervous control of muscle contraction
- describe the mechanism of muscle contraction
- explain the regulation of muscle contraction
- explain the control of muscle contraction by lower and upper motor neurons
- explain the energy requirement and metabolism of skeletal muscles.
- describe the features of smooth muscles
- describe the features of cardiac muscles.

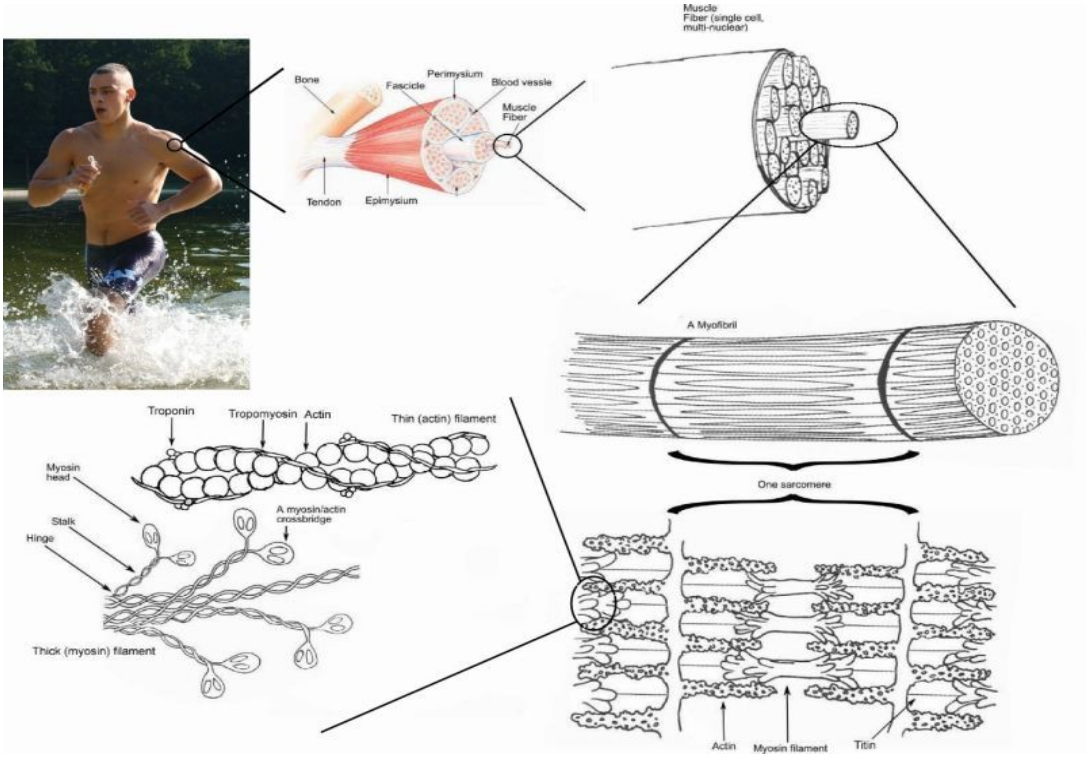
3.0 MAIN CONTENT

3.1 Structure of Skeletal Muscles

Skeletal muscle tissue acquires its name because most of the muscles involved are attached to the skeleton and they make the skeleton to move. Skeletal muscle is composed of individual specialized cells called muscle fibres that are the "building blocks" of the muscular system just as neurons are the building blocks of the nervous system. The muscle cells are called fibres because they have long cylindrical shape and several nuclei. Muscle fibers average 3.0cm in length with some measuring more than 30cm and some being as short as 0.1cm. Diameters range from 0.01cm to 0.001cm. Most skeletal muscles begin and end in tendons, and the muscle fibers are arranged in parallel between the tendinous ends. The fibrous connective tissue proteins within the tendons continue in an irregular arrangement around the muscle to form a sheath known as the epimysium. Connective tissue from this outer sheath extends into the body of the muscle subdividing it into columns called fascicles (these are the strings in stringy meat). Each of these fascicles is surrounded by its own connective tissue sheath known perimysium. Further extensions of the connective tissue inwards that surround each muscle fibre separating it from other fibers are called endomysium.

Dissection of a fascicle under microscope reveals that it is in turn is composed of many muscle fibres, each muscle fibre is surrounded by a cell membrane or sarcolemma. These fibers are actually the muscle cells.

Fig. 13: The skeletal muscle



The fibre contains several nuclei and a specialized type of cytoplasm called sarcoplasm. Within the sarcoplasm are many mitochondria and a number of individual threadlike fibres known as myofibrils.

The myofibrils are made of many thick and thin threads called myofilaments. Thick myofilaments are composed of a fairly large protein called myosin. The thin myofilaments are composed mainly of smaller protein, actin, and they also contain the proteins troponin and tropomyosin.

The contractile mechanism in skeletal muscles is dependent on these proteins. Despite their (unusual) shape, muscle cells all have the same organelles. The most distinct feature of the microscopic appearance of skeletal muscle fibres is their striated appearance. The striations are produced by alternating dark and light bands which appear to cross the width of the fibre. An overlapping of the thick myosin strands and the thin actin strands produces the dark a band; the thin actin strands alone act as the light I band.

Cutting across each I-band is a dark Z line and within the A band is a somewhat lighter H^-. Zone consisting of thick myosin strands only. Extending across the H - zone is a delicate M-line which connects adjacent thick filaments. The fundamental unit of muscle contraction is the sarcomere which is made of the muscle fibre that extends from one Z-line to the next Z-line.
Skeletal muscles are also called striated muscle, because of this

appearance of alternating light and dark strips. They are also described as voluntary muscle because we can contract them when we want to. However skeletal muscles are also capable of contracting without conscious control (involuntarily). Muscles are usually in a partial contracted state which gives them tonus or more commonly "muscle tone". Tonus is necessary to keep a muscle ready to react to the stimulus preceeding a complete contraction or to hold parts of the body such as the head erect and to aid in venous return to the heart.

3.2 Types of Muscle Contraction

Several types of muscle contraction have been identified including twitch, isotonic, isometric, treppe and tetanic contractions.

Twitch

This is a momentary spasmodic contraction of a muscle in response to a single stimulus (such as an electric current or a direct stimulation of a motor unit). It is the simplest type of recordable muscle contraction. Increasing the stimulus voltage increases the strength of a twitch up to a maximum. The strength of a muscle contraction can thus be graded or varied. If a second electrical shock is delivered immediately after the first it will produce a second twitch that may partiality add on the first. This is called summation of contractions.

Treppe

When a rested muscle receives repeated stimuli over a prolonged period, the first few contractions increase in strength (by summation). The recording on a myogram will look like an upward stair case. After several contractions a steady tension for contraction is reached and the contractions level. It stimuli and contractions continue, fatigue occurs. If controlled properly, however, as when athletes "warm up" treppe contractions increase blood flow to a muscle and prepare it for a maximum output of strength when it is needed. Treppe is believed to be due to an increase in calcium ions that bind to troponinc.

Isotononic and Isometric Contractions

When a muscle contracts by becoming shorter and thicker, the contraction is called isotonic because the amount of force or tension remains constant as movement takes place. For example on pulling open a door, the arm muscle contracts and moves the arm which moves the door. In contrast, if the load on a muscle (opposing forces gravitational pull an object) is greater than the tension developed by a muscle, the muscle retains its original length, and the contraction is isometric. That is, a typical

contraction and shortening does not occur even though energy is used. For example holding a door open involves an isometric contraction since the arm muscle does not shorten but does become more tense without producing any movement. Another example - running produces noticeable isotonic contractions (active work) and standing produces isometric contractions. Most body movements involve both isotonic and isometric contractions.

Tetanic Contractions

If a muscle receives repeated stimuli at a rapid rate, it cannot relax completely between contractions. The tension achieved under such conditions is greater than the tension of a single twitch and is called summation of twitches. A more or less contraction of the muscle is called tetanic contractions or tetanus. When incomplete relaxations are evident between contractions the state is called incomplete tetanus. Complete tetanus occurs when the muscle is in a steady state of contraction with no relaxation at all between stimuli.

3.3 Nervous Control of Muscle Contractions

Muscle fibres usually contract in groups. Skeletal muscles are packed together into fascicles having an average of about 150 fibers. The fibers within each fascicle are controlled by a single motor neuron. One motor neuron may stimulate so many fibres, up to 1600 in the powerful leg muscles. The cell body of a somatic motor neuron is located in the ventral horn of the gray matter in the spinal cord and gives rise to a single axon that emerges in the ventral root of a spinal nerve. Each axon can however produce a number of collateral branches to innervate a number of muscle fibres. This is why one motor neuron can stimulate many fibres (as much as 1600 in the leg muscles). Each motor neuron together with all the muscles fibres it innervates is known as a motor unit.

3.3.1 The Neuromuscular Junction

The site where a motor nerve ending contacts a muscle fibre is called a neuromuscular junction or myoneural junction. The axon terminals of motor neurons gain access to the muscle fibre through the endomysium. At the point of contact between the muscle fibre and the motor neuron, the muscle fibre membrane forms a motor end plate. The motor end plate is the specialized portion of the sarcolemma of a muscle fibre, that surrounds the terminal end of the axon.
At the motor end plate, nerve endings are separated from the muscle fibre by a tiny gap called synaptic cleft. The chemical transmitter acetylcholine (ACH) is released from the synaptic vesicles of nerve endings. It bridges

the synaptic cleft and flows into folds of the sarcolemma. Some ACH then become attached to the receptor sites in the sarcolemma, initiating an electro-chemical impulse across the sarcolemma of the muscle cell, so that sodium ions move into the sarcoplasm and potassium ions move out. This results in depolarization across the membrane and beginning of a muscular contraction. This depolarizing potential is called end plate potential. The impulse is transmitted successively through the cell membrane to the sarcoplasmic reticulum where it triggers the release of calcium ions which stimulate the muscle to contract.

Acetylcholinesterase, and enzyme of the muscle fibre membranes, then breaks down acetylcholine into acetate and choline and the depolarization ceases, and the muscle fibre relaxes.

3.3.2 The All-Or-None Principle

Whenever a somatic motor neuron is activated by a sufficiently strong stimulus, all the muscle fibres it innervates (in a motor unit) are stimulated to contract fully. If the contraction is subthreshold however, the fibres will not contract at all. This tendency to contract fully or not at all is called the all-or-non principle. A stimulus of above threshold intensity however will not cause the intensity of the contraction to increase.

Although individual muscle fibres follow the all-or-none principle, whole muscles usually have graded contractions. Involves for these graded contractions. In order for these graded contractions to be smooth and sustained different motor units must be activated. The strength of a muscle contraction depends on how many fibres are stimulated; the frequency of stimulation and how many motor units are activated.

These processes of neuronal control of muscle contractions involve summation, i.e. varying numbers or frequencies of muscle contraction adding up to the force of contractions. Fine neural control over the strength of muscle contraction is optimal when there are many small motor units involved. For example in the extraocular muscles the innervating ratio (neuron to muscle fibre) of an average motor unit is one neuron per 23 fibres. This makes for fine degree of control. The innervation ratio of large muscles like the gastrocnemius is an average of 1 neuron per thousand fibres. Such stimulation results in more powerful contractions at the expense of finer gradations in contraction strength. If a small job is to be done a few motor units will be involved at the same time. Motor units do not all have the same threshold. If for example motor units with low threshold are stimulated a smaller number of motor units will contract. Higher intensities of stimulation lead to the activation of more motor units. This increase in the number of motor units activated is called recruitment of motor units.

Two different methods of summation are employed in gradations of muscle contraction. In multiple motor unit summation, gradations of contraction between minimal and maximal is achieved by varying the number of units contracting. In wave summation, it is achieved by having each motor unit contracting in quick succession that can be so close together that the new ones add to the force of the new ones add the older ones thereby increasing the overall strength of contractions.

3.3.3 Refractory Period

A skeletal muscle loses its irritability and cannot contract again for about 0.005 seconds. This period is called the refractory period. In cardiac muscles it lasts about 0.3 second. There is the absolute refractory period (from the threshold stimulus, till repolarization is one third complete) and the relative refractory period (from end of the absolute period to the start of a new depolarization). The absolute refractory period is a period during which no stimulus, no matter how long or strong will cause a muscle fibre to be stimulated. In the relative refractory period, stronger-than-normal stimuli are needed to stimulate a muscle fibre.

3.4 Mechanism of Muscle Contraction

Sliding filament theory of muscle contraction. The arrangement of the myosin and actin molecules in the myofilaments is crucial to the mechanism of muscular contraction. An actin myofilament in the muscle is made up of actin, tropomyosin and troponin (troponin in itself is composed of 3 subunits, troponin I, T and C, sometimes referred to as the troponin complex). The molecules of actin, tropomyosin and troponin are arranged in thin twisted strands. The thicker myosin myofilament is composed of myosin molecules that have oval heads and long tails. For muscular contraction to occur, the heads of the myosin molecules have to move towards the actin myofilaments and form crossbrdiges. Myosin cross-bridges only get activated when they are attached to actin myofilaments.

In the sliding filament theory, the myelin cross bridges act as hooks to pull the actin myofilaments along so that the actin and myosin myofilaments slide past each other, the sarcomere becomes pulled toward each other, the sarcomere becomes shorter. The same thing happens in other sarcomeres and other fibers causing the muscle to contract.

The process can be summarized in the following sequence:

1. Nerve impulses from brain and spinal cord are carried to muscle

fibres by motor neurons.

2. Each motor neuron releases Ach which diffuses across the neuromuscular junction.

3. The wave of depolarization initiated by Ach spreads over the sarcolemma and T-tubules, which is in contact with the sarcoplasmic reticulum, from where calcium ions are released.

4. When calcium is present, they bind to troponin in the actin myofilament, causing the troponin complex to shift and expose active sites on the actin strands. The myosin cross bridges then attach to the actin myofilaments to form actomyosin.

5. At the same time myosin is activated by calcium to perform the role an enzyme. It splits ATP molecule into ADP and an inorganic phosphorus releasing energy.

6. The energy is stored in the head of the myosin and is used to move the heads of the myosin molecules toward the actin myofilaments. The myosin head form a cross bridge which attaches to the exposed active site on the actin myofilament to form actomyosin. The myosin heads tilt and change shape, pulling the actin myofilament along, so that the myosin and actin myofilament slide past each other. As they slide, the cross bridges detach and from one site and attach to the next site. Skeletal muscle contractions occur so rapidly that each myosin cross bridge may attach and release the active sites on the actin myofilament as many as 100 times.

7. When the thin actin and thick myosin myofilaments slide past each other, the actin myofilaments from opposite ends of a sarcomere move toward each other and the muscle contracts. The widths of I-bands shorten, that of A-bands remain the same and the Z-lines move closer together.

Muscle Relaxation

For a muscle to relax, the following occurs:

1. Acetylcholine is broken down by acetylcholinesterase which is released from the muscle. This breakdown prevents further stimulation of the muscle by the nerve ending.

2. The calcium ions move from the myofilaments back to the sarcoplasmic reticulum to be stored when there is no more nervous

stimulation.

3. Without calcium, troponin and tropomyosin prevent actin from combining with myosin by blocking the active sites on the actin myofilament. Thus the myosin cross bridges can no longer attach to actin myofilaments.

4. As the myosin and actin myofilament returns to their original positions in the sarcomere, the I-bands become larger and the Z-lines more farther apart. The sarcomeres return to their original (resting) length and the muscle fibre relaxes.

3.5 Regulation of Contraction

Cross bridges, are part of the myosin proteins that extend from the axis of the thick filaments to form "arms" that terminate in globular heads. These cross-bridges attach to actin, undergo power strokes and cause muscle contractions. To prevent contraction so that a muscle can relax, the attachment of myosin cross-bridges to actin must be prevented. Two proteins associated with actin in the thin filaments regulate cross bridge attachment to actin. These are tropomyosin and troponin. These two works together to regulate the attachment of cross bridges to actin; and therefore serve as a switch for muscle contraction and relaxation. Tropomyosin physically blocks the cross bridges from binding to specific attachment sites in the actin. In order for myosin cross bridges to attach to actin, the tropomyosin must be moved. This requires the interaction of troponin with Ca^{++}.

The Role of Ca^{++} in Muscle Contraction

When the muscle is relaxed and tropomyosin blocks the attachment of cross bridges to actin, the concentration of Ca^{++} in the sarcoplasm is very low. When a muscle is stimulation in made to rise rapidly. Some of the Ca^{++} attaches themselves to a subunit of troponin causing a conformated change that moves troponin and its attached tropomyosin out of the way so that cross bridges can attach to actin. Once the attachment sites on the actin are exposed, it becomes possible for myosin cross-bridges to attach to actin, undergo power strokes and produce muscle contraction. The position of the troponin-tropomyosin complex is adjustable based on whether Ca^{++} is attached to troponin or not and this controls muscle contraction. Muscle contraction is turned on when sufficient amounts of Ca^{++} bind to troponin. This occurs when the concentration of Ca^{++} in the sarcoplasmic reticulum rises above 10^6 molar. For muscles to relax Ca^{++} levels have to drop below this level. Muscle relaxation is achieved by the active transport of Ca^{++} out of the sarcoplasm into the sarcoplasmic reticulum. As long as action potentials continue to be produced - which is

as long as nervous stimulation of the muscle is maintained, Ca^{++} will remain attached to troponin and cross bridges will be able to undergo contraction cycles.

3.6 Neural Control of Skeletal Muscles

Motor neurons in the spinal cord (lower motor-neurons) as previously discussed have their cell bodies in the ventralhorns of spinal cord and axons within the nerves that stimulate muscle contraction. The activity of these neurons is influenced by (1) sensory feedback from muscles and tendons and (2) facilitatory and inhibitory effects from upper motor neurons in the brain which contribute axons to descending motor tracts. The lower motor neurons are therefore said to be the final common pathway by which sensory stimuli and higher brain centres exert control over skeletal movements.

As previously discussed, axons of these lower motor neuron cell bodies leave the ventral side of the spinal cord to form the ventral roots of spinal nerves. The dorsal roots of spinal nerves contain sensory fibers whose cell bodies are in the dorsal root ganglia. Both sensory and motor fibers join in a common connective tissue sheath to form the spinal nerves each segment of the spinal cord.

In order for the nervous system to control skeletal movements properly, it must receive continuous sensory feedback information concerning the effects of its actions. This sensory information includes (1) the tension exerted by the muscle on its tendons provided by the Golgi tendon organs and (2) muscle length provided by the muscle spindle apparatus. The muscle spindle apparatus functions as length detector.

The information from these sensory receptors (Golgi tendon organs and muscle spindles) are used to inform the motor areas of the brain, of muscle length and tension and to control muscle length and tension in negative feedback fashion by means of local spinal reflexes.
Muscle spindles are distributed throughout the fleshy part of skeletal muscles and consist of collections of specialized muscle fibers known as intrafusal fibers which lie within spindle-shaped connective tissue capsules parallel to the "ordinary" extrafusual fibres.

Whenever the whole muscle is stretched, the intrafusal fibers within its muscle spindles are stretched, increasing the rate of firing in the afferent fibres whose sensory endings terminate on stretched spindle fibres. The afferent neuron directly synapses on the alpha motor neurons that innervate the extrafusal fibres of the same muscle resulting in contraction of that muscle. This stretch reflex serves as a local negative -feedback mechanism to resist any passive changes in muscle length so that optimal

resting length is maintained (The classical example of the stretch reflex is the knee-jerk reflex which you can read up privately).

Golgi tendon organs are located in the tendons of the muscles where they respond to changes in the muscle's externally applied tension rather than to changes in its length. The Golgi tendon organs consist of endings of connective tissue - fibres that make up the tendon. When the extrafusal muscle fibres contract, the resultant pull on the tendon tightens the connective tissue bundles, which in turn increase the tension exerted on the bone to which the tendon is attached. In the process the entwined Golgi organ afferent receptor endings are stretched causing the afferent fibers to fire. The frequency of firing is directly related to the tension developed.

The afferent information is sent to the brain. Other branches of the afferent neuron arising from the Golgi tendon organ inhibit through an interneuron in the same muscle. When the tension becomes great enough, the high level of inhibitory input from the activated. Golgi tendon organs counter-balance excitatory inputs. This inhibitory response halts further contraction and brings about sudden reflex relaxation, thus helping prevent damage to muscle or tendon from excessive tension - developing muscle contractions.

Upper Motor Neuron Control

Upper motor neurons are those in the brain that influence the control of skeletal motor neurons by lower motor neurons. Neurons in the precentral gyrus of the cerebral cortex contribute axons that cross to the opposite side of the pyramids of the medulla oblongata; these pyramidal tracts include the lateral and ventral corticospinal tracts. The extra-pyramidal tracts are from neurons in other areas of the brain and the major one is the reticulospinal tracts from the reticular formation of the medulla and pons. Brain areas that influence the activity of the extra-pyramidal tracts are believed to produce the inhibition of lower motor neurons. The cerebellum like the cerebrum receives sensory information from muscle spindles and Golgi tendon organs. It also receives fibres from areas of the cortex devoted to vision, hearing and equilibrium. The cerebellum affects motor activity only indirectly through its output to the vestibular nuclei, red nuclei and basal nuclei. These structures influence lower motor neurons through the vestibulospinal, rubrospinal and reticulospinal tracts. All output from the cerebellum is in-hibitory. The inhibitory effects aid motor coordination by eliminating inappropriate neural activity. Damage to the cerebellum causes inability to coordinate movements with spatial judgement.

The basal nuclei act directly via the rubrospinal tract and indirectly

through synapses in the reticular formation and thalamus to exert profound effects on the lower motor neurons. In particular, through their synapses in the reticular formation the basal nuclei exert inhibitory influence on the activity of the lower motor neurons. Damage to the basal nuclei results in increased muscle tones.

3.7 Energy Requirements of Skeletal Muscles

Skeletal muscles at rest obtain most of their energy from aerobic respiration of fatty acids. During exercise, muscle glycogen and blood glucose are also used up as energy sources. Energy obtained by cell respiration is used to make ATP, which serves as the immediate source of energy for (1) the movement of the cross bridges for muscle contraction, and (2) the pumping (active transport) of Ca^{++} into the sarcoplasmic reticulum for muscle relaxation.

3.7.1 Metabolism of Skeletal Muscles

Skeletal muscles respire anaerobically for the first 45 - 90 seconds of moderate to heavy exercise, because the cardiopulmonary system requires this amount of time to increase the oxygen supply to the exercising muscles. If the exercise is moderate and the person is physically healthy, aerotic respiration contributes the major portion of the skeletal muscle energy requirements after the first two minutes of exercise.

The maximum rate of oxygen consumption (by aerobic respiration) called the maximal oxygen uptake is determined by a person's age, size and sex. It is 15% - 20% higher for males than females and highest at age 20 for both sexes. Genetic factors can affect it. Training can also increase it by about 20% maximum. When a person stops exercising, the rate of oxygen uptake does not go back to pre-exercise levels at once. It returns rather slowly with the person breathing heavily for some time. The extra oxygen at this time used to repay the oxygen debt incurred during exercise. The oxygen debt includes oxygen withdrawn from savings deposit (haemoglobin in blood and myoglobin in muscles); the extra oxygen required for metabolism by tissues warmed up during exercise; and the oxygen needed for the metabolism of the lactic acid produced during anaerobic respiration.

During sustained muscle activity, ATP may be used faster than it can be produced through cell respiration. At these times the rapid renewal of ATP is extremely important. This is accomplished by combining ADP with phosphate derived from another high-energy phosphate compound called phosphocreatine or creatine phosphate.
The concentration of this compound in muscle cells is more than thrice

that of ATP. Therefore it becomes a ready reserve of high energy phosphate that can be donated directly to ADP. During rest, the depleted reserve of phosphocreatine can be restored by reverse reaction the phosphorylation of creatine with phosphate derived from ATP.

3.7.2 Fast Twitch, Slow Twitch Fibres

Skeletal muscles fibres can be divided on the basis of their contraction speed (time required to reach maximum tension) into slow-twitch or type 1 fibers and fast-twitch or type II fibers. This classification is usually a function of the type of myosin ATPase enzyme type. The contraction speed ranges from about 7.3 milliseconds (for very fast twitch fibers like the extraocular muscles that move the eyes) to up to 300msec for large leg muscles. Other muscles are in a range between these two types.

Slow-twitch or type I fibers like the soleus muscle of the leg are able to sustain a contraction for a long period of time without fatigue. The resistance to fatigue is as a result of other characteristics of slow-twitch fibres. Slow twitch fibers are endowed with a high oxidative capacity for aerobic respiration. They have a rich capillary supply, numerous mitochondria and aerobic respiratory enzymes and high concentration of myoglobin pigment. (Myoglobin is a red pigment in muscles, similar to haemoglobin in red blood cells). Myoglobin improves the delivery of oxygen to slow-twitch fibers. Slow twitch fibers are also called red muscle because of their high myoglobin content. They have low myosin ATPase content.

Fast -twitch or type II fibers are thicker have fewer capillaries and mitochondria than the slow-twitch fibres, and not as much myoglobin. The are also called white fibers. Fast-twitch fibers are adapted to respire anaerobically by a large store of glycogen and a high concentration of glycolytic enzymes. These also fatigue easily and have high myosin ATPase. In humans there can also be intermediate forms of fibres. These are rather fast twitch but have a high oxidative capacity.
The fibre type seems to be determined by the motor neuron. The conduction rate of motor neurons that innervate fast-twitch fibers is faster (80 - 90 meter per second) than the conduction rate to slow-twitch fibers.

3.7.3 Muscle Fatigue

This is the inability to maintain a particular muscle tension when the contraction is sustained or to reproduce a particular tension during rhythmic contractions over time. The first one is concerned with fatigue during a sustained maximal contraction, when all the motor units are used and the rate of neuronal firing is maximal for example when lifting an

extremely heavy weight. This appears to be due to an accumulation of extracellular K^+ (call to mind that K^+ leaves axons and muscle fibres during repolarization phase of action potential). This increases the membrane potential temporarily hindering production of action potential. Fatigue under these circumstances lasts only a short time. After a minutes rest or less, maximal tension can be achieved.

The second type occurs during rhythmic contraction, over time. It can occur during moderate exercise, over a period of time. As the slow-twitch fibres deplete their reserve glycogen and fast-twitch fibers get recruited to obtain energy through anaerobic respiration, converting glucose to lactic acid, there is an accumulation of intracellular H^+. This reduces the pH. The fall in muscle ph in turn promotes muscle fatigue by mechanisms that are not completely understood.

3.7.4 Adaptation to Exercise

All muscle fibre types adapt to endurance training by an increase in mitochondria activity and thus in aerobic respiratory enzymes. The maximal oxygen uptake can be increased by as much as 20% during endurance training. The maximal oxygen uptake obtained during very strenuous exercise, average 50ml of O_2 per kilogram body weight per minute in males between the ages of 20 - 25 years. (Females average 25% lover). Trained endurance athletes (such as swimmers and long distance runners) can have maximal oxygen uptake as high as 86ml O_2 per kilogram per minute. During exercises which are performed at low levels of effort, such that the oxygen consumption rate is below 50% of its maximum, the energy for muscle contraction is obtained almost entirely from aerobic cell respiration. Anaerobic respiration with its production of lactic acid contributes to the energy requirement as the exercise level rises. Highly trained endurance athletes, however can continue to respire aerobically, with little lactic acid production at up to 80% of their maximal oxygen uptake. Such athletes thus produce less lactic acid at given level of exercise than the average person, and therefore are less subject to fatigue than the average person.

Endurance training does not increase the size of muscles. Muscle enlargement is produced only be frequent periods of high-intensity exercise in which muscles work against a high resistance, as in weight lifting. As a result of resistance training, type II muscle fibers become thicker, and the muscle therefore grows by hypertrophy (an increase in cell size, rather than number of cells). This happens first because, the myofibrils within a muscle fibre thicken, due to the synthesis of actin and myosin proteins and the addition of new sarcomeres. After a myofibril attains a certain thickness it may split into two myofibrils, each of which may then become thicker due to the addition of sarcomeres. Muscle

hypertrophy is associated with an increase in the size and then the number of myofibrils within the muscle fibers.

3.7.5 Heat Production

One of the useful by-products of muscle contraction is the production of heat. In the body heat production is necessary to help maintain a stable body temperature. Even a resting muscle gives off some heat. Initially heat is generated during muscle contraction and relaxation largely from the breakdown of phosphates. Thus initial heat is released quickly, in less than a second. Recovery heat however is produced only after the muscle has completely relaxed after a contraction. It may take up to 5 minutes to produce. This heat comes as a result of the resynthesis of ATP and creatine phosphate and includes the aerobic breakdown of pyruvic acid into water and carbon dioxide and also aerobic conversion of lactic acid to water and carbon dioxide.

3.8 Smooth Muscle

Smooth and cardiac muscles are involuntary effectors regulated by autonomic motor neurons. Smooth muscles or visceral muscles are arranged in circular layers around the walls of blood vessels and bronchioles (small air passages in the lungs). There are circular and longitudinal smooth muscle layers in the tubular digestive tract, the ureters, the ductus deferens and the uterine tubes. The alternate contraction of circular and longitudinal smooth muscle layers in the intestine produces peristaltic waves, which propel the contents of these tubes in one direction. The action of smooth muscles is thus rhythmic. Smooth muscles fibres are long; spindle shaped and contain only one centrally located nucleus.

Smooth muscles do not contain sarcomeres (which produce striations in skeletal and cardiac muscle), they do contain a great deal of actin and some myosin, which produces a ratio of thin-to-thick filaments of about 16.1 (in striated muscles, the ratio is 2.1). Unlike striated muscles, in which the thick filaments are short and stacked between Z discs in sarwmees myosin filaments in smooth muscle cells are quite long.
The long length of myosin filaments and the fact that they are not organized into sarcomeres has advantages in smooth muscle function: (1) Smooth muscles can contract even when stretched very much. For example in the urinary bladder, the smooth muscle cells can stretch up to 22 times their resting length, and in the pregnant uterus can stretch up to eight times their original length. In contrast skeletal muscles lose their ability to contract when the sarcomeres are stretched to the point where actin and myosin no longer overlap.
Smooth muscle contraction is triggered by a sharp rise in Ca^{++}

concentration in the sarcoplasm just like in striated muscle, but the sarcoplasic reticulum is not as developed as that of skeletal muscles. Therefore sustained contraction of smooth muscles is maintained by extracellular Ca^{++} which diffuse into cell through the cell membrane. Also unlike in striated muscles where Ca^{++} combines with troponin, smooth muscles do not have troponin but another protein with similar structure, calmodulin, is present in smooth muscle cytoplasm to combine with Ca^{++}.

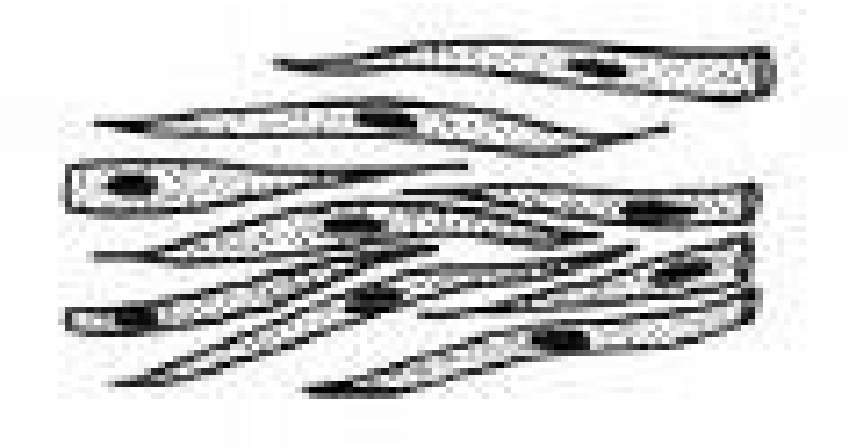


Fig 14: Diagram of a smooth muscle

The concentration of Ca^{++} determines how many myosin cross bridges that will attach to actin and thus determines the strength of contraction. The concentration of calcium is in turn regulated by the degree of depolarization. Unlike in striated muscles which produce all-or-none action potentials, smooth muscle cells can produce graded depolarizations without producing action potentials; in many smooth muscles it is only these graded potentials that are conducted from cell to cell. The triggering mechanism however are not impulses from voluntary nerves, but rather inputs that either act on the sarcoplasmic reticulum or on specific calcium channels in the sarcolemma to increase its movement into the cell. These triggering inputs include: stretching of the smooth muscle myofibrils (2) Spontaneous electrical activity (pace maker potential) within the sarcolemma, (3) Specific neurotransmitters released by autonomic neurons, (4) Hormones and hormone modulators like prostaglandins and (5) Local changes in the extracellular fluid around the smooth muscle (such as pH, O_2 and CO_2 levels).

The contractions of smooth muscles are slow and sustained. The slowness of contractions is thought to be due to a limited and slower amount of ATPase activity in splitting ATP. The slowness may be due to a Alatch@ mechanism whereby the cross bridge remains in the attached position for a long time, thus reducing the cycling rate and the rate of ATP consumption. Smooth muscles also use a wide variety of substrates for ATP production such as carbohydrates and fats. Smooth muscles use ATP as an immediate

source of energy for contraction but they do not have such energy reserves as creatine phosphate found in skeletal muscle.

Smooth muscle fibres are usually functionally classified as single unit or multiunit types.

Single-Unit Smooth Muscles Most smooth muscle are the single unit types. This means that smooth muscles have numerous gap junctions (electrical synapses) between adjacent cells that weld them together electrically, so that they behave as a single (large) unit. When a muscle cell is stimulated, it contracts and spreads the stimulation to the adjacent cells. This method produces a steady wave of contractions, such as those that push food through the intestines. The smooth muscle fibre that receives the stimulus from a motor neuron initially and passes it to adjacent fibres is known as the pacemaker cell.

Two types of contractions take place in single-unit smooth muscles: tonic and rhythmic. Tonic contractions cause the muscle to remain in a constant state of partial contraction or tonus.

This is necessary for organs like the stomach and intestine, to help move food along, and for sphincters too. Tonus prevents stretchable organs like the stomach and bladder not to stretch out of shape permanently but to maintain tension in their walls.

Rhythmic Contractions are a pattern of repeated contractions produced by the presence of self exciting muscle fibres from which spontaneous impulses travel. These rhythmic contractions in the digestive system for example produce mixing movements and propulsive movements or peristalsis.

Multi Unit Smooth Muscles These are so named because each individual fibre can be stimulated by separate motor nerve endings. There are no connections between the fibres and each multi-unit fibre can function independently. Multi-unit smooth muscle is found in the iris and ciliary muscles of the eye where rapid muscular adjustments are needed for the eye to focus properly. Also the erector muscles in the skin that cause Agoose bumps@ are of the multi-unit type and the smooth muscle of the ductus deferens. The innervation of smooth muscles differs from the way skeletal muscles are innervated. Instead of having only one junction with a somatic fibre, with receptors for the neurotransmitter located in the neuromuscular junction, the entire surface of smooth muscle cells contains neurotransmitter receptor proteins.

3.9 Cardiac Muscle

Cardiac muscle tissue is found only in the heart. It contains the same type of myofibrils and protein components as skeletal muscle and the contractile process as for the skeletal muscles.

Structure

The cardiac muscle fibre refers to a chain of cells joined end to end by cell junctions, (electrical synapses) and not a single fibre as in skeletal and smooth muscles. The cells are short, branched and interconnected. Cardiac muscles are striated, and they contain actin and myosin filaments, arranged in form of sarcomeres. The fibres are crossed by dark bands that occur in place of, but are wider than the Z lines in skeletal muscle. These bands are called intercalated discs. The discs separate the cells within a muscle fibre, strengthen the junction between cells and help an impulse to pass quickly from one cell to the next.

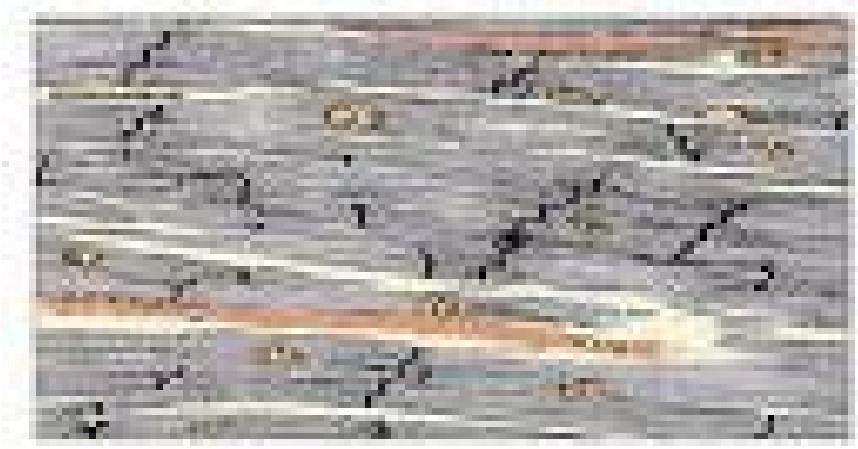


Fig. 15: Diagram of a cardiac muscle

Functioning

The cardiac muscle depends on nerve impulses only to some extent, being able to contract rthymically on its own at about half its normal rate. Cardiac action potentials normally originate in a specialized group of cells called the pacemaker. When an electrical impulse originates at any point in the myocardium, it can spread to all the cells through the gap junctions, because the cells are Aconnected@ to each other by intercalated discs into a continuous network. A myocardium functions as a single functional unit, thus unlike skeletal muscles that produce graded contractions depending on the number of fibres stimulated, the cardiac muscle contracts to its full extent each time because all of its cells contribute to the contraction.

The cardiac muscle contains two distinct myocardial - the atria and the

ventricles. Instead of contracting (beating) independently, the cells are all coordinated so that their rate and rhythm are appropriate for the job of pumping blood 24 hours a day.

Cardiac muscle differs from skeletal muscle in some ways:

1. The sarcoplasmic reticulum is less extensive in cardiac muscle.

2. The calcium-ion sensitivity of intact cardiac muscle is much greater than that of skeletal muscle. A significant amount of calcium enters the cardiac muscle cell during contraction; therefore the cell can actually contract for longer periods than a skeletal muscle cell. Cardiac muscle is also affected more by calcium imbalances than any other excitable tissue.

3. Cardiac muscle has in-built safety feature against developing a tetanic contraction. This is avoided because of the extended period of depolarization (refractory period) in cardiac muscle which is up to 200 milliseconconds as against 1 B 2 ms in skeletal muscles. Because of this a second contraction cannot be produced until the muscle has relaxed, which is not fast enough to cause tetanic contractions. Contractions of the heart last between 200 and 250 milliseconds.

Comparison of Skeletal, Cardiac and Smooth Muscle

Characteristic	**Skeletal**	**Cardiac**	**Smooth**
Appearance	Striated; actin and myosin arranged in sarcomeres.	Striated; actin and myosin arranged in sarcomeres	Non striated; more actin than myosin, actin inserts into dense bodies and cell membrane.
Sarcoplasmic reticulum	Well developed sarcoplasmic reticulum and transverse tubules	Moderately developed sacroplasmic reticulum and transverse tubules	Poorly developed sarcoplasmic reticulum tubules.
Troponin	Contains troponin in the thin filaments	Contains troponin in the thin filaments	Contains another Ca^{++} binding protein, which may be located in thick filaments.

Ca^{++} release	Ca^{++} released into cytoplasm from sacroplasmic reticulum	Ca^{++} enters cytoplasm from sarcoplasmic reticulum and extracellular fluid	Ca^{++} enters cytoplasm from extracellular fluid, sarcoplasmic reticulum and perhaps mitochondria.
Nervous stimulation	Cannot contract without nerve stimulation; denervation results in muscle atrophy.	Can contract without nerve stimulation; action potentials originate in pacemaker cells of heart.	Maintains tone, in absence of nerve stimulation; visceral smooth muscles produces pacemaker potentials; denervaton results in hypersensitivity to stimulation.
Relationship of muscle fibres	Muscle fibres stimulated independently, no gap junctions.	Gap junctions present as intercalated discs.	Gap junctions present.

Source: Human Physiology by Fox, S.I. (1991), p. 336

4.0 CONCLUSION

Skeletal muscles are individual muscle fibres that contract when stimulated by a motor neuron. Their contraction places tension on a tendon which then causes movement. Cardiac muscle can produce impulses and contract spontaneously on their own. Smooth muscles produce contractions in response to a unique regulatory mechanism.

5.0 SUMMARY

1. The basic properties of muscle tissue are contractility, excitability, extensibility and elasticity.

2. The general functions of muscle tissues are movement, posture and heat production. Three types of muscles tissue are skeletal, smooth and cardiac muscles.

3. Skeletal muscle tissue is attached to the skeleton. It is called striated muscle because it appears striped, and voluntary muscle because it basically contracts voluntarily.

4. Skeletal muscle tissue is made up of individual cells called fibres. A group of muscle fibres is called a fascicle, and a group of

fascicles is called muscle.

5. Each muscle fibre contains several nuclei, a specialized cytoplasm called sarcoplasm which has many mitochondria and individual fibres called myofibrils.

6. Each myofibril is composed of myofilaments proteins troponin and tropomyosin.

7. The myofibrils have alternating light and dark bands. The dark A bands contain myosin, the light I bands contain actin. Cutting across each I band is a Z line etc. A section of a myofibril from one Z-line to the next makes up a sarcomere which is the fundamental unit of muscle contraction.

8. Muscles are supplied with blood by arteries; each skeletal muscle fibre is contacted at least by one nerve ending. A nerve ending contacts a muscle fibre at a neuromuscular junction, A motor neuron together with the muscle it innervates is called a motor unit.

9. Muscle fibres contract fully or not at all by the all or none principle and the minimum nervous stimulation required to produce a muscle contraction is the threshold. The recovery period after a contraction is called refractory period.

10. The mechanism of muscle contraction is by the sliding filament theory. Cross bridges between myosin and actin filaments helps to slide the filaments past each other, producing contraction.

11. Neurons from the brain and spinal cord through many pathways and different synapses carry impulses to the muscle where they release acetylcholine at the neuromuscular junction. This produces an impulse in the muscle cell membrane, which is conveyed to the transverse tubules, then to the sarcoplasmic reticulum where it triggers the release of calcium. The release of calcium sets the sliding filament mechanism in motion.

12. Muscle spindles are length detectors in muscles while the Golgi tendon organs monitor the tension that the muscle exerts at its tendons.

13. Aerobic cell respiration is required for the production of ATP which is the energy source for cross bridge activity (muscle contraction). Expended ATP can be quickly replenished from the combination of ADP with phosphate derived from phosphocreatine which serves as a ready reserve of high-energy phosphate during

sustained muscle contraction.

14. Muscle fibres are of three types according to their speed of response, respiratory adaptation and tolerance to fatigue. Slow twitch fibres have slow contraction relaxation cycles; are adapted for aerobic respiration and resistant to fatigue. They are red muscles because of high concentration of myoglobin. Fast twitch fibres are white muscles adapted to anaerobic respiration, because they have fewer myoglobin. Their speed of response is fast and they tire easily.

15. Oxygen debt results during strenuous activity or sustained rhythmic activity when lactic acid is generated faster than oxygen can be supplied to the muscle fibres. The debt is paid when sufficient oxygen is restored and the lactic acid is removed. Muscle fatigue can also occur either as a result of decreased ATP or due to accumulation of extracellullar K^+.

16. Smooth muscles are not striated, are involuntary and lack sarcomeres. Their slow rhythmic contractions make it suitable for contractile control of internal organs especially the stomach, intestines, urinary bladder and uterus.

17. The contractile process of smooth muscles is essentially the same as that of skeletal muscle but smooth muscles do not have troponin. Instead calcium binds to calmodulin. This mediates the phsophorylation of cross bridges required for binding to actin.

18. Cardiac muscle is striated and contains sarcomeres. The tissue is found in the heart. It is also involuntary. The cells are closely packed together though each remains separate with its own nucleus. Intercalated discs join the cells making it easy for impulses to jump from one cell to the other.

19. Cardiac muscle depends on nervous control to some extent. It has ability to originate its action potentials through the pacemaker cells.

6.0 TUTOR-MARKED ASSIGNMENT

Describe a cycle of cross-bridge activity during contraction and discuss the role of ATP in this cycle.

7.0 REFERENCES/FURTHER READINGS

More current editions of Guyton's Medical Physiology: Holt and Saunders.

Review of Medical Physiology by Gannong: Appleton and Langue.

Human Physiology: From Cells to Systems by Sherwood L. West Publishing.

Human Physiology by Fox, S.I: W. M. C. Brown. Publishers.