Unit 3

Insect Anatomy and Physiology – I

Structure of the unit

3.1 Objectives

After reading this unit student will be able to:

- Describe the Scope and importance of insect anatomy and physiology.
- Describe muscular systems in insects.
- Describe the structure and function of digestive system.
- Know, describe and understand physiology of digestion.
- Understand the role of vitamins, proteins, amino acids, carbohydrates, lipids, minerals and other food constituents in insect nutrition.
- Describe extra and intra cellular micro organisms and their role in physiology

3.2 Introduction

All the muscles of insects are built on a similar plan with elongate cells housing the contractile elements and in many cases inserted into the integument at either end. The internal arrangement of the muscle cells however varies in different muscles and wing muscles often have characteristic forms. Shortening of the muscles involves the filaments of which they are composed sliding between each other. The muscles are stimulated to contract by the arrival of nerve impulses which cause local changes within the cell. Usually one nerve impulse causes one contraction but in specialised muscles which can oscillate at high frequency the muscles may contract several times as a result of a single nervous impulse. The speed with which these muscles oscillate depends on their mechanical properties and on the structures to which they are attached. The output of power by flight muscles may be very high and the associated metabolic rate is higher than in any other tissue. In order to maintain such a high level of metabolism the supply of oxygen and fuel must be adequate anatomically, physiologically and biochemically to ensure that this is the case.

An insect uses its digestive system to extract nutrients and other substances from the food it consumes. Most of this food is ingested in the form of macromolecules and other complex substances (such as proteins, polysaccharides, fats, and nucleic acids) which must be broken down by catabolic reactions into smaller molecules (i.e. amino acids, simple sugars, etc.) before being used by cells of the body for energy, growth, or reproduction. This break-down process is known as digestion.

Digestive system composed of alimentary canal and various glands related with it either directly (salivary glands, gastric caeca) or indirectly (malpighian tubules).

3.3 Scope and importance of insect anatomy and physiology

Entomology is a branch of zoology, which deals with the study of insect. The word entomology has two parts viz., Entomon = Insects and logos = study. Agril. Entomology deals with the study of insects in relation to agriculture.

Study of entomology aims at understanding insect body organization and function, their habitats, behaviours, relation to one another and to the surrounding in which they live, their classification, development distribution, post history and their economic importance.

Use of insects and insect products as items of medicinal value (oil beetles, use of lac, use of red ants in suturing wounds) have found a place in certain indigenous systems of treatments. Honey is used more as medicine than as a food. Parts of insects have been used as cheap jewellery by certain tribes.

As far as study of insect is concerned in agriculture it is of worth importance. Related to agriculture, insects are both useful and harmful. As a harmful role they damage our crops, lay waste vast areas of cultivated land, despoil on feed; they bring about different diseases and some of the examples are Malaria, plague, typhus, sleeping sickness etc. The serious disease malaria was earlier thought to be beyond the reach of mankind. A lot of money was just wasted in Malaria management but was of no use. When the entomologist studied the morphology and taxonomy of mosquitoes, they get interesting information on malaria transmitting mosquito, theAnopheles and the problem was solved just like anything. Another example is that of body louse spreading typhus fever in 1944 in Italy amongst the civilians living in crowded conditions. In 1939 Dr. Paul Muller discovered the insecticidal properties of DDT, which was then used in control of body louse. DDT become famous overnight as an insecticide and Muller saved thousands of soldiers from the deadly disease, typhus and not surprising, therefore that P. Muller was awarded the Nobel prize for Medicine in 1948. These are some insects, which are of international importance as a pest e.g. Locust. To show their devasting features some statistics related to them sufficient. A swarm of locust is estimated to contain more than 1500 million individuals. They fly with a speed of 150km/day. Even sunlight can not pass on earth when they are flying. They just eat everything which is green on earth. Army worms behaves like an army and destroy the crop within an overnight. This is about the harmful role played by insect.

Entomology as applied science has its own importance both in plant protection and getting benefit for mankind from the useful role played by insects. Scientific entomology is over a century old in India and a firm foundation of economic entomology has been laid by scientists like Lefroy, Fletcher, Ramkrishnan Ayyar and Ramchandra Rao in India. Till absent 1930, the subject was morphological all over the world. This study yielded considerable information on Taxonomy, insect pests and control. Towards the later period, applied entomology developed and a fundamental basis for pest study and methods of pest control including biological and legal control formed the major activity in this branch of science. Recognizing the usefulness of insect as an experimental animal Wigglesworth showed that physiology of insect is a fascinating field of study, and he established insect physiology as a separate discipline in 1930-38; in later period the same was extended into field of insect control also. In 1950-60 entomology emerged as a biological science encompassing morphology, ecology, physiology, phenology, pestology, biochemistry and ethiology (behaviour).

Scope: In their attempt to secure food insect inflict considerable damage to almost every part of the plant. The origin of insect dates back to about 350 million years ago. Of the estimated 1.35 million living species of animals more than 9,00,000 are insects. Their capacity for multiplication and wonderful adaptations has made them a serious threat to human being and his existence. They compete man for three basic needs i.e. Food, clothing and shelter. Among these food is common to both of them. Looking towards increasing population this vital item is now a days becoming scare and to secure this food man has to always think about insect as his first enemy. Due to this, entomology has its scope first in the area of plant protection. Research is continuously going on and newer insecticides are evolved as a result.

Still the problem is not solved. And hence man is taping new feeds in plant protection. As result of this new generation pesticides were born some of them are use of harmones, antihormone coupounds, chemosterilents, antifeedant, repellants, pheromones etc. which now a days replacing use of hazardous pesticides.

We are not yet able to identify most of the insects on earth where there may be chance of identifying a new pest. There is a scope for entomologist to identify more no of insects. Similarly scope is there for designing newer and cheaper methods of pest control because all the pesticides are toxic to human being causing several deaths every years. Also they are producing resistance in insect, where to control such a resistant progeny is a great challenge. To solve this problem upto certain extent a new technique adopted is IPM. (i.e. Integrated pest management) but still IPM for all the crops is not available here also a vast scope is there. New field called genetic engineering is coming up where one can develop pest resistant (immune) crop variety which will solve all further problems arising as a by product of pesticide use. Such work is in progress all over the world. (e.g Bt rice, transgenic cotton etc.)

On the other hand we haven't yet able to exploit the fullest utilization of useful role of insect in agriculture. As seen earlier insect benefit to us in several ways one of it is their valuable products. Still in India the silk industry is not growing as it is growing in other countries like Japan and France this is because of lack of knowledge, excluding Karnataka other states should come up in production of silk which has a great potential in earning foreign exchange. Similarly bee keeping it yields honey and wax which are very important commodities, other then that pollution by bees is an additional advantage and farmers should take help of these pollinators to uplift their yields.

Entomology can generate employment up to certain extent e.g. production of parasites/ predators, diseases causing agents. This job one can do by taking short training and can earn money as well as can help the farmer in adoption cheap and non polluted plant protection.

For increasing population we will be in short of food material and to secure it we have to do a lot of labour in this field . Where still a lot of scope is there.

The **morphology** of **insects** is the study and description of the form and structure of insects. Terminology is related to that of the morphology of other arthropods. There is a large variation in the modifications that have been made by various taxa to the basic insect body structure. This is a result of the high rate of speciation, short generations, and long lineages of the class of insects. These modifications allow insects to occupy almost every ecological niche, use a staggering variety of food sources, and possess diverse lifestyles. This article describes the basic insect body and some of the major variations that it can take; in the process it defines many of the technical terms used to describe insect bodies.

Insect physiology includes the physiology and biochemistry of insect organ systems.[1]

Although diverse, insects are quite indifferent in overall design, internally and externally. The insect is made up of three main body regions (tagmata), the head, thorax and abdomen. The head comprises six fused segments with compound eyes, ocelli, antennae and mouthparts, which differ according to the insect’s particular diet, e.g. grinding, sucking, lapping and chewing. The thorax is made up of three segments: the pro, meso and meta thorax, each supporting a pair of legs which may also differ, depending on function, e.g. jumping, digging, swimming and running. Usually the middle and the last segment of the thorax have paired wings. The abdomen generally comprises eleven segments and contains the digestive and reproductive organs.[2] A general overview of the internal structure and physiology of the insect is presented, including digestive, circulatory, respiratory, muscular, endocrine and nervous systems, as well as sensory organs, temperature control, flight and molting.

3.4 Muscular system

Basic muscle structure

Each muscle is made up of a number of fibres, which are long, usually multinucleate, cells running the whole length of the muscle. Each fibre is bounded by the sarcolemma, which comprises the plasma membrane of the cell plus the basement membrane. The cytoplasm of the fibre is called sarcoplasm and the endoplasmic reticulum which is not connected to the plasma membrane is known as the sarcoplasmic reticulum. The plasma membrane is deeply invaginated into the fibre, often as regular canals between the Z and the H bands, this system of invagination is called the transverse tubular or T system. It is associated with vesicles of the sarcoplasmic reticulum. When the two systems are very close the space between their membranes is occupied by electron dense material and the arrangement is called a dyad. In Philosamia (Lepidoptera) the T system is extensive and about 70% of the muscles plasma membrane is within the system. This may be a common phenomenon. The nuclei occur in different positions in the cell in different types of muscle.

The characteristic feature of muscle cells is the presence of myofibrils embedded in the sarcoplasm and extending continuously from one end of the fibre to the other. The arrangement of the fibrils varies but they are always in close contact with the mitochondria which are sometimes known as sarcosomes.

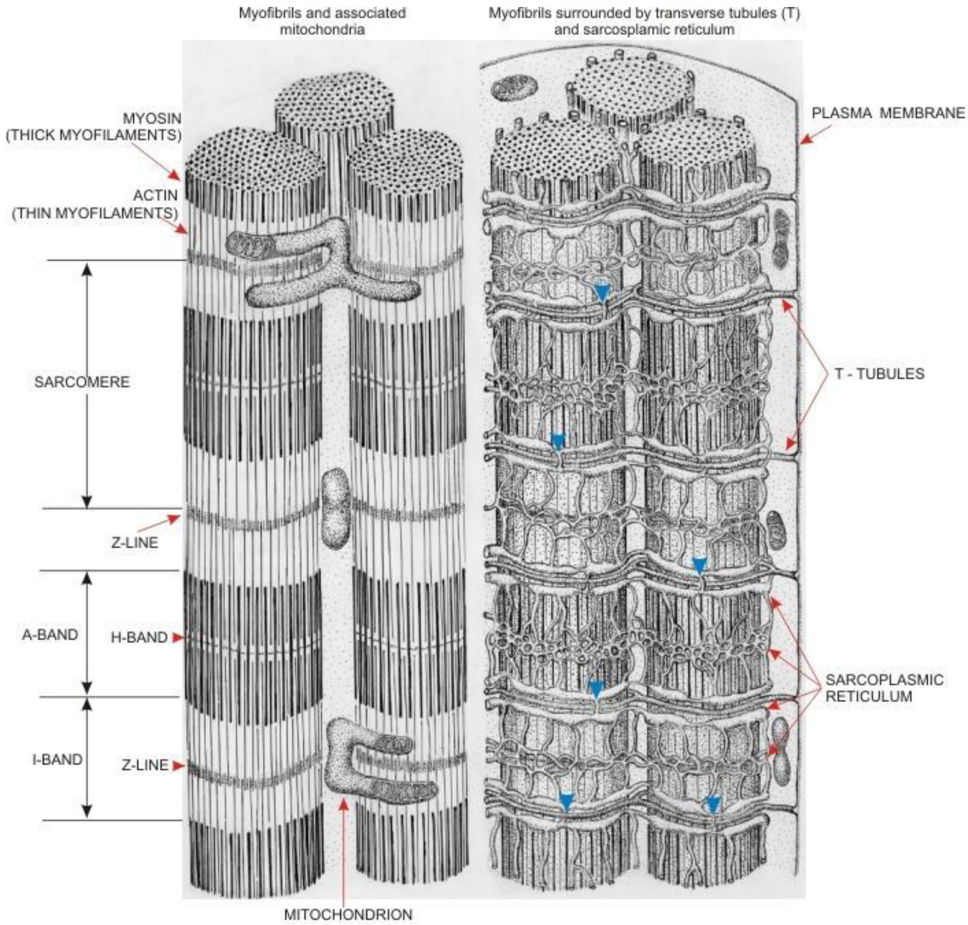


Fig. Diagram of a lateral view of part of a muscle fibre showing the arrangement of the major constituents.

The fibrils in their turn are composed of molecular filaments consisting mainly of two proteins: myosin and actin. The myosin filaments are stouter and are made up of numerous myosin molecules. These are elongate structures with two globular heads at one end and in each sarcomere all the molecules in one half are aligned in one direction while all those in the opposite half are aligned in the opposite direction. The myosin molecules are probably arranged round a core of another protein, paramyosin, with their heads arranged in a helix. The thick filaments are each surrounded by a number of thin actin filaments which consist of two chains of actin molecules twisted round each other. The actin filaments are orientated in opposite directions on the two sides of a Z line. At this line actin filaments are joined together overlapping each other and held by an amorphous material. All the filaments in a fibre are aligned with each other so that the joints between the ends of the actin filaments form a distinct line known as the Z line running across the whole fibre. The unit of the muscle between two Z lines is called a sarcomere. On either side of each Z line actin filaments extend towards but do not reach the centre of the sarcomere. The myosin filaments do not normally reach the Z lines although there is some controversy concerning the presence of a connection with the Z lines in fibrillar muscle. Hence each sarcomere has a lightly staining band at each end and a darkly staining band in the middle known respectively as the isotropic (I) and anisotropic (A) bands. In the centre of the A band where actin filament are absent is the rather paler H zone. Other bands may also be present and changes occur when the muscle contracts.

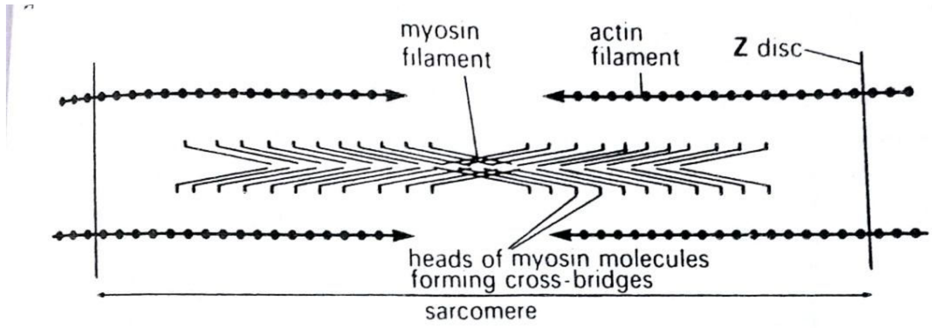


Fig. Diagrammatic representation of the orientations of the actin and myosin molecules and filaments in a muscle.

The actin and myosin filaments are linked at intervals by cross bridges formed from the heads of the myosin molecules which carry an ATPase. These cross bridges provide structural and mechanical continuity along the whole length of the muscle fibre. Further proteins, tropomyosin and troponin A and B are also present in small quantities in the contractile elements. Troponin A acts as a receptor for Ca^{++} ions.

The muscle fibres are collected into units of 10-20 fibres separated from neighbouring units by a tracheolated membrane. Each muscle consists of one or a few such units and for instance there are five in the dorsal longitudinal flight muscles of Schistocerca. Each muscle unit may have its own nerve supply independent of all the others and in this case it is the basic contracting unit of the muscle but in other cases several muscle units may have a common innervations and so function together as the motor unit.

Innervations

The nervous supply to a muscle consists of a small number of large axons. Basically each unit is innervated by a fast axon and a slow axon and sometimes also by an inhibitory axon. Such multiple innervations is called polyneuronal. Within the unit each muscle fibre receives endings from the fast axon and some may also be innervated by the slow axon. In the jumping muscle of the locust about 40% of the fibres receive branches from both axons but in the flight muscles of Odonata, Orthoptera, Diptera and Hymenoptera only fast axon are present.

Characteristically in insects there are many nerve endings spaced at intervals of 30- 80 µm along each other. Where a fibres has a double innervations it is probable that both axons have endings in the same terminals.

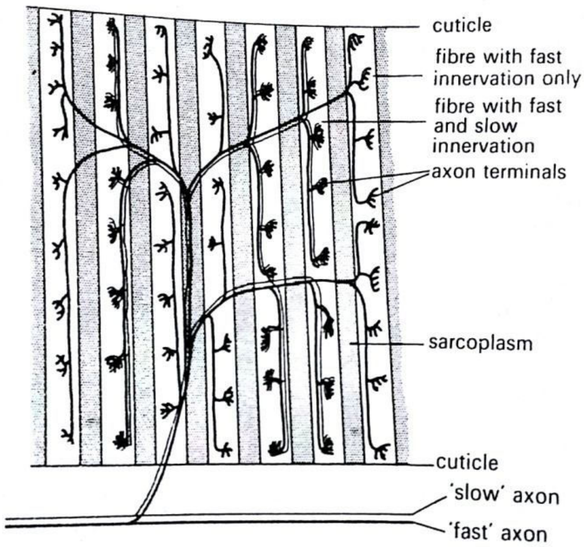


Fig. Diagram illustrating the innervations of a typical muscle unit. All the fibres receive branches of the fast axon, while some also have endings from the slow axon.

Oxygen supply

Since muscular contraction requires metabolic energy the muscles have a good tracheal supply and this is particularly true of the flight muscles, where often the respiratory system is specialised to maintain the supply of oxygen to the muscles during flight. In most muscles the tracheoles are in close contact with the outside of the muscle fibre. This provides an adequate supply of oxygen to relatively small muscles or those whose oxygen demands are not high, but in the flight muscles of many insects the tracheoles indent the muscle membrane becoming functionally, but not anatomically, intracellular within the muscle fibre.

Muscle insertion

Skeletal muscles are fixed at either end to the integument, spanning a joint in the skeleton so that concentration of the muscle moves one part of the skeleton relative to the other. Typically such muscles are said to have an origin in a fixed or more proximal part of the skeleton and an insertion into a distal, movable part, but these terms become purely relative in the case of muscles with a dual function. In many cases muscles are attached to invaginations of the cuticle called apodemes.

At the point of attachment of the muscle fibre to the epidermis the plasma membranes interdigitate and are held together by desmosomes. Within the epidermal cell, microtubules run from the desmosomes to hemidesmosomes on the outer plasma membrane and from each hemidesmosome a dense attachment fibre passes to the epicuticle through a pore canal. In earlier studies the microtubules and attachment fibres were not separated and were called tonofibrillae. Only actin filaments reach the terminal plasma membrane of the muscle fibre inserting into the dense material of desmosomes or hemidesmosomes.

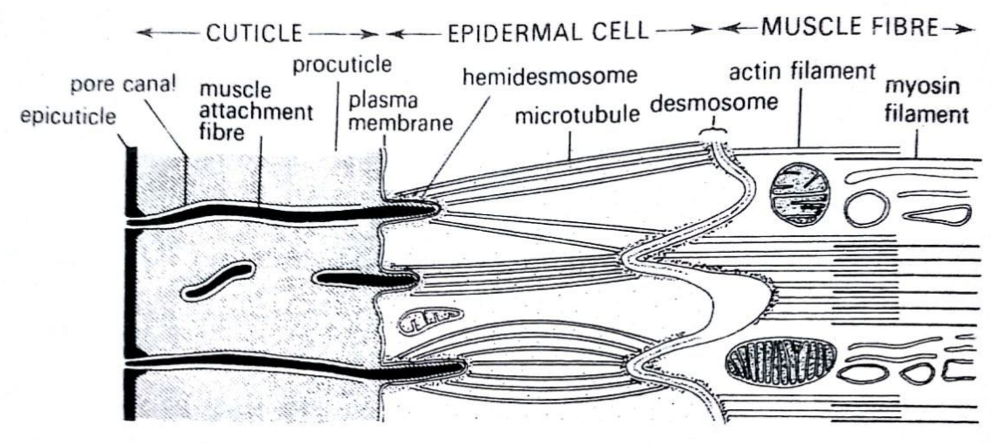


Fig. Diagrammatic representation of the attachment of a muscle fibre to the integument

The muscle attachment fibres are not digested by moulting fluid and so during moulting they retain their attachment to the old cuticle across the exuvial space between the new and old cuticles. As a result, the insect is able to continue its activities after apolysis during the development of the new cuticle. The connections to the old cuticle are broken at about the time of ecdysis.

Muscle attachment fibres which extend to the epicuticle can only be produced at a moult and most muscles appear to form their attachments at this time. Muscle attachment can occur later on however if cuticle production continues in the postecdysial period but in this case the attachment fibres are only connected to the newly formed procuticle and do not reach the epicuticle.

Variations in structure

The structure of muscles varies in different parts of the body. Two broad categories can be distinguished:

Skeletal muscles, which are attached at either end to the cuticle and move one part of the skeleton relative to another. It can be differentiated functionally into synchronous and asynchronous or fibrillar muscles. Fibrillar muscle fibres only occur in the flight muscles of Thysanoptera, Psocoptera, Homoptera, Heteroptera, Hymenoptera, Coleoptera and Diptera and in the tymbal muscles of Cicadidae. All other muscles are synchronous muscles that is they exhibit a direct relationship between contraction and motorneurone activity.

Visceral muscles, which move the viscera and have only one or more commonly, no attachment to the body wall.

Control of muscular contraction

Excitation of the muscle

With the exception of some visceral muscles, muscles are stimulated to contract by the arrival of a nerve impulse at the nerve/ muscle junctions. Where the junction involves excitation of a skeletal muscle it is almost certain the L-glutamate is the chemical transmitter across the synaptic gap and this may also be true with visceral muscle (Miller, 1975). Some spontaneous discharge of transmitter substance into the synaptic gap normally occurs, but the rate of release of the vesicle is greatly enhanced by the arrival of the nerve impulse (Usherwood, 1974).

As in a nerve, there is a difference in electrical potential across the muscle membrane so that it has a resting potential of 30-70 mV, the inside being negative with respect to the outside. Since the magnitude of the potential is not always what would be expected from the ionic concentrations in the muscle and the surrounding haemolymph, it is possible that the fluid in the tubules of the T-system, rather than the haemolymph in general, determines the size of the potential and that its composition differs from that of the haemolymph. The arrival of the excitatory transmitter substance at the postsynaptic membrane on the muscle surface causes a change in permeability leading to an influx of sodium ions and a rise (that is a depolarisation) in the muscle membrane potential. Subsequently an increase in the permeability to potassium ions leads to their movement out from the muscle and so the potential falls to its original level. The short lived increase in potential produced by these changes in the relative permeability to sodium and potassium detrermine its size. The postsynaptic potential spreads from the synapse but decreases rapidly, its effect is therefore localised and in order to stimulate the whole fibre a large number of nerve endings are necessary.

It is probable that the invaginations of the T- system convey the changes in potential deep into the muscle and close to the fibrils. This is important since activation of the fibrils involves chemical transmission within the fibres and the diffusion of a chemical from the surface membrane to the central fibrils would involve a considerable delay in contraction. The T- system greatly reduces this delay by bringing the plasma membrane to within a few microns of each fibrils.

Activation of the muscle fibre

Activation of the contractile mechanism involves the release of calcium from the sarcoplasmic reticulum and it is presumed that this occurs where the T-system and sarcoplasmic reticulum form dyads. The calcium binds to both the actin and the myosin filaments and its effect is to activate an ATPase in the myofilaments. In the resting muscle this activity is inhibited by a protein, called troponin B, in the actin filament, but in the presence of Ca++ ions the inhibition is removed, other proteins, troponin A and tropomyosin, are also involved in this process.

The effect of the ATPase is to break down ATP to ADP with the release of energy which is used in muscle contraction. It is believed that the actin and myosin filaments first become linked together by the cross bridges and that movement of these links with subsequent breaking and recombination causes the actin filaments to slide further between the myosin filaments so that the sarcomere and hence the muscle, shortens. Relaxation of the muscle possibly involves the sequestration of calcium ions so that ATPase activity is suppressed. Each cycle of contraction and relaxation of the muscle is associated with calcium release and sequestration.

In fibrillar muscle the picture is rather different. The muscles start to contract in response to a burst of motor nerve impulse, which presumably results in the release of Ca++ ions from the sarcoplasmic reticulum. However, subsequent muscle oscillations are not related directly to nervous stimulation and occur at a constant concentration of calcium within the fibre. After the initial activation, the muscle is maintained in an active state by rapid changes in length and tension which result from the mechanical properties of the muscle itself and the resonant characteristics of the thorax.

Changes in muscles banding during shortening

As a result of the sliding of the filaments during muscle contraction the I bands shorten and may disappear as the myosin approaches the Z- lines. Hence the length of the I band in relaxed muscle is roughly proportional to the degree of shortening which the sarcomere can undergo. Some muscles may shorten by as much as 50% of their length, while flight muscles may shorten by as little as 1%.

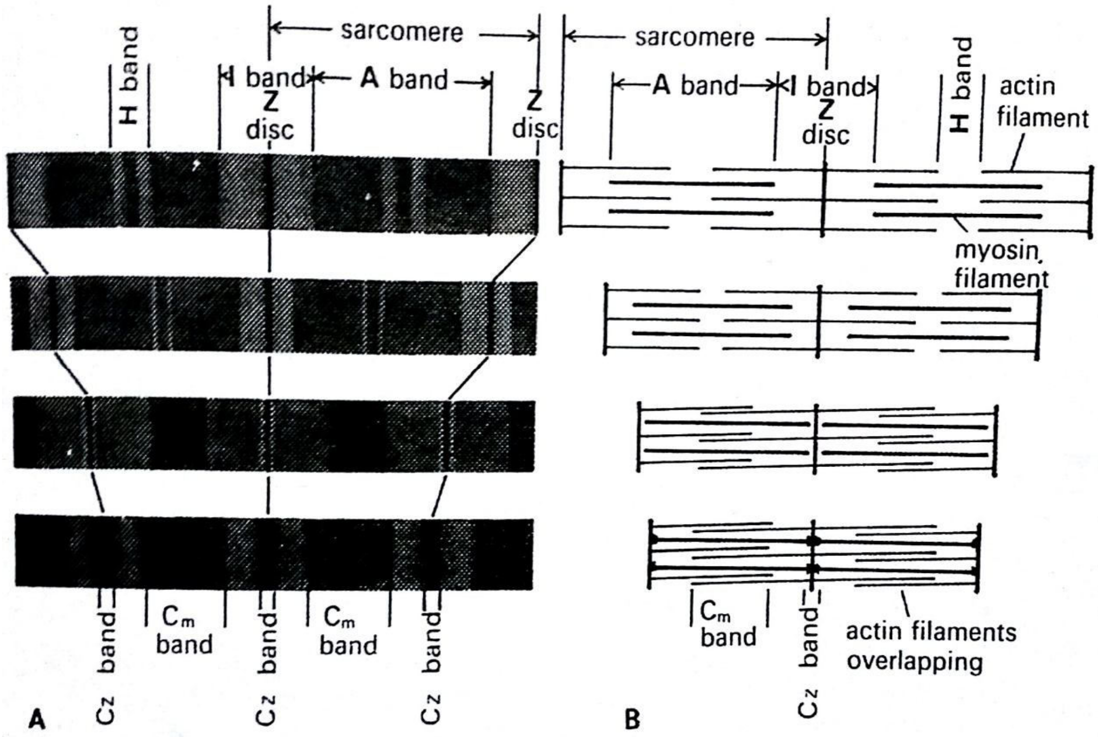


Fig. (A) The appearance of a muscle fibre in various states of contraction. (B) Diagrams showing the presumed arrangement of the muscle filaments in positions corresponding to (A)

As the I band is obliterated by the myosin filaments the H band also disappears as the ends of the actin filaments approach each other. Ultimately the actin filaments from the two ends of a sarcomere may come to overlap each other so that another dark band, C_m forms. Extreme contractions may cause crumpling of the myosin filaments at the Z- line so that a dark band, C_z is formed.

Some visceral muscles have the capacity of supercontraction the sarcomeres shortening by more than half their length. In these muscle the myosin filaments pass through pores in the Z- line so that they project into the adjacent sarcomeres. This may be made possible by the cross bridges on a myosin filament linking with the actin filaments of the next sarcomere as it passes through the Z- line pores.

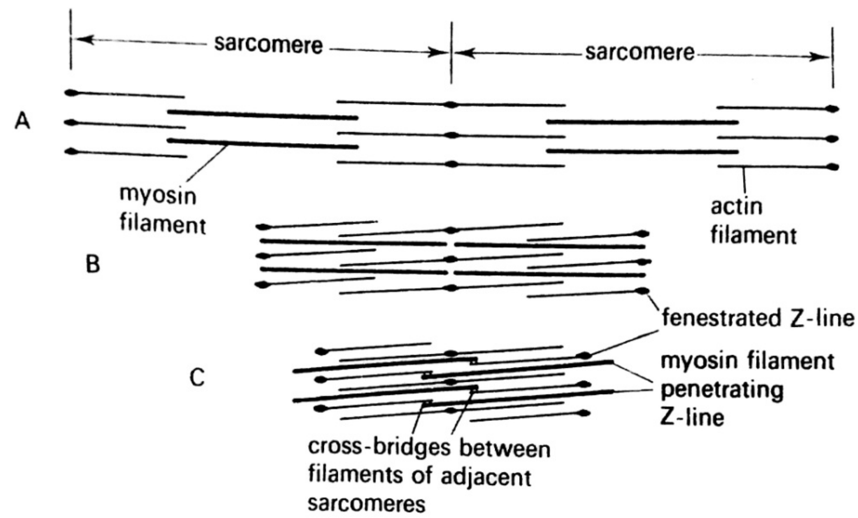


Fig. Diagrammatic representation of the probable mechanism of supercontraction in a visceral muscle. (A) Fully relaxed muscle, (B) Partially contracted, (C) Supercontracted.

Inhibition of muscle contraction

In addition to the normal excitatory innervations, some fibres of some muscles have an inhibitory nerve supply. Inhibitory axons are known to run to some leg muscles in locusts and cockroach.

At an inhibitory nerve/ muscle junction a neural transmitter, probably γ- amino butyric acid (GABA) is released and causes a change in permeability at the postsynaptic membrane but unlike the process occurring at an excitatory synapse, this results in an influx of chloride ions. As a result the membrane potential becomes even more negative the membrane is hyperpolarised and the tension exerted by the fibre decreases.

Control of visceral muscles

In visceral muscles which are innervated the principles of muscle control are the same as in skeletal muscle. L- glutamate may be involved as a neurotransmitter, but it is conceivable that different transmitters are involved in different muscles. Axons containing neurosecretory material are known to be associated with various visceral muscles in a number of insects and it is possible that these muscles are controlled via the neurosecretory system.

There is no clear picture of how the activity of muscles which have no innervations is controlled.

3.5 Digestive system: Alimentary canal and modification

One of the major reasons for the biological success of insects is their ability to eat, digest and utilise an enormous diversity of foods. This ability allows the extreme diversity observed in the modification and specialisations of the alimentary system of insects. The structural and biochemical modifications of the alimentary system of a particular species depend upon the type of food eaten. There are structural and functional differences in the way foods are obtained, stored, processed and absorbed between the sexes, e.g. caterpillars chew up plant material, whereas adults suck up only floral nectar and female mosquitoes suck up a vertebrate blood, whereas males suck up plant sap.

Alimentary canal

The insect's digestive system is a closed system, with one long enclosed coiled tube called the alimentary canal which runs lengthwise through the body. The alimentary canal only allows food to enter the mouth, and then gets processed as it travels toward the anus. The insects alimentary canal has specific sections for grinding and food storage,enzyme production and nutrient absorption. Sphincters control the food and fluid movement between three regions. The three regions include the foregut (stomatodeum), the midgut (mesenteron), and the hindgut (proctodeum).

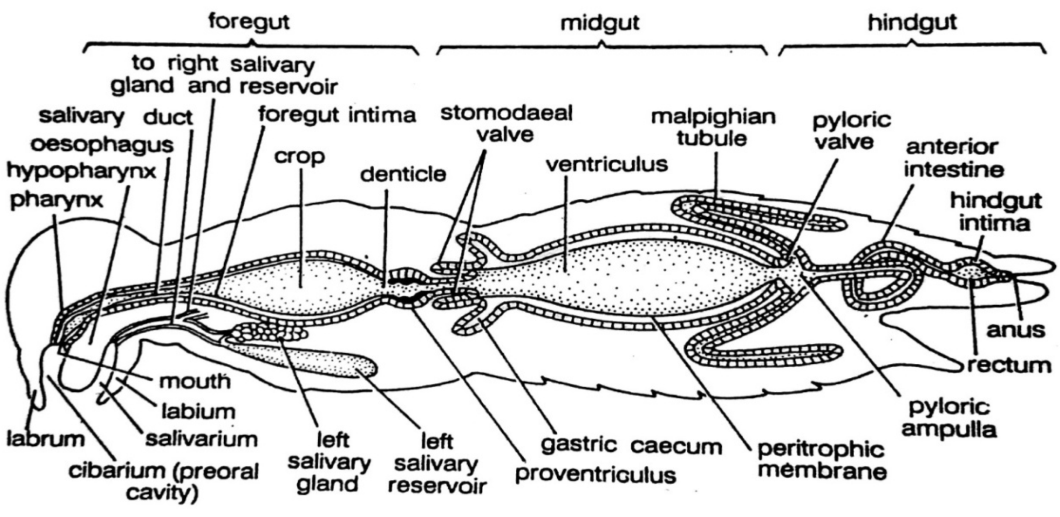


Fig. Alimentary canal of a generalized insect

In addition to the alimentary canal, insects also have paired salivary glands and salivary reservoirs. These structures usually reside in the thorax (adjacent to the fore-gut). The salivary glands produce saliva, the salivary ducts lead from the glands to the reservoirs and then forward through the head to an opening called the salivarium behind the hypopharynx; which movements of the mouthparts help mix saliva with food in the buccal cavity. Saliva mixes with food which travels through salivary tubes into the mouth, beginning the process of breaking it down.

The stomatedeum and proctodeum are invaginations of the ectoderm and are lined with chitinous intima, which is continuous with the cuticle of the integument and therefore at the moult both foregut and hindgut and their contents are shed. The mesenteron is derived from endoderm and not lined with cuticle but with rapidly dividing and therefore constantly replaced, epithelial cells. The cuticle sheds with every moult along with the exoskeleton. Food is moved down the gut by muscular contractions called peristalsis.

Foregut or stomodeum

An insect’s mouth, located centrally at the base of the mouthparts, is a muscular valve (sphincter) that marks the “front” of the foregut. Food in the buccal cavity is sucked through the mouth opening and into the pharynx by contractile action of cibarial muscles. These muscles, located between the head capsule and the anterior wall of the pharynx, create suction by enlarging the volume of the pharynx (like opening a bellows). This “suction pump” mechanism is called the cibarial pump. It is especially well developed in insects with piercing/sucking mouthparts.

From the pharynx, food passes into the oesophagus by means of peristalsis (rhythmic muscular contractions of the gut wall). The oesophagus is just a simple tube that connects the pharynx to the crop, a food storage organ. Food remains in the crop until it can be processed through the remaining sections of the alimentary canal. While in the crop, some digestion may occur as a result of salivary enzymes that were added in the buccal cavity and/or other enzymes regurgitated from the midgut.

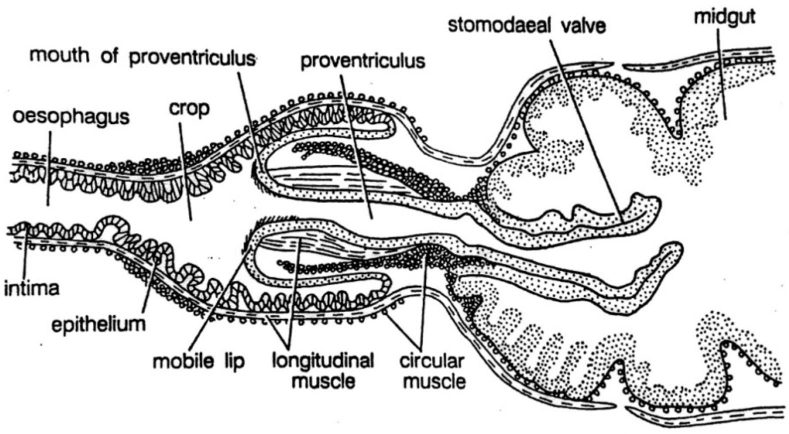


Fig. Longitudinal section of the proventriculus of honey bee

In some insects, the crop opens posteriorly into a muscular proventriculus or gizzard. It is absent in fluid feeder but is well developed in orthopteroid insects (e.g. cockroach). This organ contains tooth like denticles that grind and pulverize food particles. The proventriculus, regulates the flow of food from the stomodeum to the mesenteron. The hard denticles inside the proventriculus are made from the intima.

Midgut or mesentron or ventriculus

The midgut begins just past the stomodeal valve. Near its anterior end, finger-like projections (usually from 2 to 10) diverge from the walls of the midgut. These structures, the gastric caecae, provide extra surface area for secretion of enzymes or absorption of water (and other substances) from the alimentary canal. The rest of the midgut is called the ventriculus -- it is the primary site for enzymatic digestion of food and absorption of nutrients. Digestive cells lining the walls of the ventriculus have microscopic projections (microvilli) that increase surface area for nutrient absorption.

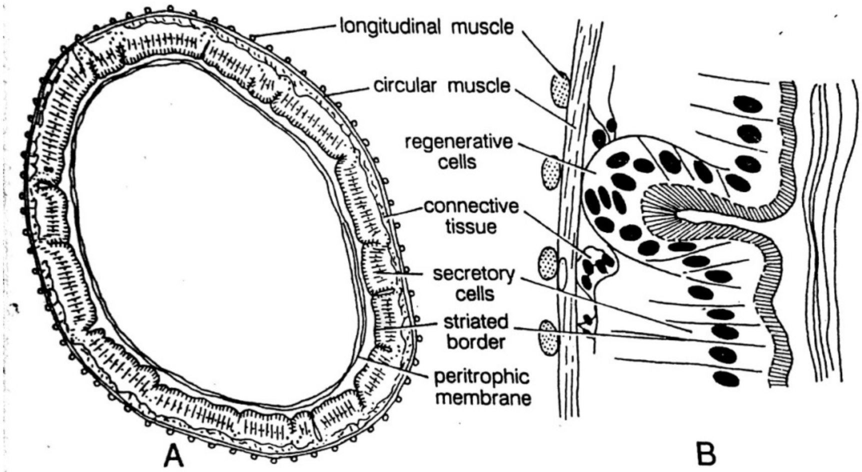


Fig. (A) Transverse section of midgut. (B) A section of midgut highly magnified.

The midgut epithelium of most insects is composed of three basic cell types: columnar digestive cells with microvilli forming a striated border regenerative cells and endocrine cells. The basal plasma membrane of digestive cells is characteristically infolded, and mitochondria are associated with these folds. These cells are involved in the synthesis of digestive enzymes and absorption of digestive food. At the bases of the midgut epithelial cells are small regenerative cells or replacement cells. These cells replace the actively functioning gut cells that die or that degenerate as a result of holocrine secretion.

The midgut is derived from embryonic endoderm so it is not protected by an intima. Instead, the midgut is lined with a semippermeable membrane secreted by a cluster of cells (the cardial epithelium) that lie just behind the stomodeal valve. This peritrophic membrane consists of chitin fibrils embedded in a protein carbohydrate matrix. It protects the delicate digestive cells without inhibiting absorption of nutrient molecules. The bugs, which are fluid feeders lack a peritrophic membrane.

The posterior end of the midgut is marked by another sphincter muscle, the puloric valve. It regulates the flow of material from the mesenteron to the proctodeum.

The plant bugs in order to obtain adequate quantity of nutrients ingest large amount of sap. In them, the gut is modified to provide the rapid elimination of the excess of water taken in to avoid excessive dilution of the haemolymph and to concentrate the food to facilitate enzyme activity. In leaf hoppers and aphids, the rapid removal of water to the rectum is achieved by the anterior midgut forming a large thin walled bladder which is closely bound to anterior hindgut and malphighian tubules by its own basement membrane. The chamber formed within this fold is called the filter chamber. Water passes directly from the hindgut along an osmotic gradient and there may be no significant flow of fluid through the lumen of the gut.

Hindgut or proctodeum

The hindgut is composed of cuboidal epithelial cells and is lined by a layer of cuticle which is thinner and more permeable than that of the foregut. The pyloric valve serves as a point of origin for dozens to hundreds of malpighian tubules. These long, spaghetti like structures extend throughout most of the abdominal cavity where they serve as excretory organs, removing nitrogenous wastes (principally ammonium ions, NH_4^+) from the haemolymph. The toxic NH_4^+ is quickly converted to urea and then to uric acid by a series of chemical reactions within the malpighian tubules. The uric acid, a semi solid accumulates inside each tubule and is eventually emptied into the hindgut for elimination as part of the faecal pellet.

The hindgut is divided into three sections; the anterior is the ileum, the middle portion, the colon, and the wider, posterior section is the rectum. This extends from the pyloric valve which is located between the mid and the hindgut to the anus. The rectum usually contains a number of pads or papillae (usually six) that project into the lumen. These structures receive an extensive supply of tracheae and are metabolically very active. They play an especially important role in the excretory system.

Functions of the hindgut include the following:

i. Water absorption from urine and faeces,
ii. Ion absorption from urine and faeces,
iii. Cryptonephridial system for water conservation,
iv. Modifications in structure for housing symbiotic microorganisms (e.g., termites).

Salivary glands

Although there may be glands associated with the mandibles (e.g.silver fishes, queen honey bee), maxillae (e.g. proturans, spring tails), and hypopharynx (e.g. worker honey bee), salivary glands are typically associated with the labial segment. The salivary glands or labial glands are paired structure lie ventral to the foregut in the head and thorax and occasionally extend posteriorly into the abdomen. Depending on the type of food eaten and the insect species involved salivary glands vary in size, shape and the type of secretion produced.

Two basic types of salivary glands exist:

a) Acinar (e.g. Orthoptera and Dictyoptera)

b) Tubular (e.g. Diptera, Lepidoptera and Hymenoptera)

In the acinar type each acinus bears a tiny duct that communicates with other similar ducts, eventually forming a lateral salivary duct. Lateral salivary ducts run anteriorly and merge as the common salivary duct, which empties between the base of the hypopharynx and the base of the labium. This region is called the salivarium and in some sucking insects forms a salivary syringe that injects saliva into whatever is being pierced. The lateral salivary ducts may communicate with salivary reservoirs, as in the cockroaches.

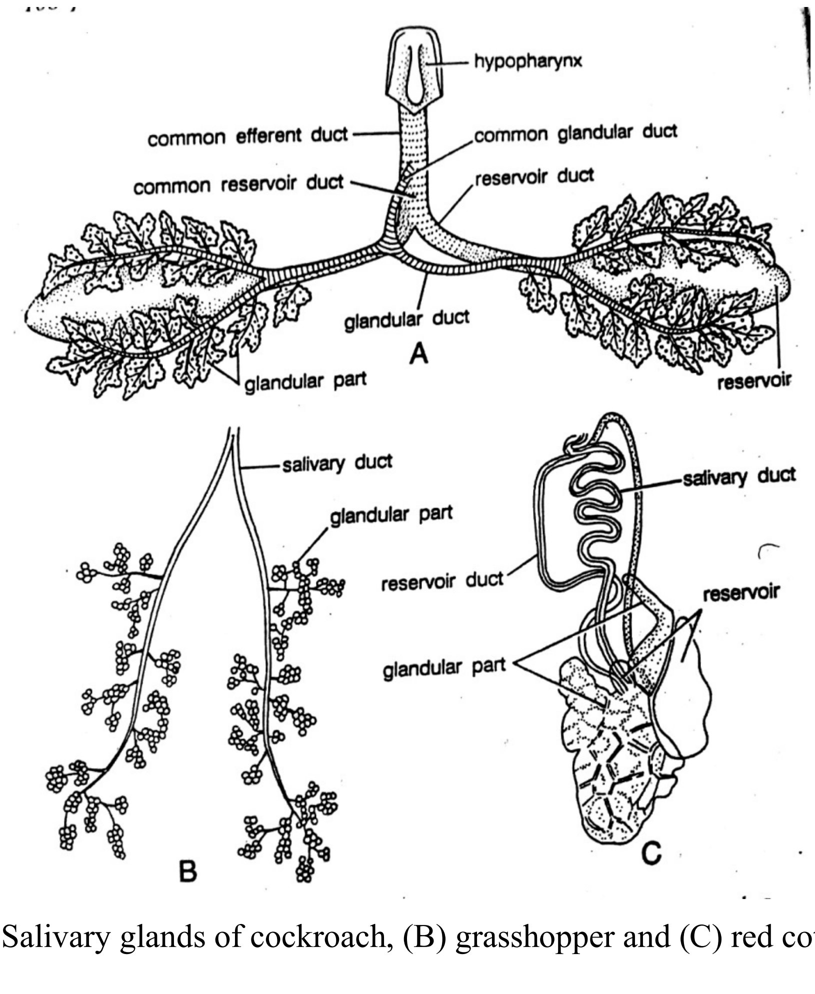


Fig. (A) Salivary glands of cockroach, (B) grasshopper and (C) red cotton bug.

Functions of salivary gland:

The secretory products of the salivary glands are generally clear fluids that serve a variety of functions in different insects:

1. They moisten the mouthparts and serve as a lubricant
2. They act as a food solvent
3. They serve as a medium for digestive enzymes and various anticoagulins and agglutinins
4. They secrete silk in larval Lepidoptera (caterpillars) and Hymenoptera (bees, wasps and relatives)
5. They are used to flue puparial cases to the substrate in certain flies
6. They serve for the production of toxins and
7. They secret antimicrobial factors (e.g. in certain blow fly larvae).

Amylase and invertase are the most common enzymes found in saliva of insects however the saliva may also contain lipase and protease. Aphids secrete a pectinase that aids their mouthparts in the penetration of plant tissues. The spreading factor hyaluronidase which attacks a constituent of the intercellular matrix of many animals has been found in the assassin bug.

Blood sucking (haematophagous) insects contain various antihaemostatic agents.

Production and secretion of saliva in the dragonflies, grasshoppers and cockroaches are regulated by nervous innervations from both the stomatogastric nervous system and the subesophageal ganglion whereas in the Diptera (e.g. the adult blow fly) these glands are controlled by an unidentified neurohormone. Salivation has been shown to be controlled by phagostimulation of external chemoreceptors on the mouthparts. This same stimulus probably also activates the salivary pump.

3.6 Physiology of digestion, including special foods

In fluid feeders, digestion may begin before the food is ingested through the injection or regurgitation of enzymes on to the food, or in foregut but in general most digestion occurs in the midgut where most of the enzymes are produced. In insects having biting and chewing type of mouthparts, food is masticated not only in the buccal cavity but also in the proventriculus. This not only facilitates passage through the alimentary canal but increases the surface area for enzymatic action. Digestion takes place by a series of progressive enzymatically catalysed steps, each producing a simpler substance until molecules of absorbable size or nature are produced.

Extra intestinal digestion

Digestion of the food taking place outside the alimentary canal before the food is ingested is known as extra intestinal digestion. It happens with fluid feeders where salivary enzymes are injected onto the food (e.g., house fly) or into the host in predatory or parasitic insects for example, assassin bugs inject saliva into the prey which histolyses the contents before ingestion.

Intestinal digestion

In general most of the digestion occurs in the midgut where enzymes are secreted however, some digestion also takes place in foregut, particularly in crop, where midgut enzymes are regurgitated into it. In locust, the major proportions of digestion takes place in crop.

The enzymes synthesized in the midgut depend upon the diet. For example, insects feeding protein diet proteases are important, whereas a nectar feeding butterflies they are absent. Aphids feeding on phloem sap having no polysaccharides or proteins lack enzymes and proteinase but have invertase.

Digestion of carbohydrates

Carbohydrates are generally absorbed as monosaccharides so that, before they are absorbed, disaccharides and polysaccharides must be hydrolysed to their component monosaccharides.

Polysaccharides: Starch, glycogen, chitin and cellulose are the major polysaccharide food to be digested by different insects. Starch (amylose) is hydrolysed to maltose, and glycogen to glucose by the action of amylase, which specifically catalyses the hydrolysis of 1,4-α-glucosidic linkage in polysaccharides. The major portion of the food of phytophagous and xylophagous insects contains cellulose, only few insects (Ctenolepisma, Schistocerca and some psocids) are able to secrete cellulase. The insects unable to secrete cellulose, either cellulose is excreted as such or they harbour micro-organisms (bacteria, flagellates) to secrete cellulase.

Other polysaccharides, viz., chitihn, lignocelluloses and hemicelluloses are digested by chitinase, lignocellulase and hemicellulase, respectively.

Disaccharides: The common disaccharides in the food are maltose, trehalose, sucrose, cellobiose, melibiose and lactose that contain a glucose residue which is linked to a second sugar residue by either α-linkage and β-linkage. In the hydrolysis water molecule is the typical acceptor for the sugar residues as follows :

$$\text{Maltose} + H_2O \xrightarrow{\text{maltase}} \text{Glucose} + \text{Glucose}$$

$$\text{Trehalose} + H_2O \xrightarrow{\text{trehalose}} \text{Glucos e} + \text{Glucose}$$

$$\text{Sucrose} + H_2O \xrightarrow{\text{sucrase}} \text{Glucose} + \text{Fructose}$$

$$\text{Cellobiose} + H_2O \xrightarrow{\text{cellobiase}} \text{Glucose} + \text{Glucose}$$

$$\text{Melibiose} + H_2O \xrightarrow{\text{melobiase}} \text{Galactose} + \text{Glucose}$$

$$\text{Lactose} + H_2O \xrightarrow{\text{lactase}} \text{Glactose} + \text{Glucose}$$

Digestion of proteins: Insects possess a series of proteases. A trypsin like proteinase is secreted in the midgut which hydrolyses protein to peptones and polypeptides. The products are then broken down by peptidases. The carboxypolypeptidase attacks peptide chain from the –COOH end and aminopolypeptidase attacks the chain from the $–NH_2$ end. Some of these occur in the gut lumen, but most of them are found in the intestinal epithelium. It indicates that most of the polypeptides are absorbed before being further digested to amino acids. Certain insects are able to digest ordinarily stable proteins. For example, chewing lice and a few other insects are able to break down keratin a protein that occurs in hair and feathers.

Digestion of lipids: Many insects secrete lipases which hydrolyse fats to fatty acids and glycerol. Wax moth (*Galleria*) is able to digest beeswax (a mixture of esters, fatty acids and hydrocarbons). The insect is known to produce not only the lipase, but also lecithinase and cholinesterase with the help of bacteria.

Midgut pH (typically pH 6-8) buffering capacity, oxidation reduction potential and temperature are important factors in the digestive process. These factors vary from species to species and may also vary from one region of the another within the same insect.

Absorption of the digested food

The midgut is the major site of absorption. In hindgut only reabsorption of urine components occur while in foregut no absorption takes place. All the substances are absorbed in solution and no phagocytosis of food particles occurs. There are three major factors that affect the absorption of digested food materials:

I. The presence of microvilli, which increase the surface area for absorption,
II. The functional differences in membrane permeability of various regions of the digestive tract and
III. The presence of a counter current.

Absorption may be active or passive. Passive absorption takes place from the higher concentration inside the lumen of the gut to lower one (inside the gut epithelium). Active absorption depends on some metabolic process for movement of a substance against a concentration or electrical gradient.

Carbohydrate: Carbohydrates are mainly absorbed as monosaccharides that diffuse concentration gradients between the midgut lumen and haemolymph. The diffusion of simple sugars like glucose and fructose is enhanced by the rapid conversion of these sugars to trehalose in the fat body a process called facilitated diffusion that maintains a concentration gradient across the gut epithelium. Some insects are able to absorb disaccharides as such.

Proteins: Proteins are absorbed as amino acids after hydrolysis mainly in the midgut and caeca. Some amino acids in urine are also reabsorbed in hindgut. Insects are unique in that they maintain rather high levels of free amino acids stores in the haemolumph, thus many amino acids have to be actively absorbed against a concentration gradient. Some insects are able to absorb peptide fragments or even the protein as such e.g., midgut cells of a haemolymph bug *Rhodnius* absorb haemoglobin as such. Active absorption of amino acids varies among insect species and depends on the composition of the diet and the haemolymph.

Lipids: Like some disaccharides and proteins, lipids are also sometimes absorbed unchanged. The products of wax are absorbed in a phosphorylated form while cholesterol is esterised before absorption. The midgut caeca appear to be particularly active in lipid absorption, but in few insects like adult Hymenoptera, lipid is absorbed in hindgut.

Water: Water is absorbed mainly in midgut and also in hindgut either by diffusion or active transport depending upon the need of the insect as insects regulate the salt water balance very precisely. As the amount of food is very poor in the contents of phloem and xylem, insects feeding on them, e.g., plant bugs, in order to obtain sufficient amount of amino acids and other nutrients, they possess various mechanisms for concentrating the necessary nutrients from a dilute food source by eliminating water. The filter chamber, present in the Cicadoidea and Cercopidae (order Homoptera) is a modification of the anterior midgut, which in combination with the malpighian tubules facilitates water removal and concentration of the desired nutrients prior to absorption.

Inorganic ions: Inorganic ions are absorbed in the midgut and reabsorbed in the fluid in the rectum. Even in the midgut there are specified cells that absorb particular ions, e.g., Fe^{++} and Cu^{++} . All the three ions Na^+, K^+ and Cl^- are absorbed actively as their concentrations is very high in haemolymph than the gut lumen.

The active transport of Na^+ may play a key role in the diffusion of other molecules. When Na^+ molecules are pumped from the midgut cells into the haemocoel, they are replaced by Na^+ diffusing into the midgut cells from the lumen. The movement of Na^+ across the cells tends to produce a water gradient between the lumen and the cells concentrating water in the lumen. Hence, water would diffuse into the cells which, in turn, tend to concentrate other molecules that would then diffuse down gradients into the cells. It implies that the work necessary to produce the gradients for diffusion (a passive process) of water and other absorbable molecules would be the active transport of Na^+.

Regulation of the alimentary system/ metabolism

Regulation of the alimentary system in insects involves control of food movement, control of enzyme secretion, and control of absorption. The alimentary canal is regulated in part through the action of the stomatogastric nervous system. Food is ingested by the actions of the mouthparts, cibarium and pharynx and is typically stored in the crop. It is then released gradually, via the stomodeal valve, into the midgut where digestion and absorption occur. In most insects that have been studied stretch receptors associated with the crop provide information to the brain (via the frontal ganglion) regarding crop distension and help prevent overfilling of this organ. In some insects, stretch receptors in the abdominal wall have a similar role.

Control of passage of food from the crop to the midgut (rate of crop emptying) has been studied mainly in the cockroach, Periplaneta americana. Passage of food from the cockroach crop is inversely related to the osmotic pressure of the food, i.e., the higher the concentration of food, slower the passage. Osmotic receptors have been identified in the wall of the cockroach pharynx.

Two mechanisms for the control of enzymes secretion in the insect gut have been suggested: Secretogogue (a substance in the ingested material may stimulate enzyme secretion) and hormonal. The secretogogue control is an immediate response to food, whereas hormonal control is more related to developmental and environmental effects. Nervous control is highly unlikely because the midgut is sparsely innervated or not at all.

Absorption appears to be controlled by the availability of absorbable molecules, release of food material from the crop being so regulated that digestion and subsequent absorption occur at an optimal rate for a given circumstance.

Many insects ingest foods with a very high water content. Some of these insects (e.g., butterflies and many true flies) store the dilute food in the impermeable crop and pass it gradually to the midgut. In others (e.g., many blood feeding insects) food may go to the midgut where excess water is rapidly absorbed in the haemolymph and then excreted via the malpighian tubules. Both mechanisms probably prevent extensive dilution of the haemolymph and removal of water concentrates solid food increasing the efficiency of digestion.

Movements of the alimentary canal (mainly foregut and hindgut) that complement the action of the digestive enzymes and help absorption are under neural or neurosecretory control in some insects. In others, having no neural connections, gut movements are assumed to be myogenic. Hormonal stimuli may also have a great deal to do with the rate of gut movement.

3.7 Insect nutrition

Like other animals, insects also require a balance diet having appropriate amount of proteins, amino acids, carbohydrates, lipids, vitamins, minerals etc. The dietary requirement of the insect is species specific. For the proper development and growth, the insects derived most of the nutrients either by taking food or from the stores inside the body (e.g. fat bodies), or as a result of synthesis (by the insect itself or through associated micro-organisms). Certain moths do not feed as adult, and the food accumulated during larval stages is used for their metabolic processes. All insects are able to synthesise nucleic acids, however only some insects are able to synthesise vitamins, non essential amino acids.

Amino acids: Amino acids are the building blocks of protein making the tissues and enzymes. Different insects have different requirements, depending upon which amino acids they are capable of synthesizing. Although some 20 amino acids are needed for protein production only ten are essential in the diet, the others can be synthesised from these ten. The ten essential amino acids are arginine, lysine, leucine, isoleucine, tryptophan, histidine, phenylalanine, methionine, valine and threonine. In addition to essential amino acids, few insects need glycine (e.g., flies) or alanine (e.g., Blatella) or proline (e.g., Phorima), however in these cases methionine is not essential.

In general the absence of any one of these essential acids prevents growth. Although other amino acids are not essential, they are necessary for optimal growth to occur because their synthesis from the essential acids is energy consuming and necessitates the disposal of surplus fragments (Dadd,1973). Consequently glutamic acid and aspartic acid are necessary in addition to the essential amino acids for good growth of Bombyx larvae and further improvement is obtained if alanine, glycine or serine are also present. Good growth of Mysus persicae depends on the presence of cysteine with glutamic acid, alanine or serine.

Carbohydrate: Carbohydrate are not considered to be essential nutritive substance for most insects, but they are probably the most common source of chemical energy utilised by insects. However, many insects (e.g., many moths) do, in fact, need them if growth and development are to occur normally. Schistocerca for instance needs at least 20% sugar in an artificial diet for good growth. Tenebrio fails to develop unless carbohydrate constitutes at least 40% of the diet and growth is optimal with 70% carbohydrate. The carbohydrate may be converted to fats for storage or to amino acids. In the diet of Galleria carbohydrate can be entirely replaced by wax and this is also true in many Diptera, such as Musca. Larval Phorima which normally live in necrotic tissues containing little carbohydrate are adversely affected by any carbohydrate in the diet.

There may be differences in the ability of larvae and adults to utilise carbohydrates. For instance, the larva of Aedes can use starch and glycogen while the adult cannot.

Lipids: Lipids or fats, like carbohydrates are good sources of chemical energy and are also important in the formation of membranes and synthesis of steroid hormones. Most insects are able to synthesise lipids from carbohydrates and protein sources. However, some insect species do require certain fatty acids and other lipids in their diets. For example, certain Lepisoptera require linoleic acid for normal larval development. All insects need a dietary source of sterol (cholesterol, phytosterols or ergosterol) for growth and development. Carotenoids are necessary in the diets of all insects as the visual pigment retinene is derived from the food.

Vitamins: Vitamins are unrelated organic substances that are needed in very small amounts in the diet for the normal functioning of insects as they cannot be synthesised. They provide structural components of coenzymes. Vitamin A (fat soluble) is required for the normal functioning of the compound eye of the mosquito. Insects principally require water soluble vitamins (e.g., B complex vitamins and ascorbic acid). In the absence of ascorbic acid (vitamin C) locusts undergo abortive moults and dies.

Minerals: Like vitamins several minerals are required in traces by insects for normal growth and development, e.g., potassium, phosphorous, magnesium, sodium, calcium, manganese, copper, iron, chlorine, iodine, cobalt, nickel and zinc. The aquatic larvae of mosquitoes are able to absorb mineral ions from the water through the thin cuticle.

The nucleic acids: Nucleic acids (DNA and RNA) constitute the genetic material. Like other animals, insects are also able to synthesise them. However, dietary nucleic acids (e.g., RNA) have been shown to have an influence on growth of certain fly larvae.

Water: Like all animals, insects require water. Insects fulfil their water requirements from body, by drinking, from absorption through the cuticle (in aquatic forms) or from a by product of metabolism. Insects vary greatly with respect to amounts of water needed. Some, like the rice weevil *(Sitophilus oryzae)* can survive and reproduce on essentially dry food. Others, for example honey bees and house flies, require large amounts of water for survival. The excrement of the rice weevil is hard and dry with almost all the water absorbed by the insect, while the excrement of bees and house flies contains large amounts of water.

Microbiota and nutrition

Types of micro-organism

The most commonly occurring micro-organisms in insects are bacteria or bacterium like forms which are found in Blattoidea, Isoptera, Homoptera, Heteroptera, Anoplura, Coleoptera, Hymenoptera and Diptera. In addition flagellates are found in wood eating cockroaches and termites, yeasts in Homoptera and Coleoptera and an actinomycete in Rhodnius. In many cases the precise nature of the micro-organisms is not known.

Location in the insect body

In some insects the symbionts are free in the gut lumen. This is the case with the flagellates which live in the hindguts of wood eating cockroaches and termites and with the bacteria living in the caeca of the last segment of the midgut in plant sucking Heteroptera. In Rhodnius, Actinomyces lives in crypts between the cells of the anterior midgut.

Most micro organisms are intracellular in various parts of the body. The cells housing the symbionts are known as mycetocytes and these may be aggregated together to form organs known as mycetomes.

Mycetocytes are large, polyploid cells occurring in many different tissues. Normally the micro organisms are incorporated into them when the cells are first differentiated in the embryo, but sometimes the cells develop for a time before they are invaded. Most commonly the mycetocytes are scattered through the fat body, as they are in cockroaches and coccids, but in *Haematopinus* (Siphunculata) they are scattered cells in the midgut epithelium and in other insects they may be in the ovarioles or free in the haemolymph.

The presence of microbes in the gonads ensures the infection of any egg produced thus transferring the microbes in next generation.

The wood eating cockroaches have two sets of symbionts : intestinal flagellates and intracellular bacteroids in the fat body. This situation also occurs in the termites *Mastotermes darwiniensis* but the remainder of the wood eating termites only retain the intestinal fauna.

The association of microbes with the insects may either be casual or constant. The microbes are almost present in food and are ingested by the insects during feeding, e.g., locusts. Such casual association with microbes are important in the nutrition of dung beetles that have fermentation chamber in the hindgut in which decaying food with its content of microbes is retained. The insects may have constant association with the microbes, e.g., insects feeding on wood, dry cereal, feather and hair.

The roles of micro organisms in the insect

It is known that the intestinal flagellates of cockroaches and termites are concerned with the digestion of wood and that they release products which can be utilised by the insect. The yeast of Stegobium (Coleoptera) provides vitamins and sterols, which may be secreted into the gut or released by the digestion of the micro organisms. There is some evidence that the micro organisms particularly those in Homoptera and Heteroptera are concerned with nitrogen metabolism (Toth, 1952).

In the coccid *Stictococcus sjoestedti* the bacterium like micro organism may be concerned with sex determination. In the mature insect mycetocytes invade the ovary but only infect those oocytes to which they are adjacent. Consequently two types of eggs are developed : those with and those without micro organisms. The eggs develop parthenogenetically and the uninfected eggs develop into males, while the infected ones give rise to females (Richards and Brooks, 1958).

3.8 Summary

- Each muscle is made up of a number of fibres, which are long, usually multinucleate, cells running the whole length of the muscle. Each fibre is bounded by the sarcolemma, which comprises the plasma membrane of the cell plus the basement membrane. The cytoplasm of the fibre is called sarcoplasm and the endoplasmic reticulum which is not connected to the plasma membrane is known as the sarcoplasmic reticulum.
- The unit of the muscle between two Z lines is called a sarcomere.
- Digestive system composed of alimentary canal and various glands related with it either directly (salivary glands, gastric caeca) or indirectly (malpighian tubules).
- The salivary glands or labial glands are paired structure lie ventral to the foregut in the head and thorax and occasionally extend posteriorly into the abdomen.
- The most commonly occurring micro-organisms in insects are bacteria or bacterium like forms which are found in Blattodea, Isoptera, Homoptera, Heteroptera, Anoplura, Coleoptera, Hymenoptera and Diptera. In addition flagellates are found in wood eating cockroaches and termites, yeasts in Homoptera and Coleoptera and an actinomycete in Rhodnius.

3.9 Self Learning Exercise

Section -A (Very Short Answer Type)

1. Define sarcomere.
2. What is mycetocytes?
3. Define apodemes.

Section -B (Short Answer Type)

1. Describe structure of muscles with suitable diagram.
2. Write short essay on insect nutrition.

3. Write short notes on :
    a) Function of salivary glands
    b) Activation of muscle fibres

Section -C (Long Answer Type)

1. Describe the muscular system of insects?
2. Write short notes on:
    a) Control of muscular contraction
    b) Salivary gland
3. What do you mean by digestion? How does it take place in insects? Describe.
4. Write short notes on :
    a) Microbiota and nutrition of insects
    b) Absorption of digested food
5. Describe the physiology of digestion in insects.

3.10 References

- **Elements of Entomology by Rajendra singh**
- http://bugs.bio.usyd.edu.au/learning/resources/Entomology/importance/importance.html
- http://www.shivrai.co.in/elearning/lesson_1.html

Unit - 4

Insect Anatomy and Physiology – II

Structure of the unit

4.1 Objective

After going through this unit you will be able to explain that

- Different organs associated with circulatory and respiratory system.
- Function of hemolymph.
- Various adaptation of different insects living under different habitat.
- How parasitic forms cope up with environment?
- What is the importance of hemolymph?
- How the circulatory system is called open and closed?

4.2 Introduction

Generally the circulatory system concern with transport of nutrients, gases, hormones, blood cells towards and away from cells in the body to protect, stabilize body temperature and pH to maintain internal body environment i.e homeostasis. This system includes cardiovascular system which distributes blood and the lymphatic system which distributes lymph. It includes dorsal vessel, heart, ostia, pusatile organs and hemolymph. The flow is unidirectional from posterior to anterior region and having open spaces or cavities called heamocoel as the insects consists of open circulatory system.

The respiratory system is a way to distribute oxygen to all cells of the body and for excrete waste product carbon dioxide (CO2) in cellular respiration. The respiratory system of insect is separate from the circulatory system as it is a complex network of tubes called a tracheal system that delivers oxygen-containing air to every cell of the body in case of aerial respiratory system. The air enters through openings called spiracles and transport to the body parts through many longitudinal and transverse channels. Other larval forms, parasitic forms adapt and modify themselves according to the environment. All insects are aerobic organisms. They must obtain oxygen (O2) from their environment in order to survive. They use the same metabolic reactions as other animals (glycolysis, Kreb's cycle, and the electron transport system) to convert nutrients (e.g. sugars) into the chemical bond energy of ATP. During the final step of this process, oxygen atoms react with hydrogen ions to produce water, releasing energy which is captured in a phosphate bond of ATP.

4.3 Circulatory organs in insects

Insects are deficient of veins or arteries but they do have separate system to circulate fluids. As blood moves in large spaces instead of vessels, the organism is known to possess an open type of circulatory system. It differs from closed circulatory system found in vertebrates and higher invertebrates both in structure and function. In an open circulatory system, blood/ hemolymph lies in large and opened body cavities called haemocoel and thus blood makes direct contact with all internal tissues and organs. The thoraco abdominal body cavity is divided into three major compartments with the help of two partitions. These partitions are called dorsal diaphragm placed dorsally and ventral diaphragm placed ventrally. Due to these diaphragm the insect body cavity is divided into three cavities pericardial cavity that surrounds the dorsal aorta, perivisceral cavity that surrounds the alimentary canal and perineural cavity that surrounds the nerve cord.

Difference between open and closed circulatory system:

During the evolution of animals the lower animal phyla like porifera, colenterata and platyhelminthes do not have definite circulatory system. As the complexity started from lower to higher animal phyla the arthropods and mollusca are having efficient circulatory system with open type as the blood flowing in vessels opens into open spaces called sinus or body cavities called hemocoel. All the organs and tissues are bathed in blood and remain in direct contact with the blood. Due to the open channels low blood pressure is maintained in insects. As far as closed type of circulatory system is concerned blood flows in arteries divide and redivide into capillaries reach to the organ and come back to heart via veins as in annelid and vertebrates (FIG 4.1).

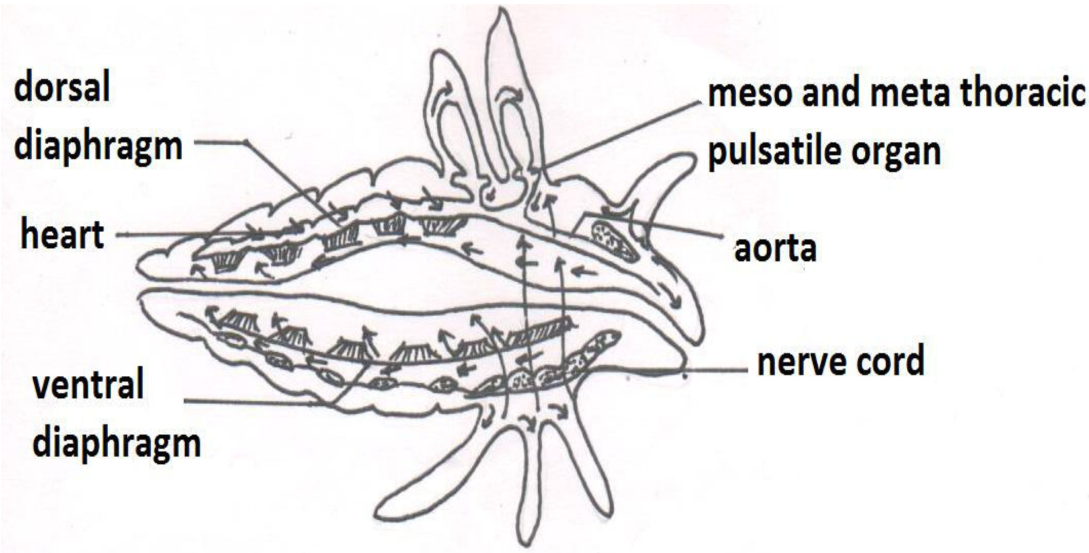


FIG 4.1: Direction of circulation in L.S. of insect.

4.3.1 Circulatory organs

1. Dorsal Vessel/ dorsal aorta/heart

Dorsal aorta as the name suggests lie in the dorsal region of the body below the body wall. It is a longitudinal tube runs from thorax and abdomen and constitute major structural component of an insect's circulatory system. It is further divided and often constricted into 5 to 6 heart chambers separated by valves (ostia) to ensure unidirectional flow of hemolymph. In *Nymphalid* butterfly only larva has both forward and backward peristaltic movements exceptionally. It is a fragile simple tube without ostia and sometimes connected with vertical diverticulum associated with pulsatile organs. In most insects, hemolymph flows in a direction from posterior to anterior end of the body that is from abdomen to the head. It consists of aortic valve near heart and divides into 2-3 cephalic arteries which again further divides into smaller vessels.

2. Ostia

In heart incurrent and excurrent both types of ostia are present. Incurrent ostia consist of 9 pairs in abdomen and 3 pairs in thorax. The ostia are valvular in generalized insects like cockroach. Numbers of incurrent ostia are variable like in wasp 5 pairs and in housefly 3 pairs are present. Excurrent ostia are non valvular, in grasshoppers, silverfishes 2 thoracic and 5 abdominal pairs are present. In cockroaches where excurrent ostia are absent certain lateral segmental vessels are associated with heart. During each diastolic phase/relaxation, the ostia open to allow inflow of hemolymph from the body cavity and during contraction of heart these ostia closes and the hemolymph move forward.

3. Alary/ Aliform muscles

Many pairs of alary muscles are attached laterally to the walls of each chamber of heart so as to keep them in position. Alary muscles are 2 thoracic and 10 abdominal in grasshoppers and 4-7 pairs in bugs. It is due to these muscles, peristaltic contractions occur which force the hemolymph forward from one chamber to another.

4. Accessory pulsatile organs

These organs are there in mesothorax or sometimes in metathorax which are concerned with circulation of hemolymph into legs/ wings/ antenna. In some insects, pulsatile organs are located on the base of the wings, appendages or antenna in grasshoppers and cocokroaches. Pulsatile organs do not usually contract on a regular basis, but they force hemolymph out into the extremities.

There are two diaphragm dorsal and ventral which separates the haemocoel into three compartments or sinuses perineural, perivisceral and pericardial (FIG 4.2).

4.3.2 Heart beat

The rate of pulse is 30-200 beats/minutes. As the temperature falls or rises the heart beat vary. In larva of stag beetle heart beat is 14 beats/minutes and in flies it is 150 beats/minutes. Heart beat of larva is slower as compared to adult, and in older pupa no heart beat is found. Younger larva sometimes stops beating.

4.3.3 Control of heart

Insect's heart is myogenic and it lacks pacemaker. In cockroach neurogenic nerves supplied from corpora cardiac and motor fibres of segmental ganglia controls heart. Cardioaccelerator neuropeptide proctolin acts as myotropins and regulate heart. Indolalkylamine in insects is equivalent to adrenaline of higher organisms that accelerate the heart beat.

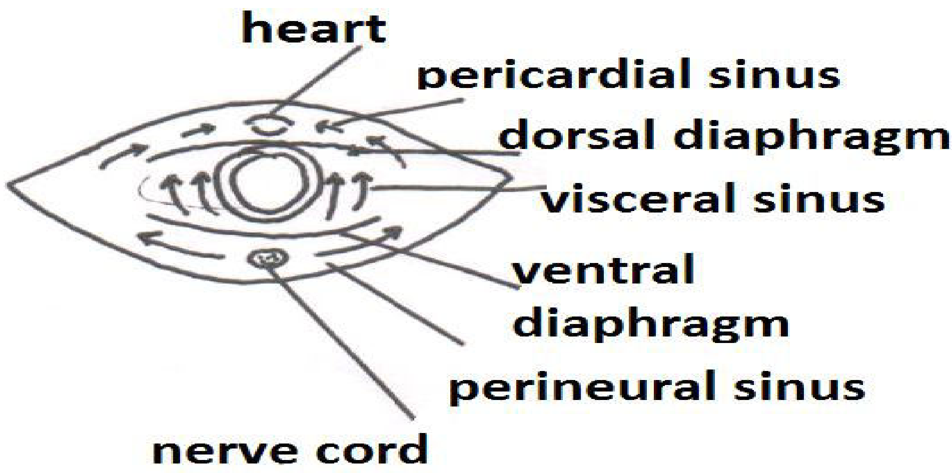


FIG 4.2: Direction of circulation in T.S.

4.4 Composition and function of hemolymph

Hemolymph or blood flows in aorta, small vessels in open channels in insects. The body cavity/ blood sinus is divided into three compartments pericardial surrounding heart, perivisceral surrounding alimentary canal and perineural sinus around nervous system by two thin sheets of muscles or membrane known as the dorsal and ventral diaphragms. The dorsal diaphragm is formed by alary muscles of the heart and related structures separating the pericardial sinus from the perivisceral sinus. The ventral diaphragm separates the perivisceral sinus from the perineural sinus in the same way. Hemolymph is composed of plasma and haemocytes. In insects 170µl of hemolymph contains 7-20 millions of circulating cells.

4.4.1 Plasma

Major portion about 90% of insect hemolymph is plasma and carries 5-40% of total body weight. It is a watery fluid containing 85% water, usually clear colorless fluid, but sometimes green, yellow or brown in color. It is slightly acidic in pH and consist of almost all amino acids. In comparison to vertebrate blood, insects have high concentrations of amino acids, proteins, sugars (glucose in honeybees), uric acid, pigments and inorganic ions. Haemolyph is a dynamic fluid that changes with diet, environmental factors or life stages. For example; In carnivores they have high concentration of Mg+ and K+, In herbivores high Na+,in terrestrial insects high protein, amino acids and uric acids.In aquatic insects high allantion, allantoic acid, NH3, urea are there. Trehalose is a major blood sugar in most insects which is a non reducing dimer of glucose. In certain insects blood sugar may be glucose, fructose or ribose depending upon their food sources . Hemolymph also contains sorbitol or glycerol which is a cryoprotectants or antifreezing agents in the plasma to prevent it from freezing during the winters and fight against cold stress. Lipophorin is a lipoprotein that functions to transport fatty acids, cholestrol, carotenoids, xenobiotics and hydrocarbons. Tyrosin plays important role in sclerotization of cuticle previously explained and proline acts as a flight energy source.

4.4.2 Haemocytes

Left 10% of hemolymph volume is made up of various cell collectively known as hemocytes. All types of cells occurs in haemopioetic organs present in developing stages and adults in exopterygotes and these organs are absent in endoterygotes adult. Different types of cells are as follows;

1. Prohaemocytes are like archaeocytes of sponges that give rise to all other cells. They are spherical in shape having large nucleus and quite RNA rich.
2. Plasmatocytes are of variable shapes with vacuolated cytoplasm. It is most abundant of all and phagocytic in nature.
3. Granulocytes are the largest and phagocytic in nature like plasmatocytes. They have granulated and acidophilic cytoplasm.
4. Oenocytoids are special cells present in some Coleopterans, Dipterans, Lepidopterans and Hemipterans having large and rounded nucleus eccentric in position, but they are not derived from prohaemocytes.
5. Coagulocytes/ cystocytes having scattered granules and helps in coagulation.
6. Spherules may be spherical, oval or spindle shaped with spherules present in cytoplasm. They are present in only Diptera and Lepidoptera.

Porhaemocytes, plasmatocytes and granulocytes are present in all types of insects. Total number of cells varies and depends upon species, developmental stage and physiological state of insect (FIG 4.3). Number of haemocytes increases with instars development, decreases first in early pupal stage and increases in later pupal stage, then decreased in adult stage.

The hydraulic (liquid) properties of blood are important. The hydrostatic pressure generated internally by muscle contraction is used to facilitate hatching, moulting, expansion of body and wings after moulting, physical movements (especially in soft-bodied larvae), reproduction (e.g. insemination and oviposition), and evagination of certain types of exocrine glands. In some insects, the blood aids in thermoregulation: it can help cool the body by conducting excess heat away from active flight muscles or it can warm the body by collecting and circulating heat absorbed while basking in the sun.

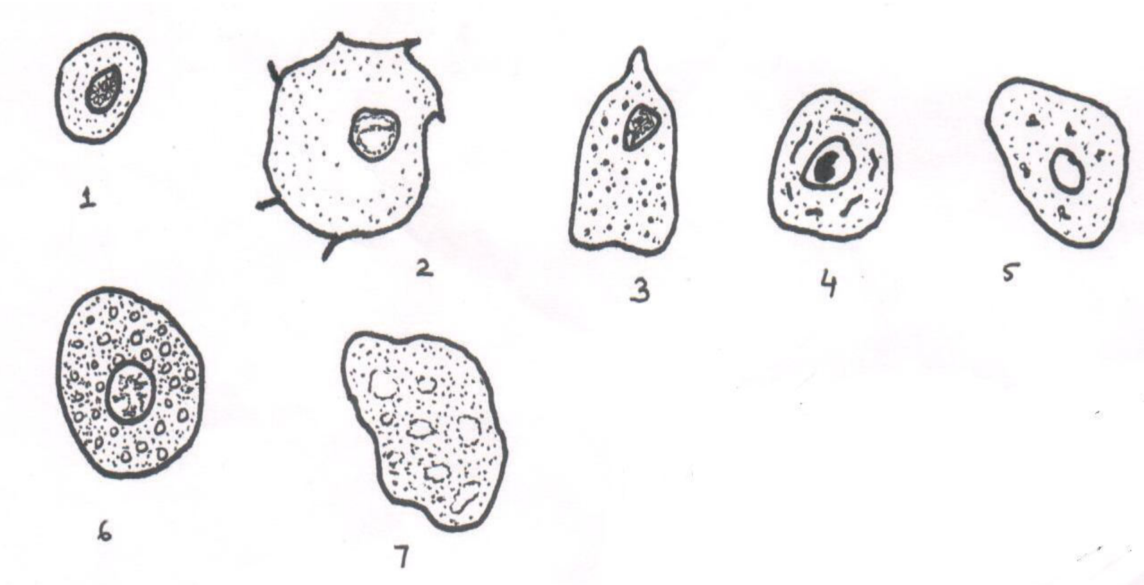


FIG 4.3: Different types of haemocytes 1. Prohaemocytes 2. Plasmatocyte 3. Granular haemocyte 4. Oenocyte 5. Cytocyte 6. Spherule 7. adipocyte

4.4.3 Function of hemolymph

1. Haemolymph creates hydrostatic pressure generated due to muscle contraction that helps the insect to circulate many things.
2. It also facilitates hatching, moulting and expansion of body.
3. Physical movements especially in soft-bodied larvae.
4. It also helps in reproduction like insemination and oviposition.
5. In some insects, the haemolymph aids in thermoregulation, it cool the body by conducting excess heat away from active flight muscles or it can warm the body by collecting and circulating heat absorbed while basking in the sun.

6. It seals off wounds through a clotting reaction.
7. The main function of hemolymph, is to transports hormones, nutrients and waste products.
8. It is important for osmoregulation, temperature control, immunity and storage.
9. It also plays an essential part in predatory defence by having chemicals that deter predators.

4.5 Insect immunity against pathogens

Immunity can be innate/ natural and acquired/ induced. Innate comprises mainly of cell mediated phenomenon like phagocytosis and encapsulation which is performed by the haemocytes. Acquired comes in function when any antigen enters the host. They are different from vertebrate immunity as the antigen antibody reaction is non specific, does not have memory cells and immunogens are not proteins. Two types of humeral immunity are found non inducible and inducible. Non inducible is one which does not require synthesis of RNA and protein like lectins (haemoagglutinin), phenyloxidases. Other is inducible immunity which requires synthesis of RNA and protein like lyzozymes, cercopins, attacins etc. It encapsulates and destroys internal parasites and produces distasteful compounds that provide a degree of protection against predators. Example; hairy caterpillar contains poison in hemolymph.

4.6 Respiratory organs in insects

All insects consume oxygen so they are aerobic. The simple channel for respiration is named as tracheal system which is a complicated system carries many channels.

4.6.1 Types of tracheal system

a) On the basis of connectives and commissure

1. **Simple type**: It is simple and opens through spiracles but it does not connect one trachea to another. Example, springtails.
2. **Complex type**: It consists of dorsal, ventral and lateral trachea connected with commissure and connectives. With this spiracles and air sacs are also present.

b) On the basis of spiracles

1. **Open tracheal system**: Spiracles present. Example, most insects.

2. **Closed tracheal system**: Spiracles absent and gaseous exchange takes place through integument. Example, *Chironomus* larva, mayfly nymph.

They carry oxygen from their environment and use the same metabolic reactions as other animals do like glycolysis, Kreb's cycle, electron transport chain to convert nutrients into ATP. At the last step of this process, oxygen atoms combine with hydrogen ions to produce water, releasing energy that is stored in the form of ATP.

Insects inspire oxygen and exhale carbon dioxide, as a waste product of cellular respiration. Oxygen is transported to the cells directly through respiration, and not carried by blood as in vertebrates. Carbon dioxide diffuses 35 times faster than oxygen.

4.6.2 Respiratory organs

1. Spiracles

The sides of the thorax and abdomen consist of a row of small openings called spiracles. These allow the intake of oxygen from the air into the tracheal system (FIG 4.5, B). The number and types of spiracles varies according to the species.

Types of spiracles

- **Simple spiracles:** It is simply a hole with no provision of regulating the size of aperture. Example, Apterygote, Plecoptera.
- **Typical spiracles**: This type of spiracle has a sclerotic plate called peritreme which surrounds the opening at atrial orifice. The atrial opening leads to the sac called atrium which further leads another opening .Tracheal orifice leads to trachea. It is found in most insects.
- **Biforous spiracles:** Here two orifices are present primary and secondary. Primary orifice is functional only in moulting and secondary orifice is functional. Example, larva of certain Coleopterans.
- **Lid type:** They are spiracles with external closing apparatus. The opening and closing of aperture is controlled by outer lips of atrium. Example, most insects.

- **Valvular type**: They are the spiracles bearing internal closing apparatus called filter apparatus with bristles and a valve that regulate the aperture. Example, abdominal spiracles (FIG 4.6).

In flies, beetles and moths spiracles are covered with sieve plate having large number of pores.

On the basis of number of spiracles: The insects are also called polypneustic having many pairs of spiracles, oligopneustic having few and apneustic having no spiracles. In the case of polypneustic the insects may carry 10, 9 or 8 functional spiracles and named as holopneustic (in cocroaches), peripneustic (in some fly larva) and hemipneustic. Oligopneustic type consist of one mesothoracic and one abdominal spiracles functional while all rest are non functional in amphineustic (second maggot stage of mosqutio), only last abdominal functional in metapneustic (first maggot stage of mosqutio) and only mesothoracic in propneustic type (in most of the dipteran larva). The older orders Collembola, Protura and Chironomid larva consist of absolutely no spiracles (FIG 4.4).

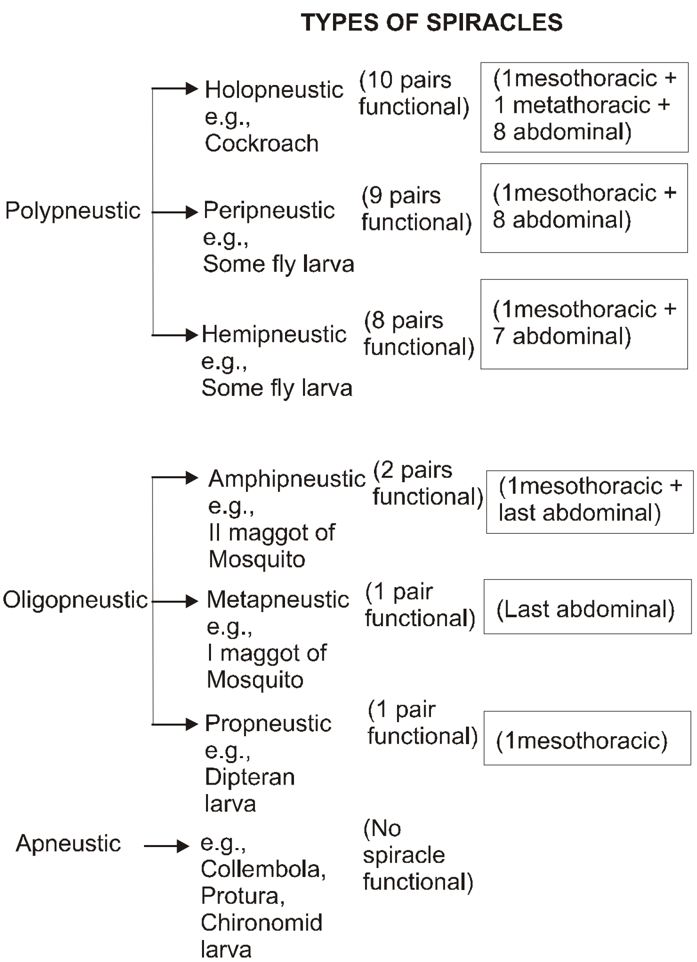


FIG 4.4: Types of insects on the basis of number of spiracles functional

2. **Trachea**

The spiracles leads to the longitudinal tube called trachea lined with intima propria. Cuticulin layer of epicuticle covers entire integumental surface including trachea and tracheoles. The intima of of trachea sheds in each moult. Trachea develops from the invagination of ectoderm during embryonic development (FIG 4.5, A). Trachea is absent in Collembolla, Protura and endoparasitic forms. The intima of the tracheal tube is folded and forms spiral ridges called taenidia that protect the insect from collapsing. Trachea is classified according to the place they are situated as dorsal, ventral, lateral, dorso-lateral and ventro-lateral.

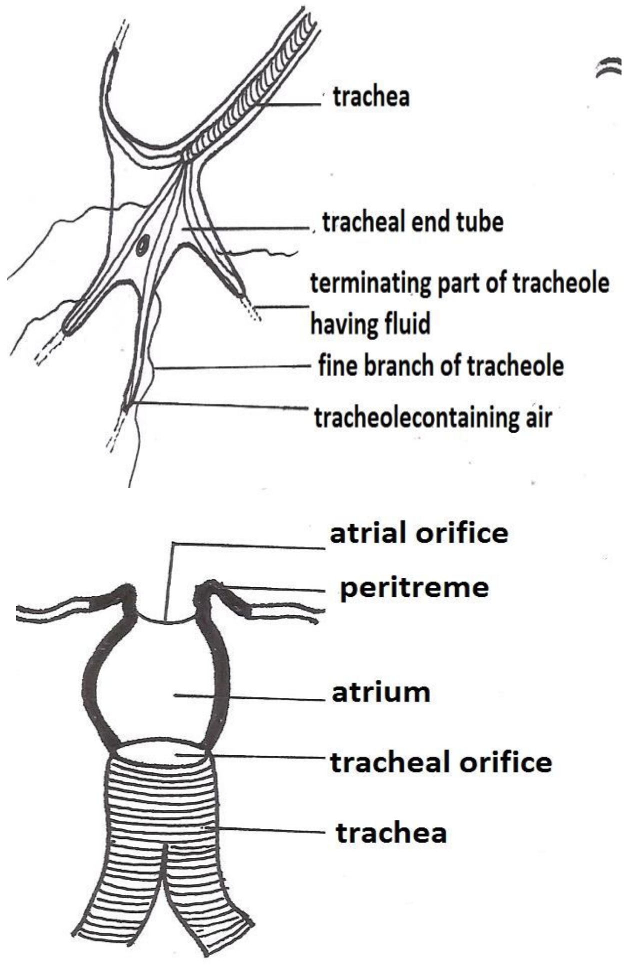


FIG 4.5: A) Tracheole B) Spiracle

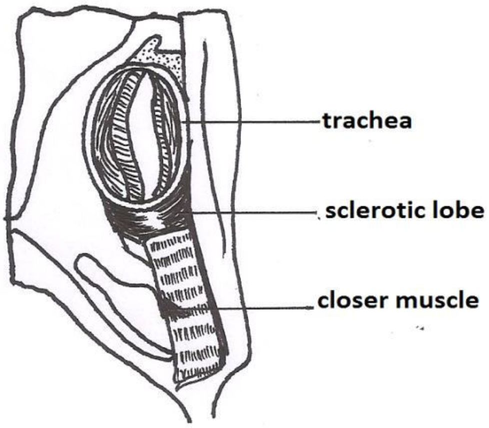


FIG 4.6: Outer and inner view of 2nd thoracic spiracle of grasshopper

3. Tracheoles

The longitudinal tracheal trunk gives a complex, branching network of tracheal tubes that subdivides into smaller and smaller diameters and reaches every part of the body called tracheoles. Tracheoles are enclosed in a very thin layer of cytoplasm from the tracheal end cell (tracheoblast). It is 0.2µ- 1µ in diameter and is associated with the organs having more oxygen demand like flight muscles, ovaries, fat body, malphigian tubules, rectal papilla and gut epithelium. Large tracheoles consist of cuticle and epidermis but in small tracheoles only epicuticle is present. In fifth instar of silkworm , 1.5 million tracholes are present (FIG 4.7).

4. Air sacs

In some areas, however, there are no taenidia, and the tube swell like a balloon to form air sac capable of storing/reserve air. Air sacs are mostly the characteristic feature of flying insect as taenidia absent. It increases the volume of air which performs various functions prevent collapsing, heat conservation, forms tympanic cavity aid in hearing organ in *Cicada* moth.

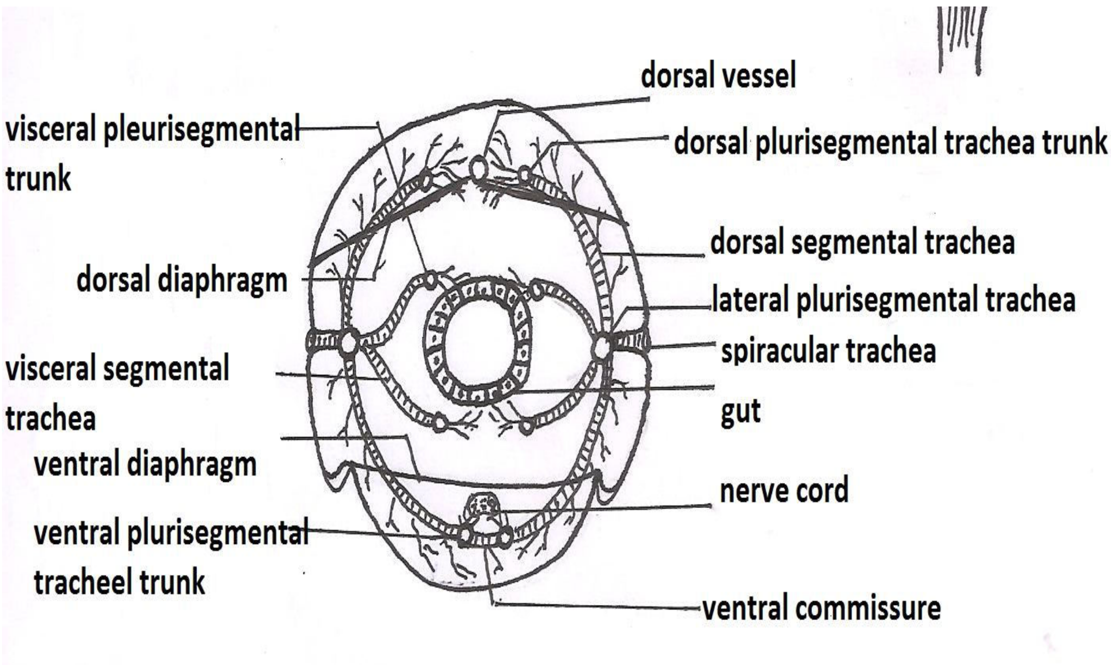


FIG 4.7: T.S. of generalized insect through abdomen showing main tracheal trunks

In terrestrial insects during high evaporative stress, air sacs conserve water by closing its spiracles. In aquatic insects stored air in sacs provide buoyancy in water. It also helps in moulting by air sacs enlargement that breaks old exoskeleton and expands a new one.

4.6.3 Mechanism of respiration

Gaseous exchange takes place between tissues and wall of tracheoles by the process of diffusion, active ventilation and passive ventilation.

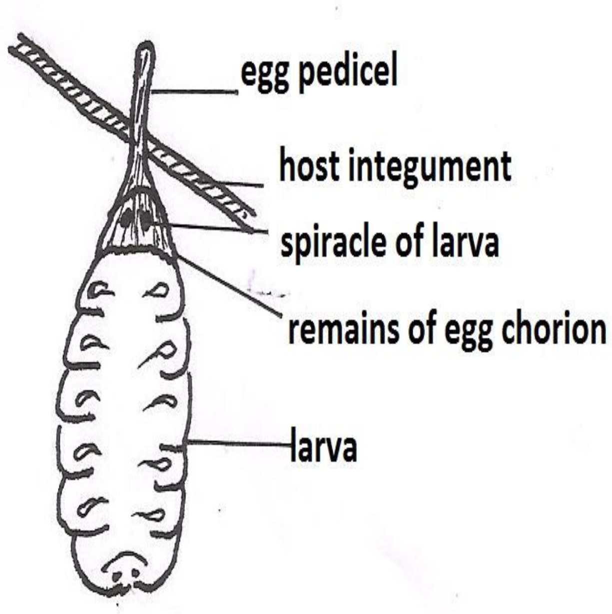
1. Diffusion is based on tracheal length, its diameter and permeability. Oxygen in the tracheal tube first dissolves in the liquid of the tracheole and then diffuses into the cytoplasm of an adjacent cell. At the same time, carbon dioxide, produced as a waste product of cellular respiration, diffuses out of the cell and, eventually, out of the body through the tracheal system.
2. **Passive ventilation** facilitates respiration in larval stages and pupal ventilation occurs through suction. This uses high solubility of carbon dioxide in water and spiracular valve kept closed. When CO2 is produced it is stored partly in haemolyph in the form of bicarbonates and partly in tracheal system.
3. **Active ventilation** occurs through alternatively decreasing and increasing the volume of tracheal system. This is due to the contraction

of abdominal dorso-ventral muscles that increases the hemolymph pressure.

Autoventilation may occur in orders Odonata, Orthoptera, Hemiptera, Isoptera, Lepidoptera and Hymenoptera.

4.7 Respiration in endoparasitic forms

Mostly endoparasitic insects fulfill their requirement through cutaneous respiration. In larva of *Blastothrix* (FIG 4.8, A), (Order Hymenoptera) attaches remains of egg posteriorly and maintains contact with atmosphere. In larva of *Thrixion* (FIG 4.8, B). order Diptera forms respiratory funnel formed by ingrowth of host integument. In first instar larva of endoparsitic Hymenoptera and Diptera tracheal system is filled with liquid. In *Cotesia* larva hindgut has an everted structure called caudal vesicle.



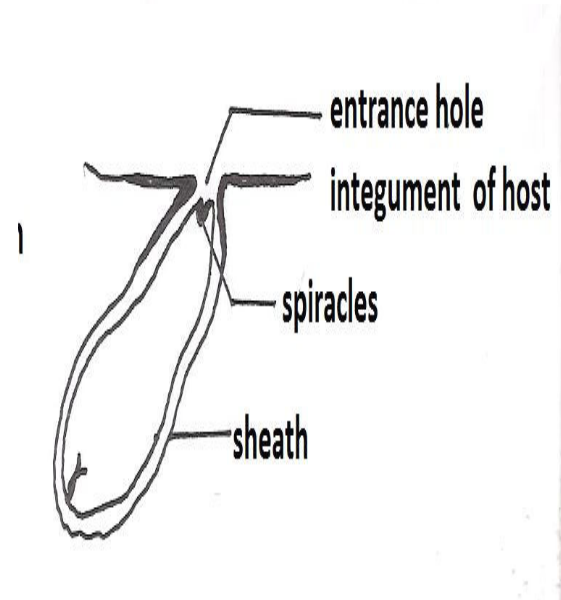


FIG 4.8: A) larva of Blastothrix (Hymenoptera) B) larva of Thrixion (Diptera)

4.8 Adaptations in aquatic insects and immature stages

Aquatic insects also respire through intake of oxygen but air has to be stored in air sacs so that they can breathe under water. The insects having open tracheal system come to the water surface to store air in tracheal system often at regular intervals. The insects with closed tracheal system the air may be directly taken by body wall. They are equipped with a variety of adaptations as follows:

1. **Tracheal gills**: They are the outgrowth of body wall of hindgut, example, Mayflies and Damselflies larva. The outgrowth may be of

caudal region called caudal lamella in Zygoptera, lateral abdominal gills in Ephemeroptera, Plecoptera, Coleoptera and rectal gills in Anisoptera.

2. **Hydrofuge hairs:** In some aquatic insects spiracles are surrounded by water repellent hairs on the base lies special oil secreting cells, dipteran larvae, *Notonecta* (FIG 4.9, A).
3. **Cuticular Respiration:** Many aquatic species can exchange gases through thin and permeable integument, black fly pupa.
4. **Spiracular gills:** They are the outgrowth of body wall near spiracles, pupa of *Psephenoides gahani* (Coleoptera) and pupa of certain Diptera.
5. **Plastrons:** These are special hydrophobic hairs which are bending on tip and thickened at base so as to create air space next to the body. Air is trapped within a plastron when insect comes regularly to exchange gases. Examples, *Elmis* (Coleoptera) and *Aphelocherirus* (Hemiptera, FIG 4.10).
6. **Biological Gills:** These are organs which can allow dissolved oxygen from the water to pass into an organism's body by the process of diffusion. In insects gills are usually outgrowths of the tracheal system. They are covered by a thin layer of cuticle that is permeable to both oxygen and carbon dioxide. Example, *Dytiscus, Notonecta*.
7. **Breathing Tubes/ siphons**: Many aquatic insects living under water and come to surface to get air from hollow breathing tubes, in mosquito larvae, the siphon tube is an extension of the posterior spiracles in abdomen. The opening of the tube is surrounded by a waterproof layer of hairs. When the insect goes down in water the hairs comes close to each other and closes the opening.
8. **Air Bubbles:** Some aquatic insects carry a bubble of air with them whenever they dive beneath the water surface, such as in diving beetles. This bubble may be held under the elytra, specialized hairs or around one or more spiracles. An air bubble provides insect with a short-term supply of oxygen.
9. **Integument/ cuticular respiration:** Many aquatic insects have comparatively thin integument for the diffusion of gases oxygen and carbon dioxide. These are present in insects living in cold and fast moving streams where there is enough dissolved oxygen. Sometimes integument acts as respiratory organ, example, *Chironomus* larva.

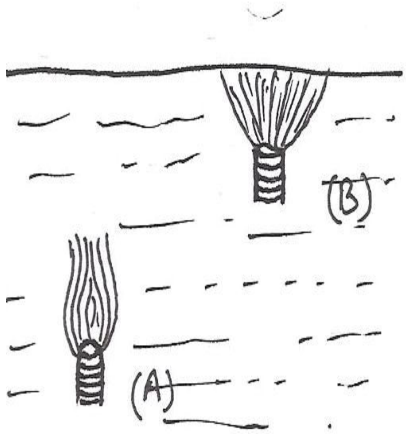


FIG 4.9: A) Hydrofuge hair around spiracle in submerged stage B) on water surface

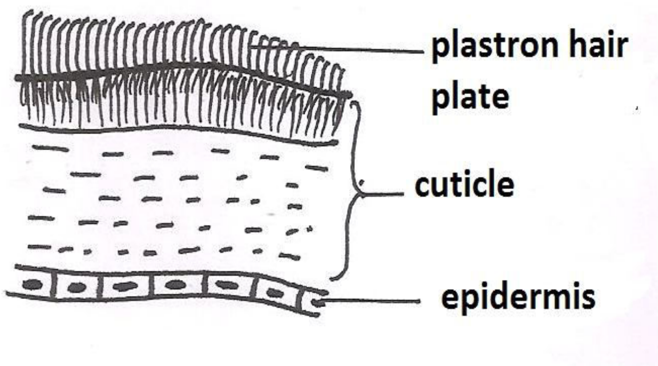


FIG 4.10: Diagram showing plastron hair for respiration

Respiratory pigments in insects

Respiratory pigments are the molecules that can carry oxygen and other gases present in blood. Crustaceans and arachnids contains haemocyanin respiratory pigment.Most insects does not have these pigments but Chironomus larva (midges/ commonly known as bloodworms), backswimmers, horse bot fly (*Gasterophilus*) are red in color due to haemoglobin in plasma. Kat haemoglobin in *Rhodnius*, carotene, flavin, xanthophil in herbivore insects and protapin in aphids are present in plasma. Riboflavin, flurocyanine, insectoverdin are found in locust.

4.9 Summary

The circulatory system includes contractile dorsal aorta, heart, ostia, sinuses and hemolymph. The blood or haemolymph is made of plasma and cells performing different functions and make up less than 25% of an insect's body weight. The main function of hemolymph, is to transports hormones, nutrients and wastes and is important for osmoregulation, temperature control, immunity and storage. It also plays an essential part in the moulting process, predatory defence by chemicals that deter predators.

Body fluids enter through unidirectional way through valved ostia which are openings situated on the aorta. Flow of the hemolymph occurs by peristaltic contraction, originating at the posterior end which pumps the hemolymph forwards into the dorsal vessel. The hemolymph is circulated to the appendages with the help of accessory pulsatile organs found at the base of the antennae or wings or legs.

Respiratory system is meant for gaseous exchange and oxygen is more readily diffuses than carbon dioxide. This exchange is possible through tracheal system in insects which is a system developed from invagination of the integument. Two diaphragm divides whole thoraco-abdominal cavity into three compartments pericardial, perivisceral and perineural cavities. Insect respiration is specialized system without lungs by a complicated system of internal tubes and sacs through which gases either diffuse in and out of the body. Oxygen is directly transported to the tissues that need oxygen and eliminate carbon dioxide via their cells as RBC are not present in the haemolyph. Air is taken in through spiracles, situated laterally in the pleural wall, usually a pair on the anterior margin of the meso and meta thorax, and pairs on each of the eight or less abdominal segments. Numbers of spiracles vary from 1 to 10 pairs on which basis the insect is said to be holopneustic, oligopneustic, apneustic. The oxygen passes from the tracheae to the tracheoles and lastly to the end cell.

The major tracheae are thickened spirally by taenidia that prevent it from collapsing and often swell into air sacs. Spiracles are closed and opened by means of valves and are of different types. The closures of spiracles are essential from losing moisture from the body. There are some aquatic insects have a closed tracheal system, for example, in Odonata, Tricoptera, Ephemeroptera, which have tracheal gills for respiration and having no functional spiracles. The tracheal system may be open or close and number of spiracles may vary from species to species. Aquatic and endoparasitic insects have modification to adapt their environment.

4.10 Glossary

- **Alary muscles:** Muscles which are attached laterally to the walls of each heart chamber to keep them in position.
- **Apneustic:** No functional spiracle.
- **Haemocoel:** These are the open body cavities with blood/ haemolyph.
- **Oligopneustic:** Having one or two functional spiracles.
- **Pericardial sinus:** It is the cavity surrounding heart.
- **Perineural sinus:** It is the cavity around nervous system.
- **Perivisceral sinus:** It is the cavity surrounding alimentary canal.
- **Polypneustic:** Having three or more functional spiracles.
- **Spiracles:** Small openings on the sides of thorax and abdomen.
- **Respiratory pigments:** They are the molecules that can carry oxygen and other gases present in blood.

4.11 Self Learning Exercise

Section -A (Very Short Answer Type)

1. Which cell functions as archeocyte of sponges?
2. What are the percentages of plasma and heamocytes in hemolymph?
3. Name the major blood sugar in insect?
4. Name the abundant type of cell in insect hemolymph?
5. Name the cells which are phagocytic in nature?
6. What is the component in insects that regulate heart beat like that of adrenaline in vertebrates?
7. How many pairs of alary muscle are there in grasshoppers?
8. Which insect has the most primitive and generalized mouthparts in insects?
9. Name the cryoprotectant in insect?
10. Name the amino acid responsible for flight and sclerotization of cuticle?

Section -B (Short Answer Type)

1. Define hemolymph and haemocyte?
2. Differentiate between open and closed tracheal system?
3. Draw labeled diagram of tracheal system?
4. What makes insect to respire in water?
5. Explain the immunity in insects?
6. What are the types of haemocytes?

7. Write the types of spiracles on the basis of their number?
8. Write a short note on respiratory pigments?
9. Write differences between open and closed circulatory system?

Section -C (Long Answer Type)

1. Explain different organs of respiration?
2. What are the different organs associated with circulation?
3. Write down in brief adaptation of endoparasitic and aquatic insect?
4. What is the mechanism of respiration?
5. Write the composition and function of hemolymph?
6. How insects protect themselves against diseases and antigen?

Answer Key of Section-A

1. Prohaemocytes
2. 90% and 10%
3. Trehalose
4. Plasmatocyte
5. Plasmatocyte and granulocyte
6. Indol alkylamine
7. thoracic and 10 abdominal
8. Grasshoppers and cockroaches
9. Sorbitol and glycerol
10. Proline and tyrosine

4.12 References

- Cedric Gillot: Entomolgy
- Kachhwaha N.: Principles of Entomology- Basic and Applied

Unit - 5

Insect Anatomy and Physiology – III

Structure of the Unit

5.1 Objectives

After reading this unit student will be able to:

- Describe the excretory system in insects.
- Describe excretory organs and their modification, including cryptonephridial arrangement in insects.
- Describe the Physiology and regulation of excretion in insects.
- Know, describe and understand nervous system and its basic component.
- Understand the role of brain in nervous system and transmission of nerve impulse in insects.

5.2 Introduction

The function of the excretory system is to maintain a constant internal environment (homeostasis) which is largely determined by the haemolymph as it surrounds the visceral organs of the insects. Thus the excretory system maintains the uniformity of the haemolymph which is achieved by the elimination of nitrogenous metabolic wastes and the regulation of salt and water. The malpighian tubules are concerned in the excretion whereas the rectum is involved in reabsorption of salts and water. Both excretory substances and salts and water pass into the rectum. Nitrogen is usually excreted as uric acid with minimum of water and thus conserves water. Nitrogenous wastes are eliminated either as: 1) Ammonia – as in aquatic insects, meat eating maggots and aphids, 2) Urea- as in clothes moths (and humans), 3) Uric acid – as in most insects. The choice of nitrogenous excretory product is dependent upon the need to conserve water.

An insect's nervous system is a network of specialized cells (called neurons) that serve as an "information highway" within the body. These cells generate electrical impulses (action potentials) that travel as waves of depolarization along the cells membrane. Every neuron has a nerve cell body (where the nucleus is found) and filament like processes (dendrites, axons or collaterals) that propagate the action potential. Signal transmission is always unidirectional-moving toward the nerve cell body along a dendrite or collateral and away from the nerve cell body along an axon.

5.3 Excretory organs and their modification, including cryptonephridial arrangement

Excretory organs

A. Malpighian tubules

The Malpighian tubule system is a type of excretory and osmoregulatory system found in some insects, myriapods, arachnids, and tardigrades. The system consists of branching tubules extending from the alimentary canal that absorbs solutes, water, and wastes from the surrounding hemolymph. The wastes then are released from the organism in the form of solid nitrogenous compounds. The system is named after **Marcello Malpighi**, a seventeenth-century anatomist. It is unclear as to whether the Malpighian tubules of arachnids and those of the Uniramia are homologous or the result of convergent evolution.

Structure

Malpighian tubules lie in the haemocoel and are attached to the gut at the junction between the midgut and hindgut. Each tubule is usually long slender blind tube and may open directly into the midgut or hindgut or more commonly into a dilated ampullar structure. These tubules are commonly convoluted and are usually free in the body cavity. Their number varies depending on species, from 2 (in scale insects) to 250 or more (in Orthopterans) with large surface area. In *Periplaneta*, with 60 tubules, their total surface area is about 1320 cm^2. Certain insects lack malpighian tubules, e.g., springtails and aphids. They contain actin for structural support and microvilli for propulsion of substances along the tubules. Malpighian tubules in most insects also contain accessory musculature associated with the tubules which may function to mix the contents of the tubules or expose the tubules to more hemolymph. The insect orders,Thysanura, Dermaptera and Thysanoptera do not possess these muscles.

Association of the Malpighian tubules with the gut: at least two types of arrangement of Malpighian tubules and posterior part of the gut are observed : gymnonephridial (free kidney) and cryptonephridial (hidden kidney) arrangement.

a) **Gymnonephridial arrangement:** The distal ends of the Malpighian tubules are lying freely in the body cavity. This type of Malpighian tubules are of two types:

    i. **Orthopteran type:** Histologically the malpighian tubules are alike throughout its length and are only secretory in nature.

    ii. **Hemipteran type:** Histologically the basal absorptive region of the Malpighian tubules differs from the distal secretory region.

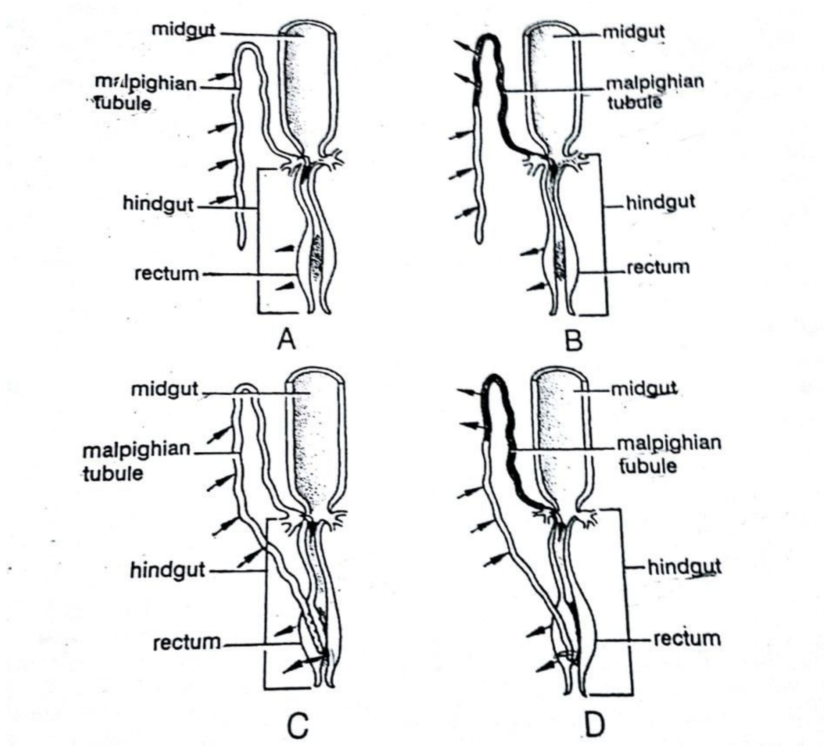


Fig. Major types of Malpighian tubule- hindgut system. (A) orthopteran type, (B) hemipteran type, (C) coleropteran type, (D) lepidopteran type. Arrows indicate the direction of movement of substances in and out of the tubule lumen.

b) **Cryptonephridial arrangement:** The distal ends of the tubules are embedded in the tissues surrounding the rectum. Such an arrangement is concerned with improving the uptake of water from the rectum. This type of Malpighian tubules are also of two types:

   i. **Coleopteran type:** similar to orthopteran type the Malpighian tubules are alike throughout its length and are only secretory in nature.

   ii. **Lepidopteran type:** similar to hemipteran type the basal absorptive region of the Malpighian tubules differs from the distal secretory region.

Histology of Malpighian tubules

Except silver fishes, earwigs and thrips, muscles are associated with the tubules which produce serpentine movement in the Malpighian tubules that helps in propelling the contents of the lumen toward the opening into the alimentary canal, mixing of the luminal contents and exposure of the tubules to more haemolymph. The tubules are usually well tracheolated and are one cell thick with one or a few cells encircling the lumen. These cells rest on a tough basement membrane.

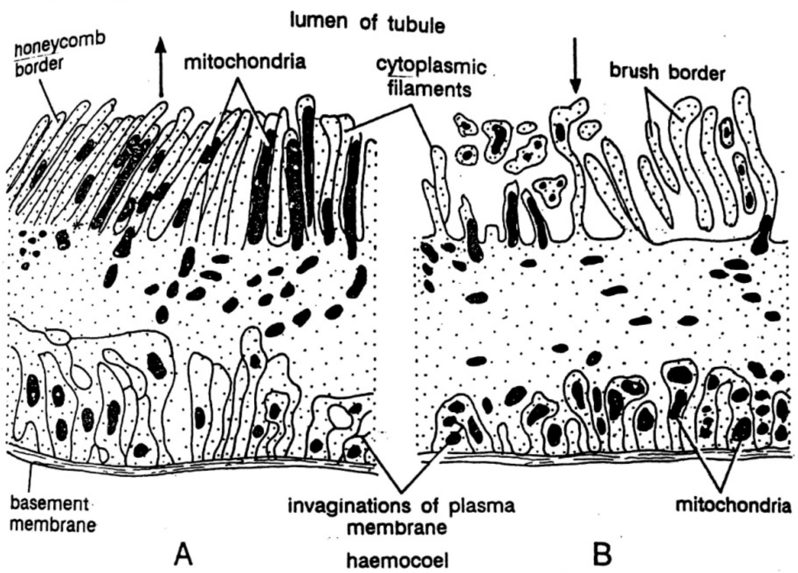


Fig. Transverse section of a cell from (A) the distal end of a Malpighian tubule showing the regular cytoplasmic filaments of the honeycomb border, (B) the proximal region showing the irregular filaments of the brush border. Arrows indicate the direction of secretion.

The cytoplasm of these cells varies in appearance and is usually colourless. It is generally filled with various refractile or pigmented inclusions and sometimes contains needle like crystals but may be nearly clear. In some insects the free margins of the cells of more distal parts of the tubules are produced into cytoplasmic filaments and packed very close together, forming the so called honey comb border and is secretory in nature. The more proximal cells have a typical brush border. This too, is formed of cytoplasmic filaments, but these are separated from each other by their own width and are concerned with absorption through active transport. The tubular cells contain a very large number of mitochondria.

B. Nephrocytes

Nephrocytes occur singly or in groups in several parts of the body. Their size varies with insect species. They are large in dipterous larvae whereas are small and may be multinucleated in others. They are closely associated with pericardium and hence are also known as pericardial cells. In dragonfly the nephrocytes are scattered throughout the fat body. The nephrocytes transform the original waste materials into a form that enter routine metabolic pathway later on. It is supposed that nephrocytes also take part in protein metabolism and regulation of heartbeat.

C. Excretion by rectum

The Malpighian tubules of *Periplaneta* do not contain uric acid but the granules of it are found in the wall of the rectum and in the faeces suggesting that the hindgut may have an excretory function. There are typically six rectal pads in *Periplaneta* each is a longitudinal folding of cuticle containing thickened patches of epithelium and many tracheal branches. In ammoniotelic insects. Ammonia passes directly into the gut without involving Malpighian tubules. In certain aquatic insects ammonia is secreted directly into the rectum.

D. Other excretory organs

Springtails that have no Malpighian tubules and larvae of wasps and bees and oriental cockroaches in which Malpighian tubules do not excrete uric acid, uric acid is eliminated through other organs given below :

1. **Labial glands:** In springtails, labial glands are supposed to be involved in excretion which consist of an upper saccule followed by a coiled labyrinth and have a gland opening into the outlet duct.

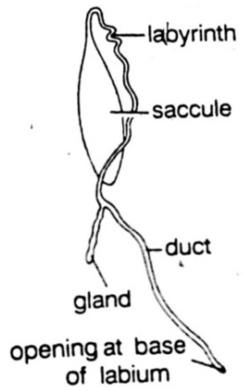


Fig. Labial gland of a springtail.

2. **Utricular glands:** In cockroaches (*Blatta, Blatella*), uric acid is stored temporarily in the utricular glands (male accessory glands) and then is poured out over the spermatophore during copulation. Recent studies demonstrated that it provides an alternate source of nitrogen to the embryo. Also, the female's own uric acid stores could be passed onto her embryos. Thus, it is suggested that both sexes can make a parental investment in the offspring. Uric acid in embryo is hydrolysed by the enzyme uricase produced by micro organisms (in mycetocytes of fat body) and serves as a nutritional nitrogen source.
3. **Fat body:** In the oriental cockroaches, uric acid is also stored in the urate cells of fat body. It is possible that the uric acid in urate cells provide a store of nitrogen (storage excretion) for use in the production of new tissue or that after reduction it supplies adenine for nucleoprotein synthesis. Uric acid stored in the fat body of larvae may be the end product of metabolism of the individual cells and is subsequently, in pupa, it is transferred to the Malpighian tubules and excreted with meconium.
4. **Other tissues:** Epidermis of *Rhodnius* also accumulates uric acid and during each moulting it is removed. Uric acid produced during pupal stage may also be stored in scales of wings in butterflies.

Nitrogenous excretion

Excretory products

Nitrogenous products of various types are usually accumulated in the haemolymph as a result of protein, amino acid and nucleic acid metabolism. These materials are usually of no use to an insect and may be toxic and it must either be excreted or stored in an inert state until they can be used for another function or be excreted. Insects excrete nitrogenous wastes in the form of ammonia, urea, uric acid, allantoin, allantoic acid, amino acids and even protein.

The habitat of the insects usually determines the type of excretory end products. Like other animals most terrestrial insects are uricotelic (excrete uric acid), whereas most aquatic insects are ammoniotelic (excrete ammonia). The aquatic larvae produce ammonia as its major excretory product while the terrestrial adults produce uric acid. Uric acid, however is the major waste product and excreted making up to 80% or more of the nitrogenous end products observed in the urine of most terrestrial insects as it does not need a large amount of water for its elimination being less soluble in water. Excreting uric acid the insects also conserve water. On the other hand, ammonia is the major nitrogenous waste produced by aquatic insects as ammonia is highly soluble in water. The red cotton bug (*Dysdercus*) excretes a large amount of allantoin but no uric acid, although the latter is present in the haemolymph. The meconium of moths and butterflies contains allantoic acid. Urea is commonly present in the urine of insects in very small quantity. In tse tse fly (*Glossina*) two amino acids arginine and histidine from the blood of the host are excreted unchanged after absorption. The allantoin, allantoic acid and urea are produced from the breakdown of uric acid.

5.4 Physiology of excretion and regulation of excretion

Materials in excess in the haemolymph are basically filtered through the Malpighian tubules which are highly permeable to small molecules. They enter the lumen of a tubule either by simple diffusion (e.g., sugars, amino acids, urea, certain ions) or linked with active transport of potassium ions, which generates fluid flow (e.g., uric acid). Figure shows the movement of ions, water and other molecules between the haemolymph and Malpighian tubules and the hindgut and the haemolymph in a generalised insect. In some insects e.g., *Rhodnius*, instead of uric acid, potassium urate is secreted. Either the whole of the tubules or more distal parts of the tubules are secretory. The substances that are needed by the insects are reabsorbed into the haemolymph either in the proximal portion of the tubules (hemipteran and lepidopteran types of Malpighian tubules) or in the rectum. These reabsorption processes may also be active transport or simple diffusion. A continuous flow of water down the tubules to the rectum carries the uric acid with it so that ultimately the nitrogenous waste is excreted with the faeces through the anus. The rate of movement of K^+ and hence of water is proportional to the concentration of K^+ in the haemolymph as the movement of water is linked with the movement of K^+. The K^+ movement is also correlated with the rate of secretion.

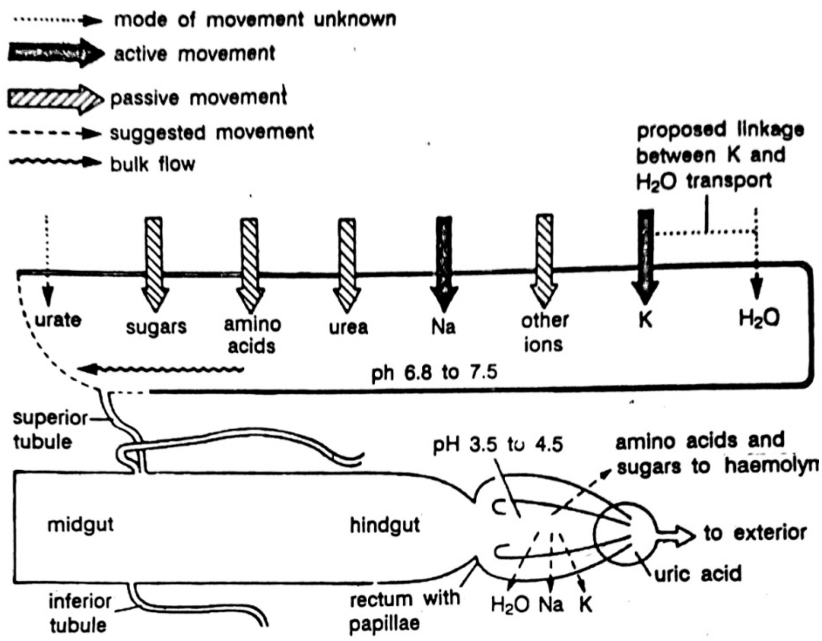


Fig. Diagrammatic representation of the movement of ions, water and organic molecules between the haemolymph and Malpighian tubules and the hindgut and the haemolymph in a generalised insect.

Salt and water balance (osmoregulation)

Different environmental conditions pose different salts and water problems for insects. Terrestrial forms are constantly faced with the tendency to lose water through evaporation and are generally dependent on ingested food for needed water and salt. Depending on the water content of their diet, the faecal material may be quite watery (e.g., plant sap feeding insects that take in an excess of water), or a dry powdery pellet (e.g., insects that feed on materials of very low water content such as cereals). Similarly, freshwater insects in which a large amounts of water is absorbed through the integument and by the gut along with ingested food must excrete water and at the same time must conserve the inorganic ions. Marine insects similar to terrestrial insects must constantly conserve water or utilise metabolic water. They also take high amount of salt with the food and the excess is eliminated in the urine after regulated resorption from the rectum.

Active transport is probably not always involved in rectal absorption. For example, in *Dysdercus,* absorption is entirely passive and occurs only when the rectal fluid is hypotonic relative to the haemolymph.

Certain other factors, e.g., spiracular control, integument permeability, food selection and habitat selection are also involved with the regulation of salt and water in insects. In certain aquatic insects (e.g., mosquito larvae), chloride ions are taken into the haemolymph by way of papillae surrounding the anus. This is an active process, occurring against very high concentration gradient. In addition, these papillae are also responsible for Na^+, K^+ and water uptake.

Some insects are able to absorb water from a drop on the cuticle. The cuticle of *Periplaneta* is asymmetrical with regard to the passage of water since water passes in more quickly than it passes out.

Dietary problems and excretion

Insect diets considerably affect the excretory system to enable the insect to encounter the problems created by the type of food ingested. Insects feeding on vertebrate blood must actively conserve sodium by reabsorption of Na^+ from a food source low in that particular ion, whereas herbivore insects face a different problem (i.e., the food is high in both K^+ and Ca++). Thus, they must excrete the excessive amounts of both ions to maintain homeostasis of the haemolymph.

In addition to the problems associated with differences in ionic concentrations between the food sources and the haemolymph, herbivore insects face in additional problem, i.e., the toxic phytochemicals. Though such insects have ability to detoxify these chemicals, but if absorbed into the haemolymph, the detoxified chemicals and the toxic chemicals themselves must be excreted. In such a situation following ingestion of plants containing the toxicant, the transport mechanism of the Malpighian tubules is induced, thus facilitating rapid excretion of the toxin from the insect's haemolymph. However, some insects retain and sequester these toxicants to their benefit rather than to excrete them, e.g., *Zonocerus* (a grasshopper).

Control of diuresis and gut motility

Diuresis, or the production of urine in insects is controlled by diuretic or antidiuretic hormones. These substances have been isolated from the pars intercerebralis of the brain, the corpus cardiacum and various ventral chain ganglia, including the sub oesophageal ganglia. A diuretic peptide (DP) from *Locusta* and an antidiuretic hormone (ADH) effecting the Malpighian tubules of the house cricket, *Acheta domesticus*, have been isolated. Similarly a chloride transport stimulating hormone (CTSH) has been isolated, which has shown to regulate both ions and water balance in the rectum of the locust. Proctolin, a neuropeptide that was isolated from the hindgut of *Periplaneta americana* is widely distributed in the insect nervous system and functions as an excitatory neurotransmitter. It produces a myotropic effect on the visceral muscles of the hindgut.

5.5 Nervous system: Basic component and functional anatomy, Brain

Insects have a complex nervous system which incorporates a variety of internal physiological information as well as external sensory information. Like other animals the nervous system in insects serves to coordinate the activities of its various systems. The units of this system are elongated cells or neurons which carry information in the form of electrical impulses from external and internal sensilla (sensory cells) to appropriate effectors (e.g., glands, muscles) and special cells called glial cells which protect, support and provide nutrition for the neurons.

Structure of the nervous system

Neurons

The basic functional unit of the nervous system is the nerve cells or neuron. Typically a neuron consists of a cell body (perikaryon or soma) and one or more long, very thin fibres or axons that end in terminal arborisation. Frequently the axon has collateral branch. Associated with the perikaryon or near it there are tiny branching processers, the dendrites.

The neurons may be unipolar (monopolar), bipolar or multipolar. Unipolar neurons possess single stalk from the cell body and are more frequent in insects. Peripheral neurons are bipolar the cell body bears an axon and a single, branched or unbranched dendrite. In hypocerebral and frontal ganglia the neurons have an axon and several branched dendrites hence they are multipolar.

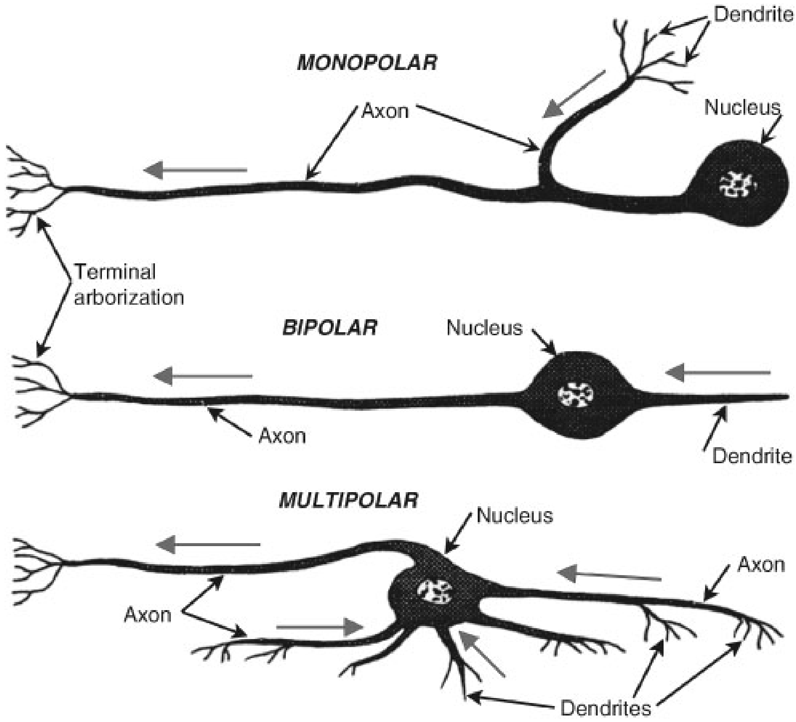


Fig. Show various types of neuron.

The terminal arborisations of an axon come into extremely close association with the dendrites or axon of another neuron or they may end near a muscle (i.e., a neuromuscular junction). The association between terminal arborisations and dendrites is called a synapse and the space between the arborisations and dendrites is called the synaptic cleft. The perikarya lie within the ganglia.

Several histological components of a ganglion have been identified. The entire nervous system is enveloped in a connective tissue called the neural sheath or neural lamella. It provides a mechanical support for the central nervous system, holding the cells and axons together. Beneath the neural sheath there is a thin layer of cells rich in mitochondria called as perineurium which probably secretes the neural lamella. Below this regions containing the perikarya with associated glial cells are found. Indeed glial cells invest the neurons and serve as protective sheet and insulation. The glial cells also provide nutrition to the neurons. There is a central region consisting of intermingling, synapsing axons encapsulated by processes of glial cells, the neuropile. Between the glial cells are extracellular spaces with fluid. The fluid in these spaces contains higher concentrations of sodium and potassium ions and a lower concentration of chloride ions than the haemolymph. Maintenance of the proper ionic concentration of this fluid is critical to neural function. The neural lamella, perineurium and glial cells are involved in maintaining the composition of this fluid as well as transporting and storing nutrients used by neurons.

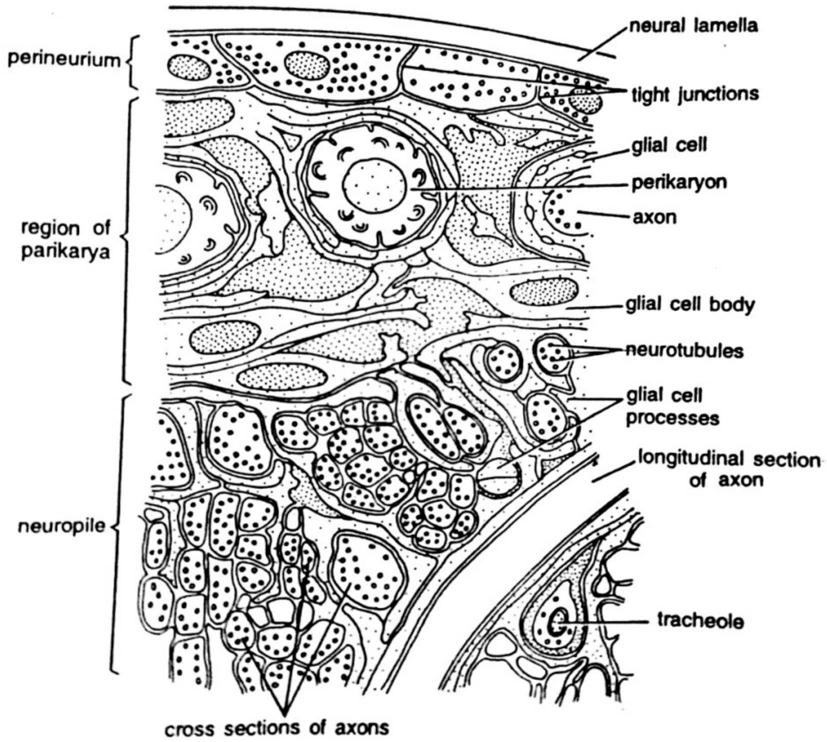


Fig. Cross section of part of the caudal ganglion of the cockroach. Darkly shaded areas indicate extracellular spaces.

Nerves are bundles of axons invested in the neural lamella and the underlying glial cells that form the perineurium. The nerves provide connection among ganglia and between ganglia and other parts of the nervous system.

Neurons are usually classified in ways that relate to function e.g., sensory or afferent that receive stimulus from the environment and motor or efferent that carry the information to glands or muscles; excitatory or inhibitory; and cholinergic (acetylecholine as neurotransmitter); glutaminergic (glutamic acid as neurotransmitter) etc.

Sensory neurons are usually bipolar with peripherally located cell bodies. The dendrite is associated with a sensory structure of some type; the proximal process usually directly associated with a motor neuron or more with one or more interneurons. Their distal processes usually frofusely branched over the inner surface of the integument or over the alimentary canal, while their axons enter the ganglia of the central nervous system.

Motor neurons are unipolar with perikarya lacking dendrites are located in the periphery of a ganglion. The bundles of axons from the cell bodies form the motor nerves that activates muscles.

Cell bodies of interneurons and association neurons are also located in the periphery of a ganglion and may synapse with one or more other interneurons, sensory neurons or motor neurons. Some interneurons being quite large (giant axons) having very large diameters (45μ) may run the entire length of the ventral nerve cord (e.g., in *Periplaneta americana*). These axons serve as a rapid conduction system for alarm reactions.

Based on anatomy the insect nervous system is divided into three major parts :

1) The central nervous system
2) The visceral (sympathetic or stomatogastric) nervous system and
3) The peripheral nervous system.

Central nervous system

The basic units of the central nervous system (CNS) are essentially the brain and a double chain of ventral nerve cord having segmental ganglia joined by lateral and longitudinal connectives.

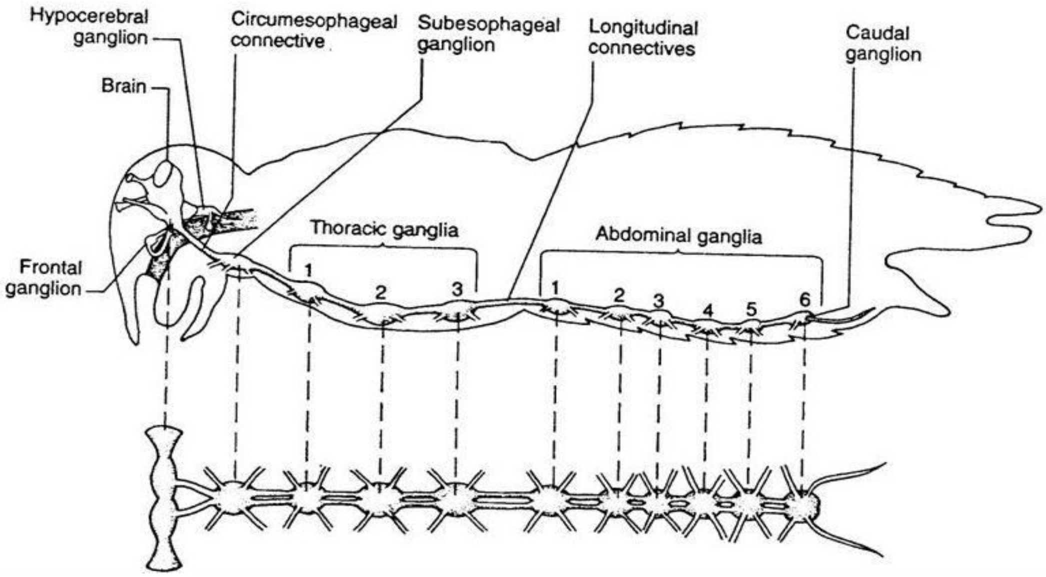


Fig. Central nervous system of a generalised insect.

1. **Brain:** The brain is very complex and is located in the head dorsal to the oesophagus. The brain is connected behind to the suboesophageal ganglion by circumoesophageal connectives ventral to the oesophagus. The insect brain is a very complex structure formed by the fusion of three anterior most paired segmental ganglia during development and thus three distinct lobes from dorsal to ventral are observed: protocerebrum, deutocerebrum and tritocerebrum.

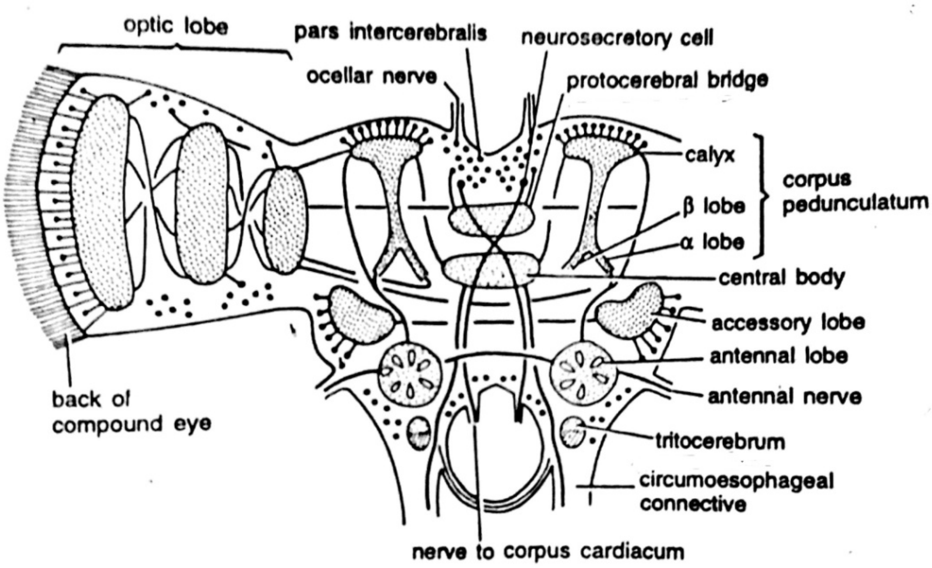


Fig. Diagram showing major neuropile region (shaded) of the brain and some connections between these regions. Black dots indicate location of perikarya.

a. **Protocerebrum:** The protocerebrum is the largest and most complex part of the brain having following distinct cell masses and regions of neuropile : optic lobes, ocellar centers, central body, protocerebral bridge, pars intercerebralis and corpora pedunculata.

   i. **Optic lobes:** The optic lobes are lateral extensions of the protocerebrum and receive sensory input from the compound eyes. Each optic lobe is composed of three neuropiles viz., lamina ganglionaris, medulla externa and associated perikarya and connectives (chiasma). The axons of retinular cells of the compound eyes pass into the lamina ganglionaris where they synapse with monopolar neurons.

   ii. **Ocellar centres:** The ocellar centers are associated with the bases of the nerves from the ocelli.

   iii. **Central body:** Centrally located central body is a neuropile and connects the right and left lobes of the protocerebrum. It receives axons from various parts of the brain and may be the source of premotor outflow from the brain.

iv. **Protocerebral bridge:** The protocerebral bridge or pons cerebralis is a mass of neuropile located medially dorsal to central body. It is connected with axons from many parts of the brain except the corpora pedunculata.

v. **Pars intercerebralis:** The pars intercerebralis is located in the dorsal median region above the protocerebral bridge. It contains two groups of neurosecretory cells that transport neurosecretory material (neurohormone) to the corpus cardiacum.

vi. **Corpora pedunculata:** The corpora pedunculata (mushroom bodies) are located at the sided of the pars intercerebralis. It is composed of a central stalk that splits ventrally into α and β lobes and capped dorsally by the calyx. The calyx is a mass of neuropile and associated perikarya. The corpora pedunculata contain interneurons which do not extend outside of these bodies and terminal portions of axons that enter from perikarya located in other parts of the brain. The connections to the calyx and α lobe are mainly sensory; those connecting with the β lobe are premotor axons which in turn synapse with motor fibres.

The protocerebrum is considered to be the location of the higher centers in the central nervous system, which control the most complex insect behaviour. The fact that the corpora pedunculata are comparatively large in the social Hymenoptera (ants, bees and wasps) and small in less behaviourally sophisticated insects (true bugs, flies etc.) strengthens this concept.

b. **Deutocerebrum:** The deutocerebrum contains the antennal or olfactory lobes. Each lobe is divided into dorsal sensory and ventral motor neuropiles. The antennal lobes is divided into dorsal sensory and motor axons from the antennae. The two neuropiles are connested with each other by a commissure. Tracts of olfactory fibres connect the antennal lobes and corpora pedunculata of the protocerebrum. The antennal lobes are important as they are the centres for receiving and processing several kind of information related with host selection, mate location, food finding, locating oviposition sites etc.

c. **Tritocerebrum:** The tritocerebrum is a smallest part of the brain and consists of a pair of lobes beneath the deutocerebrum. It connects the brain to the stomatogastric nervous system via the frontal ganglion and to the ventral chain of ganglia via the circumoesophageal connectives. The tritocerebrum also receives nerves from the labrum. The connecting nerves contain both sensory and motor elements.

2. **Ventral nerve cord:** In the thorax and abdomen there is typically a nerve ganglion in the ventral portion of each segment. The ganglia of adjoining segments are joined by paired connectives.

   a. **Suboesophageal ganglion:** The first ganglion in the ventral chain is the suboesophageal which is composed of three fused ganglia representing the mandibular, maxillary and labial segments. It innervates sense organs and muscles associated with the mouthparts, excitatory or inhibitory effect on the motor activity of the whole insect.

   b. **Thoracic ganglia:** There are typically three segmental thoracic ganglia behind the suboesophageal ganglion, each having the sensory and motor centre for its respective segment. Two pairs of major nerves arise from each ganglion supplying the legs and the musculature of each segment. In winged insects the mesothoracic and metathoracic ganglia each give rise to a third pair of nerves supplying the wing musculature. There is a tendency of fusion of thoracic ganglia in some insects belonging to Hymenoptera, Diptera and some Coleoptera.

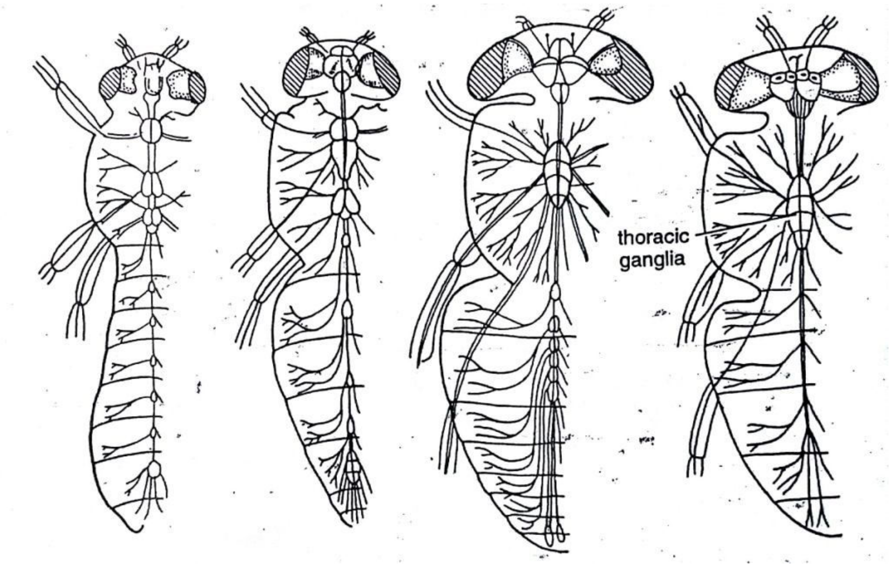


Fig. Variation in the concentration of the thoracic and abdominal ganglia of four species of Diptera.

c. **Abdominal ganglia:** The largest number of a abdominal ganglia occurring in larval or adult insects is 8 in the first 8 abdominal segments in apterygote insects and many larval forms. The last abdominal ganglion is formed by the fusion of last 4 abdominal ganglia (of segment 8-11). However, there has been a tendency toward reduction in the number of abdominal ganglia e.g., 7 in dragonfly, 5 or 6 in grasshoppers and their relatives and even 1 in several adult flies which is partially fused with the large single thoracic ganglion. The last abdominal ganglion furnishes the sensory and motor nerves for the genitalia and is therefore involved in the control of copulation and oviposition. The other abdominal ganglia typically give rise to a pair of nerves to the segmental muscles. Although ganglia are associated with specific body segments the muscles of one segment may receive nerves from a ganglion associated with a different segment.

3. **Visceral nervous system :** Insects possess a so called visceral or sympathetic nervous system that controls some of the involuntary motions of the anterior portion of the gut and dorsal blood vessel. It is made up of three separate subsystems : stomatogastric (stomodeal), ventral visceral and caudal visceral nervous systems.

I. Stomatogastric nervous system: The stonatogastric nervous system consists of a number of small ganglia and their associated nerves.

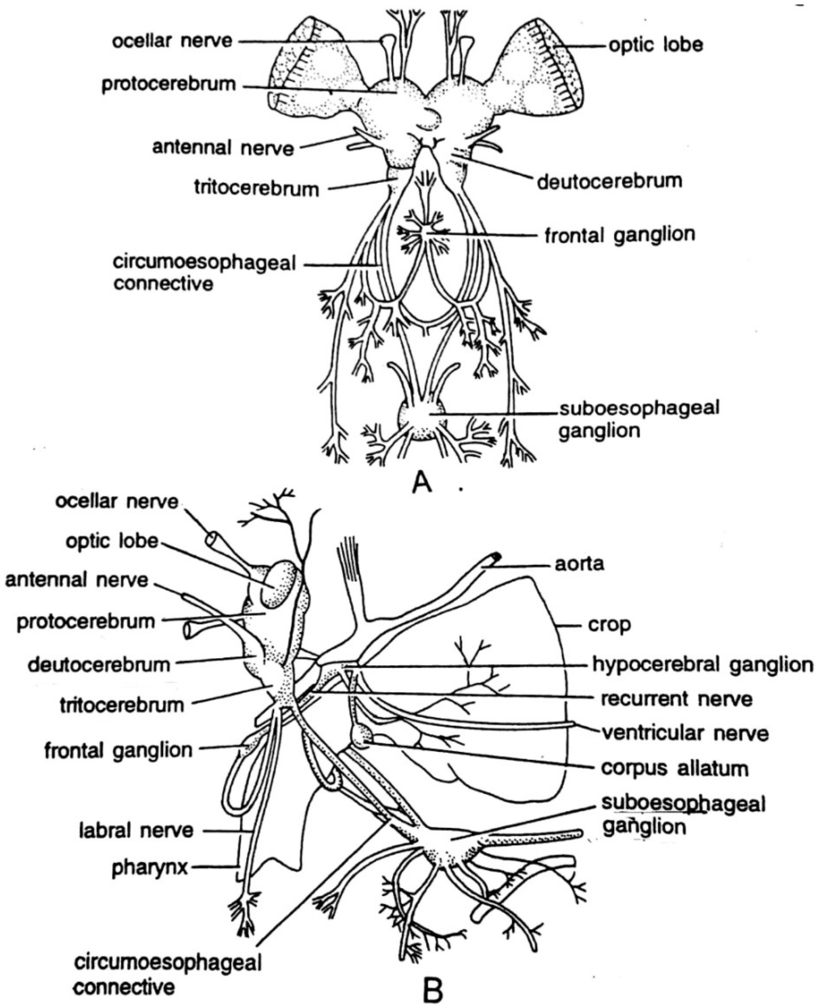


Fig. Brain and stomatogastric nervous system of the grasshopper. (A) Anterior view and (B) Lateral view.

It includes a frontal ganglion which lies on the dorsal midline of the oesophagus in front of the brain. The frontal ganglion connects with the tritocerebrum of brain by nerves on either side. The recurrent nerve srises medially from the frontal ganglion and extends beneath and posterior to the brain.

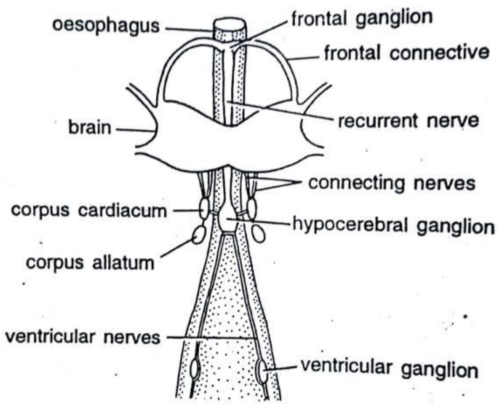


Fig. Relationship between stomatogastric nervous system and endocrine glands.

The recurrent nerve ends posteriorly in a hypocerebral ganglion which may give rise to one or two gastric nerves or ventricular nerves which continue posteriorly and terminate with a ventricular ganglion. Two endocrine glands corpora cardiac and corpora allata are connected with nerves to the hypocerebral ganglion. Sometimes suboesophageal ganglion is also connected with hypocerebral ganglion by nerve.

The stomatogastric system regulates the swallowing movements and possibly the labral muscles, mandibular muscles and the salivary glands. In *Locusta* the frontal ganglion also control the release of the secretion by the corpora cardiaca.

II. **Ventral visceral nervous system:** Ventral visceral nervous system is associated with the ventral nerve cord and its ganglia. From each segmental ganglion a single median nerve arises and divides into two lateral nerves. These nerves innervate the muscles and regulate the closing and the opening of the segmental spiracles. These nerves may be absent in some insects.

III. **Caudal visceral nervous system:** The caudal visceral nervous system is associated with the posterior segments of the abdomen. The nerves of this system arise from the caudal ganglion of the ventral chain and supply the posterior portions of the hindgut and the internal reproductive organs.

4. **Peripheral nervous system :** All the nerves emerging from the ganglia of the central and visceral nervous systems comprise the peripheral nervous system. The dendrites of sensory neurons within these nerves are associated

with sensilla, whereas the axons usually synapse with neurons within a ganglion of the central nervous system. Nerves contain motor fibres. The perikarya of these nerves are located in the ganglia of the central nervous system and the axons terminate in the muscles, glands and other effector organs. The peripheral nervous system continuously inform the insect about its surroundings by receiving stimuli through sensory organs. These sensory structures are located all over the body but are generally concentrated on the antennae, tarsi, palps, labellum, ovipositor and cerci. Sense organs such as the eyes and tympana also provide information. The information about the external and internal environment is continuously carried from the sensilla to the central nervous system where it is integrated in a way that appropriate behavioural and regulatory changes are made.

5.6 Transmission of nerve impulse in insects

Axonal transmission

In the resting condition (polarized state) due to the presence of abundant sodium ions ($Na^{+)}$ outside, the outer membrane is charged positively and the inner membrane is charged negatively. This is due to the movement of sodium ions from axoplasm to the outside of the axons. The outward flow of the sodium ions is known as sodium pump. On the other hand the potassium ions are more abundant in the axoplasm.

Upon stimulation by an external stimulus the permeability of the membrane is charged and the flow of sodium ions stops. This causes the movement of sodium ions inside the axons and depolarization of the membrane takes place. Further more on account of flow of sodium ions inside is very fast causing inner membrane positively charged and the outer part of membrane is charged negatively. Thus propagating a short electro chemical current or impulse along the axon. This is known as action potential.

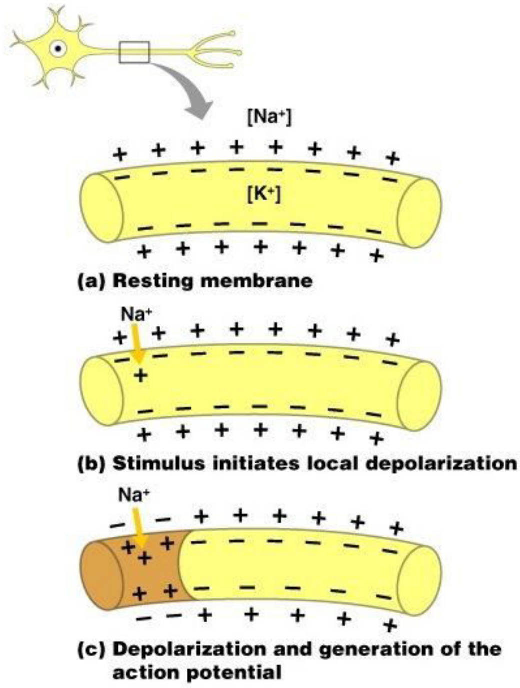


Fig. Axonal transmission in nerves.

The period of permeability to sodium ions is short lived and is followed by a period of increased permeability to potassium ions. As a result of which the potassium ions flow outside the axon , negatively charges the inner membrane. This is called as falling phase of the action potential. In this way nerve impulse are propagated in the axons. As the impulse passes in the forward direction, the permeability of the membrane assumes original state i.e. polarized condition due to decreased flow of potassium ions outside the axons as a result of which repolarization takes place.

Synaptic transmission

The axon terminals of the neurons are not continuous but are contiguous with that of other terminals having a short gap. This gap is known as synaptic gap. When an impulse has passed along an axon it must cross the synapses in order to stimulate another neuron. Transmission across the synaptic gap takes place with the help of a neurotransmitter stored in the synaptic vesicles. This is acetylcholine (ACH). As soon as the impulse reaches the terminal end of the axon, the synaptic vesicle fuse with the membrane of axon, the intermediate wall dissolve and the neurotransmitter is released into the synaptic gap.

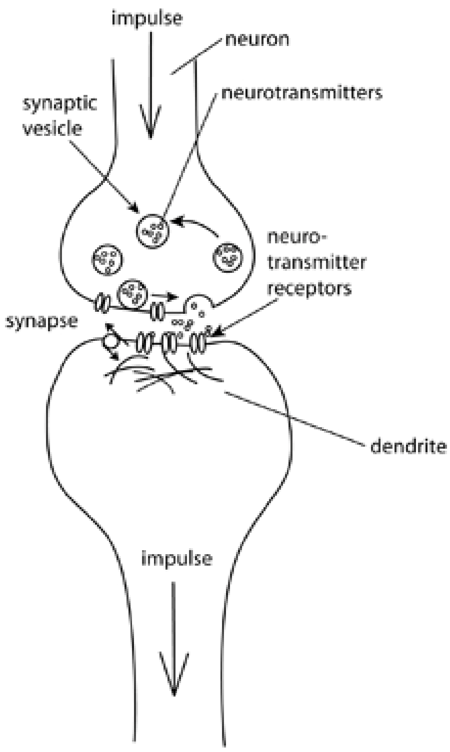


Fig. Shows synaptic transmission.

The ACH comes in contact with post synaptic terminal of the next neuron having ACH receptors. Now ACH molecules bind with ACH receptors present on post synaptic terminal. It changes the permeability of the membrane causing depolarization and this initiates propogation of nerve impulse. In this way the impulses caused by external stimuli reach from one neuron to next neuron via axon through synapses.

After the synaptic transmission the ACH is hydrolized into acetic acid and choline by the action of an enzyme acetyl cholinesterase (ACHE). In this way the ACH receptors become unoccupied in order to receive the second message. Thus in the synaptic transmission the neurotransmitter (ACH) acts as stimulus to the receptor axons.

5.7 Summary

- The function of the excretory system is to maintain a constant internal environment (homeostasis) which is largely determined by the haemolymph as it surrounds the visceral organs of the insects.
- The Malpighian tubule system is a type of excretory and osmoregulatory system found in some insects, myriapods, arachnids, and tardigrades. The system consists of branching tubules extending from the alimentary canal that absorbs solutes,

water, and wastes from the surrounding hemolymph. The system is named after **Marcello Malpighi**, a seventeenth-century anatomist.

- Diuresis, or the production of urine in insects is controlled by diuretic or antidiuretic hormones.
- The basic functional unit of the nervous system is the nerve cells or neuron.
- Based on anatomy the insect nervous system is divided into three major parts :
  The central nervous system, The visceral (sympathetic or stomatogastric) nervous system and The peripheral nervous system.
- In the resting condition (polarized state) due to the presence of abundant sodium ions ($Na^{+)}$ outside, the outer membrane is charged positively and the inner membrane is charged negatively.
- The axon terminals of the neurons are not continuous but are contiguous with that of other terminals having a short gap. This gap is known as synaptic gap. Transmission across the synaptic gap takes place with the help of a neurotransmitter stored in the synaptic vesicles. This is acetylcholine (ACH).

5.8 Self Learning Exercise

Section -A (Very Short Answer Type)

1. Who discover malpighian tubules?
2. Define diuresis.
3. Give any four names of excretory organs in insects.
4. How many types of neuron present in insects and write their names?
5. What is the basic functional unit of nervous system?
6. Define unipolar and multipolar neurons.

Section -B (Short Answer Type)

1. Describe mechanism of excretion.
2. Write short notes on:
   a) Axial transmission
   b) Osmoregulation in insects
3. Describe structure of neurons with suitable diagram.
4. Write short notes on:
   a) Protocerebrum
   b) Utricular gland and Nephrocytes

Section -C (Long Answer Type)

1. Give an account of excretory organs of insects.
2. Describe the excretory physiology of insects.
3. Write brief notes on :
   a) Malpighian tubules
   b) Excretory products
   c) Visceral nervous system
4. Describe various parts of insects nervous system.

5.9 References

- Entomology by Rajendra singh
- Introduction to general and applied entomology by V.B. Awasthi
- https://en.wikipedia.org/wiki/Malpighian_tubule_system

Unit - 6

Insect Anatomy and Physiology – IV

Structure of the unit

6.1 Objective

After going through this unit you will be able to understand

- The role of brain and hormones in insects.
- Different types of hormones and pheromones.
- Different types of sense organs which receives external messages and pass on to the CNS.
- Male and female reproductive organ and their associated glands.
- Role of pheromone in reproduction, mating, oviposition etc.
- Role of hormones in polymorphism, caste regulation, phases of locust etc.

6.2 Introduction

This unit comprises of many system which coordinates in a manner to show a particular behavior or character. As nervous excitation is caused when external stimuli is perceived by sense organs like photoreceptors, audio-receptors, visual receptors, mechano- receptors, chemo- receptors. These receptors pass message to the CNS and from their endocrine glands are triggered to secrete hormones or pheromones. Endocrine glands are important for mating, growth, development, metamorphosis, polymorphosis, moulting and many more. Reproductive system consists of separate male and female insects with only a few insects that show hermaphroditism. Female reproductive system has a pair of ovaries, lateral oviduct, median oviduct and a genital pore. Male reproductive system has a pair of testis, lateral vasa deferens, median ejaculatory duct with an aedegus as opening aperture and a device for transfer of sperms. Reproductive system and glands associated with the process of fertilization, production of gametes eggs/ sperms and oviposition.

6.3 Neuro-endocrine system

This system comprises of neurosecretory cells and hormones produced by endocrine glands. In neuro-endocrine system the neurosecretory system translate neural information received by external stimuli into hormonal messages secreted by triggering endocrine glands (FIG 6.1).

6.3.1 Endocrine organs

1. **Neurosecretory cells-** Neurosecretory cells of the brain and ganglions (pars intercerebralis of protocerebum) secrete hormone called brain hormone peptide in nature and are stored in neuro-haemal organs and bind to the protein molecules (carrier) named neurophysin.

2. **Prothoracic glands**- Two prothoracic glands/ecdysial glands are ectodermal in origin and are located in the ventro-lateral areas of prothorax. It is also associated with lateral longitudinal tracheal trunks and absent in apterygotes (wingless insects). If these glands are cut out in a full grown larva, pupation does not takes place. And if these glands are transplanted somewhere else in the larval body, larva metamorphose into pupa.

3. **Corpora allata**- Two small glandular bodies named corpora allata present on either side of corpora cardiacam on sides of the oesophagus. These are mostly paired but they are single in Dermeptera and Heteroptera .
4. **Copora cardiaca-** It acts as a neurohaemal organ lying behind the brain on dorsal part of foregut associated with cephalic aorta. It is absent in Collembola.

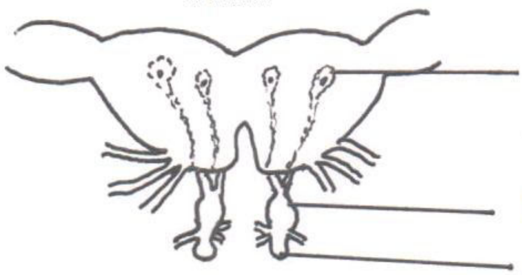


FIG 6.1: Position of endocrine glands

6.3.2 Hormones and pheromones

Hormones and pheromones are the chemicals which are responsible for a specific function and behavior. Hormones are secreted by endocrine glands and deals with the maintenance of the internal body environment. Pheromones are secreted by body parts which communicate between the same species or opposite sex for mating.

Hormones

The word hormone was given by C. M. Williams and it is also called third generation pesticide/ Insect Growth Regulators (IGR). These are the chemicals which are secreted by endocrine glands and its function is to regulate internal environment of body.

1. **Brain hormone**- Neuro-haemal organs on stimulation releases neurohormone which diffuses into the blood, and activate other endocrine gland. Brain hormones directly or indirectly control all the life processes of insect. Brain hormone stimulates feeding in blood sucking bug *Rhodnius* and stretch receptor in pharyngeal wall in grasshopper and locust.
2. **Prothoracicotropic Hormone (PTTH)/ Ecdysone-** Moulting a process when the cuticle is shed and larva metamorphose into next larval stage and pupation a process when last larval stage prepares itself for next

stage pupa. Both the moulting and pupation require it, PTTH, secreted by a prothoracic gland that is bilobed. Under the influence of PTTH, they secrete the steroid hormone ecdysone also known as moulting hormone. Moulting hormones are of two types' α-ecdysone and β-ecdysone. PTTH triggers every moult, larva to larva as well as pupa to adult. It maintains the changes during metamorphosis. PTTH is a homo-dimer of two polypeptides of 109 amino acids originated from protocerebrum targeted to ecdysial gland for ecdysone production. PTTH does not drive pupation directly but, as its name suggests, acts on the prothoracic glands. Ecdysone secreted by ecdysial gland target to epidermis for shedding the cuticle. Insects have rigid exoskeleton and can grow only by periodically shedding their exoskeleton called moulting. Moulting occurs repeatedly during larval development.

3. **Juvenile hormone-** Juvenile hormone is secreted by corpora allata and it is a non sterolic compound generally terpenoid. JH target fat body, accessory reproductive glands and follicle cells. Its function is to control metamorphosis or maintains larval stages. It is responsible for yolk deposition in eggs, egg maturation, vitellogenin production and tanning of the cuticle. They are also involved in green brown polymorphism in locust. And sometimes it is noted that mating behavior in social insects are due to neotenin. As long as there is much amount of JH, ecdysone promotes larva to larva moults. As the amounts lowers, ecdysone promotes pupation. Complete absence of JH results in formation of the adult. Therefore, if the corpora allata are removed from an immature silkworm, it immediately spins a cocoon and becomes a small pupa. A miniature adult eventually emerges. On the contrary, if the corpora allata of a young silkworm are placed in the body of a fully mature larva, metamorphosis does not takes place. The next moult produces an extra large caterpillar (FIG 6.2).

4. The hormone secreted by corpora cardiaca is not specific but it is found to regulate the heart beat, oxygen consumption and affects respiratory metabolism. In male cockroach copulation movement depends upon this gland and its secretion.

In the protocerebrum the neurosecretary cells releases the brain hormone. It triggers the prothoracic glands to secrete moulting hormone and corpora allata secretes juvenile hormone. Both the hormones are involved in moulting and metamorphosis during the life cycle of an insect.

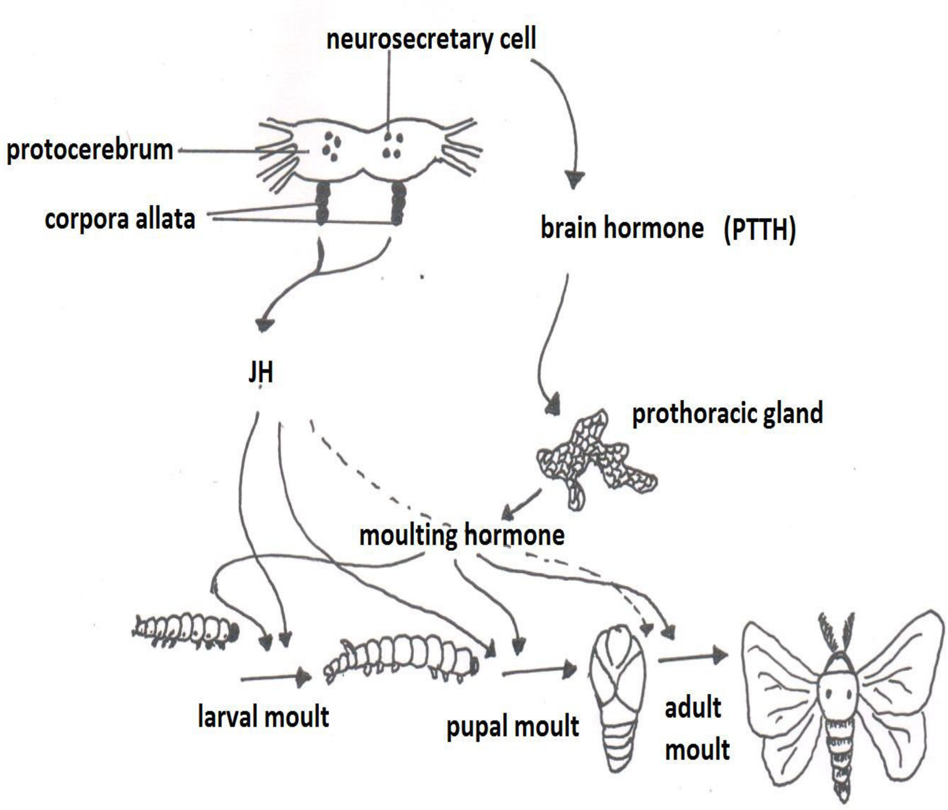


FIG 6.2: Role of hormones during metamorphosis

Pheromones

The term *pheromone* was introduced by Peter Karlson and Martin Lüscher (1959) and is based on the Greek word *pherein* (to transport or to carry) and *hormon* (to stimulate or to excite) is a chemical that triggers a natural behavioral response in another member of the same species. Among the insect orders it is observed in Orthoptera, Heteroptera, Diptera, Isoptera, Neuroptera, Siphonoptera, Coleoptera, Hymenoptera and Lepidoptera.

They are called ectohormones as they are secreted by exocrine glands. It may be volatile or non volatile in nature. They are species specific, sex specific and can be artificially synthesized.

Types of Pheromones

There are alarm pheromones, food trail pheromones, sex pheromones, and many others that affect behavior or physiology. They can be classified:

a) Based on sense organ influenced it can be
    i. Olfactory acting pheromones
    ii. Orally acting pheromones
b) According to the response it can be categorized into
    i. Releaser substances: Those chemicals that produces an immediate change in the behavior of the recipient.
    ii. Primer substances: Those chemicals which trigger off a chain of physiological changes in recipient without any immediate change in behavior.

c) On the basis of biological functions: Sex Pheromones (Aphrodisiaces), queen mandibular pheromones, spacing pheromones, trail pheromones, alarm pheromones, aggregation and trail making pheromones.

i. **Trail Pheromones** are common in social insects. For example, ants mark their paths with these pheromones to communicate their members for food finding which basically non volatile hydrocarbons. *Dolichoderine* ants synthesize pheromones in their pavan's gland, *Solenopsis* fireants in dufour's gland and Myrmicinae ants in poison glands. In termites trail pheromone is secreted by sternal gland located on 5^{th} abdominal segment. Example, *Zootermopsis* secretes caproic acid.

ii. **Alarm/Alerting Pheromones** are released if attacked by a predator and trigger flight (in aphids) or aggression (in bees) in members of the same species. This behavior is commonly seen in Hymenoptera and Isoptera and appears to be chemical releasers for social behavior. Honeybees also have an alarm pheromone e.g. *Melipona* stingless bees and *Trigona* bees secrete citral pheromone and formicine ants secrete undecane. The workers of *Coromyrma pyramica* produces alarm pheromone 2-heptanone. Honey bee's leaves traces of isoamyl acetate at sting region to induce other bees to sting on it.

iii. **Aggregation Pheromones** are secreted by con-specific insects of both sexes to secure themselves from predators, maximum utilization of food source, and attraction of social insects and to mate. They are produced by one or the other sex, these pheromones attract individuals of both sexes. Examples, bark beetles and *Ambrosia* beetle (Scotylinae).

iv. **Territorial Pheromones** (Area Making Pheromone) are laid down in the environment and mark the boundaries of an organism's territory. In dogs, these hormones are present in the urine, which they deposit on landmarks serving to mark the perimeter of the claimed territory. Example, male bumble bee secretes 2, 3-dihydro-6-trans farnesol by its mandibular gland to mark their territory sites.

v. **Caste regulating pheromone** differentiates caste in social insects and regulated by corpora allata/ Juvenile hormone that acts as pheromones in termites.

6.3.3-Endocrine control of Polymorphism in insects

Polymorphism means many forms of an organism in the same life stage. This phenomenon is found in some insects of order Orthoptera, Lepidoptera, Isoptera, Hymenoptera. The well known examples are phases of locust, caste system in social insects, alary polymorphism in crickets and color polymorphism in butterflies. Polymorphism is controlled genetically, influence by external factors or endocrine system. If the interior environment of the body is changed by the change in hormones concentration it leads to polymorphism. If JH is more than the amount required the adult will retain juvenile characters like lack of wings on the contrary if JH is low, the larva shows early maturation by developing reproductive system.

In aphids there are sometimes eight distinct forms are found. In spring and summer when food is abundant it reproduce parthenogenetically or paedogenetically to give rise large number of wingless individuals. In other season when food is in shortage it reproduce sexually to form winged individuals called alate forms. The alate forms develop when factors like photoperiod, temperature, water content and population density changes which ultimately brings changes in endocrine activity.

Termites and aphids shows **discontinuous polymorphism** as the forms are totally different to each other but locust shows **continuous polymorphism** as the forms are slightly different. In locust if population density is low, abundant food is available solitary phases occurs which lays more eggs, short winged, enlarge body accumulates less fat. Conversely if population density is high and food availability is low gregarious forms come into role that exhibits character like small body, large wings, accumulate more fat and lays less eggs as compared to solitary phase. All these factors affect endocrine gland specially corpora allata. It is experimentally proved that if JH is applied to solitary forms they develop into gregarious larvae.

In termites number of primary reproductive caste (king and queen), supplementary reproductive caste, workers and soldiers have a fixed proportion in a colony by means of inhibitory pheromones which is modified by corpora allata of endocrine system.

6.4 Sense organs

The internal and external environment is always changing so insect has to maintain itself to sense these changes. There are specialized structures which receive this information to the central nervous system. Chemical senses includes chemoreceptor's, related to taste and smell, affect mating, selection of habitat, feeding sites, breeding sites and parasite-host relationships. Taste receptors are present on the mouthparts and antenna sometimes. Insects are able to smell due to the presence of olfactory sensilla found in the antennae.

Mechanical sensilla provide the insect with to make directed orientation, general movement, fight from enemies, reproduction and feeding. They are sensitive to mechanical stimuli such as pressure, touch and vibration. Hearing structures are located on different body parts wings, abdomen, legs and antennae. They are responsive to various frequencies between 100 to 240 kHz depending upon insect species. Pressure on the body wall is detected by the campiniform sensilla and internally distributed stretch receptors that senses muscle distension and stretching.

The insects see the objects with the help of compound eyes and ocelli. More the number of ommatidia greater will be the visual acuity. The ocelli are not to form focused images but are sensitive to different light intensities. Many insects have temperature and humidity sensors and due to their small size, they cool more quickly than larger animals. Insects are cold-blooded or ectothermic as their body temperature rising and falling with the environment. In flying insects their body temperature raises through the action of flight, above environmental temperatures. The body temperature of butterflies and grasshoppers in flight may be increased by 5 °C or 10 °C above environmental temperature. In the recent research, the discoveries of new receptor nocioreceptors which are sensitive to pain found in the larvae of fruit flies.

6.4.1 Mechanoreceptors

These are the receptors which sense mechanical stimuli as they are sensitive to physical touch to solid surfaces, air movements, sound waves and gravitational forces. Even they can detect their position in air and water while flying and swimming (FIG 6.3,A).

- **Sensory hairs/ sensilla trichodea-** They are the simplest type of mechanoreceptors. They are distributed to all parts of the body but they are more on those parts of insect body which are in continuous contact to the medium like antenna, mouthparts and tarsal segments. Hair is placed in a socket and four associated cells. These associated cells are inner cell called trichogen cell which generate the hair cell, outer cell called tormogen cell which produces membrane of the cell, neurilemma cell which cover cell body and axon of sensory neuron and the sensory neuron. The hairs may be long which are sensitive to slight touch or short thick hair which stimulated to considerable force.
- **Proprioreceptor-** They are sensitive to pressure and detect change in length, tensions, compression, and body posture and body position. Different types of proprioreceptors hair plate, campaniform sensilla (FIG 6.3, B), chordonotal organs, stretch receptors and nerve nets. Campaniform sensilla are homologous to tactile hair except hair shaft replaced by dome shaped plate. Chordonotal organs consist of chordonotal sensilla (FIG 6.3, C) which lacks exocuticular component and associated with body wall, skeletal structure and trachea. Stretch receptors attach to connective tissue and other end connected with body wall/ intersegmental membrane/ muscle and associated with multipolar neurons. It gives message to the CNS about breathing, gut peristalsis and locomotion. Nerve plexus/net consists of many bipolar and multipolar neurons placed below body wall. It detects movement and stress on body.

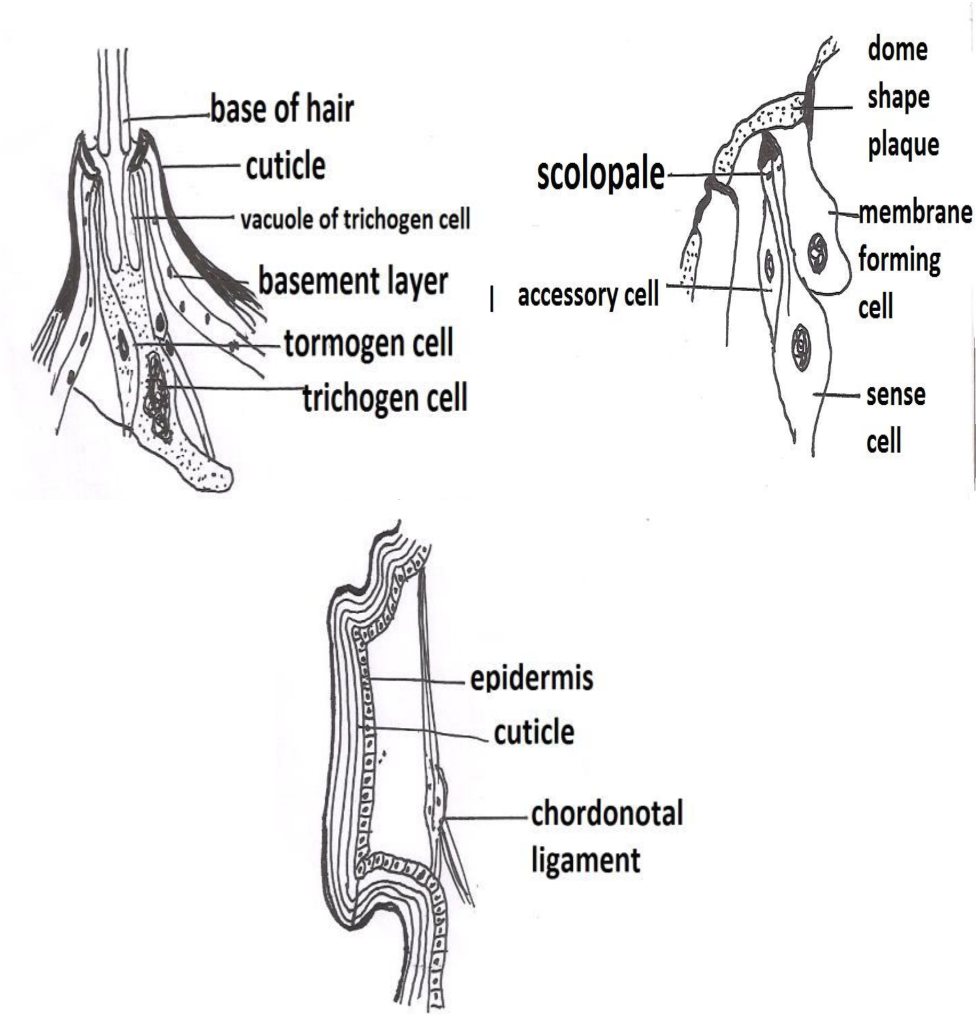


FIG 6.3: A) Mechanoreceptor B) Campaniform sensilla C) Chordonotal organ

6.4.2 Chemoreceptors

These receptors deal with taste (gustatory) and smell (olfactory) of food, oviposition sites, locating host, mate finding, detect attractants and repellents. Sometimes the same sensilla function of both smell and taste as they are identical structures. Chemosensilla are of two types:

1. One is uniporous chemosensilla which are thick walled, terminate in a single pore and innervated by many neurons. Example, food canal of aphids, hypopharynx of cockroach, labellum of flies. They resemble with the tactile sensilla.
2. The other type is multiporous which are thin walled, consist of many to several thousand pores and connected to multineural innervations. Example, antenna of many orders.

In general they are present on mouthparts specially palps, body surface, antenna in Hymenoptera, ovipositor in parasitic Hymenoptera, Diptera and tarsi of many Lepidoptera.

6.4.3- Sound and light producing organs

Sound is produced either by rubbing one part of body to another part or one part by other external object.

- Sound can be produced simply by beating of wings which are audible in flies and bees. They can be calculated by counting beats/ cycle per second like bees beats at the rate of 250 c/sec, *Culex* mosquito 280-340 c/sec and grasshoppers 60-6400 c/sec.
- Termites produce by striking the head/jaws by hard surface.
- Hind femur and elytra rubbed against each other producing sound in Acridiae family (Orthoptera).
- Posterior femora with 2 or 3 abdominal segments producing sound waves in Gryllidae (Orthoptera).
- Elytral stridulation in crickets, Coleopteran and larval psyllids.
- Tip of rostrum against sterna file.
- In *Acherontia* (deaths head hawk moth) moth a whistling sound is produced by sucking air through proboscis which enlarges pharynx and this vibrates epipharynx 280 c/sec.
- In cicada tymbal is covered with thin sheet called tymbal cover which are associated with air sacs and tymbal muscles. By the contraction of tymbal muscles the tymbal gets pulled producing a click and when it relaxes another click is produced when tymbal takes back its position.

Light is produced by light producing bioluminescent organs. There are some insects which consist of photogenic cells called **photocytes** which contain membrane bound vesicles called **luminelle**. In these luminelle there are many tiny vesicles called **lumisomes** (FIG 6.5).

Mechanism:

It is a mechanism where reactions occur in a cascade fashion. A nerve impulse stimulates acetylcholine which on hydrolysis gives acetic acid and choline. In presence of ATP and CoA it is converted into acetyl CoA, pyrophosphate and adenylic acid. Now luciferin comes in action and in the presence of enzyme luciferase and magnesium or manganese salts produces adenyl-luciferin and pyrophosphates. This on oxidation gives oxyluciferin and adenylic acids emitting light (FIG 6.4).

$$Luc + D\text{-}LH2 + ATP \xrightarrow{Mg^{2}+} Luc.LH2\text{-}AMP + PPi \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(i)$$

$$Luc.LH2\text{-}AMP + O2 \longrightarrow Luc.oxyluciferin^{*} + AMP + CO2 \ldots\ldots\ldots\ldots\ldots\ldots(ii)$$

$$Luc.oxyluciferin^{*} \longrightarrow Luc.oxyluciferin + light \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(iii)$$

$$Luc + L + ATP \xrightarrow{Mg^{2}+} Luc.L\text{-}AMP + PPI \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(iv)$$

FIG 6.4: Mechanism of bioluminescence

It is noted in various representatives of orders:

- Collembola- spring tails, *Achrorutes muscorum* whole body produces light.
- Homoptera- lantern flies, *Fulgora lanternaria* by head region.
- Coleoptera– *Lampyris noctiluca, Photinus* (fire flies), *Lucicola* light emitted by ventral side of abdomen, *Photuris* by 6-7 abdominal segment in males and 7 segment in females, *Pyrophorus* by either side of thorax.
- Diptera - glow worms *Platyura fultoni* by caudal region, *Arachnocampa luminosa* by end of malphigian tubules.

The nature of light also differs like *Lampyris noctiluca and Photinus* emits yellow green light, lantern flies white light, larva and adult of *Phrixothrix* green light. The flow of light can be uniform as in female of *Lampyris,* intermittent glow in *Photinus* pulsation glow in *Lucicola*.

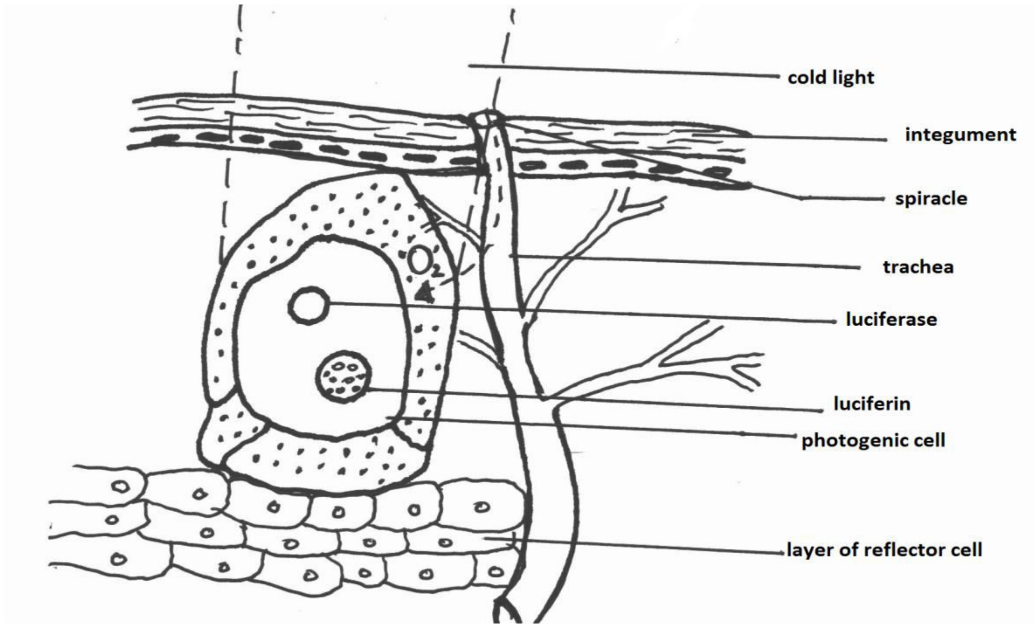


FIG 6.5: Bioluminescence in glow worm

Function:

- It is important for mutual attraction of sexes.
- It is of taxonomic value as it is species specific. Example, male firefly flies above 50 cm from ground.
- It attracts others members for locating food, e.g *Balitophilia***.**

6.4.4 Audioreceptors

Sound are the waves which are air borne or water borne as the particles in the medium vibrate and these vibrations are received by organ of hearing. They are present on antenna and cerci and named as sensilla trichodea. There are some organs associated with audioreceptors Johnston's organs of in antenna and tympanal organ which respond to air borne vibrations, subgenual organ respond to solid vibrations.

- **Johnston's organ**- It is located on the pedicel of the antenna in all adults and some of the larval forms. It is important organ for deciding position of head, direction and orientation of body. In male mosquito and chironomids these locate female while flying to mate. For this reason male bears bushier antenna with long hair which vibrate and give information to the organ. The Johnston's organ consists of two rings of scolopidia inner ring parallel to flagellum and outer ring perpendicular to flagellum. Inner scolopidia are more sensitive.

- **Tympanal organ**- They are located on foretibia of Tettigonidae, Gryllidae (Orthoptera), abdomen in cicada (Hemiptera) and metathorax in Noctuidae (Lepidoptera). They consist of many chordonotal sensilla (FIG 6.6).
- **Subgenual organ**- They are present on tibia (10-40 sensilla) in Coleoptera, Diptera and Thysanura.

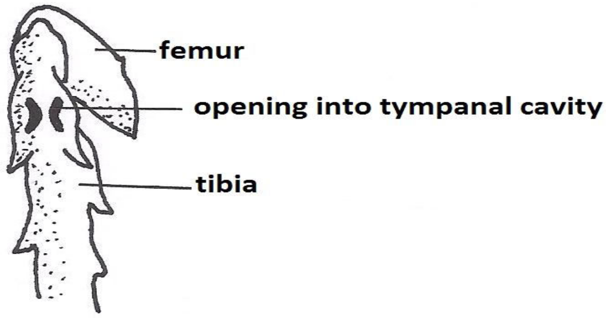


FIG 6.6: Tibial Tympanal organ of *Decticus*

6.3.5- Photoreceptors and Visual organ

All insect can detect light energy due to photo sensory structures like compound eyes, ocelli or stemmata**.** They are still wanting in cave dwelling and nocturnal insects where they can sensitize through general body surface. Fruit fly oviposition is stopped if light source ceases, on the contrary codling moth lays eggs in darkness. In aphids the non sexual to sexual reproduction occurs in short day length.

- **Compound eyes:** A pair of compound eyes is present on the dorsal side of the head and is well developed in most of the insects. It may be reduced or absent in parasitic forms like lice, fleas, female scale insect etc. **Holoptic condition** is found in some insects like dragon flies, horseflies, male tabanids in which eyes are large and meet posterior at mid dorsal line. Number of small units called ommatidia each forms a part of image and join to each other therefore called compound eyes. Each ommatidium (FIG 6.7,A) consists of cornea, cornegean cells, cone cells, crystalline cone, retinal cells, rhabdom, primary and secondary iris pigment. The ommatidium consists of light gathering component made of corneal lens and crystalline cone. The retinular cells are the primary sense cells which collect and transduce light energy. Crystalline cone is secretes by four cone cells/ Semper's cell. There are actually eight retinal cells but one degenerate and left seven eccentrically arranged with centrally placed a receptive area called rhabdom. It contains visual pigment which are conjugated proteins called rhodopsin resembling the pigment of vertebrate eye. The photosensitive chromophores consist of aldehyde of vitamin A *i.e* retinaldehyde. Secondary pigment cells consisting of ommochromes which contain granules of brown, red and yellow pigments.

Types of compound eyes:

1. **Eucone**- in this type of compound eye cone cells secrete hard refractive crystalline cone. Example Orthoptera, Lepidoptera, Odonata,Coleopetra.
2. **Pseudocone**- Cone is filled with gelatinous fluid since crystalline cone is absent. Example : Diptera.
3. **Acone-** Cone is totally absent. Example, Hemiptera, Dermaptera.
4. **Exocone**- The inner surface of cornea extends inside replacing the crystalline cone. Example: some of the Coleopterans.

- **Ocelli:** They are simple eyes located at dorso-frontal region of head and contain 500-1000 photosensitive cells below the common lens. At the distal part each of them forms rhabdom which together form rhabdom (FIG 6.7,**B**). They are more sensitive and respond more rapidly than compound eyes. They are able to form image below rhabdom that is why no physiological significance. They can measure light intensity and are essential to maintain diurnal rhythms. Ocelli are found in many adult insects and young ones of many exopterygotes .
- **Stemmata/ lateral ocelli:** They are another type of simple eye found in larva of many endopterygotes behaving as the only photosensitive structure in body. They lie lateral in position so also called lateral ocelli (FIG 6.7,C). In saw fly and beetle larva one pair of stemmata on either side is present consist of single lens with many photosensitive cells lying beneath ending in a single rhabdom. Several stemmata are present in larvae of Neuroptera, Trichoptera and Lepidoptera but with above components they also bear corneal and retinal cells. Sometimes, from outside there is no sign of stemmata but pocket of photosensitive cells are present below cuticle in larvae of Diptera (cyclorrhaph). They are responsible for color discrimination.

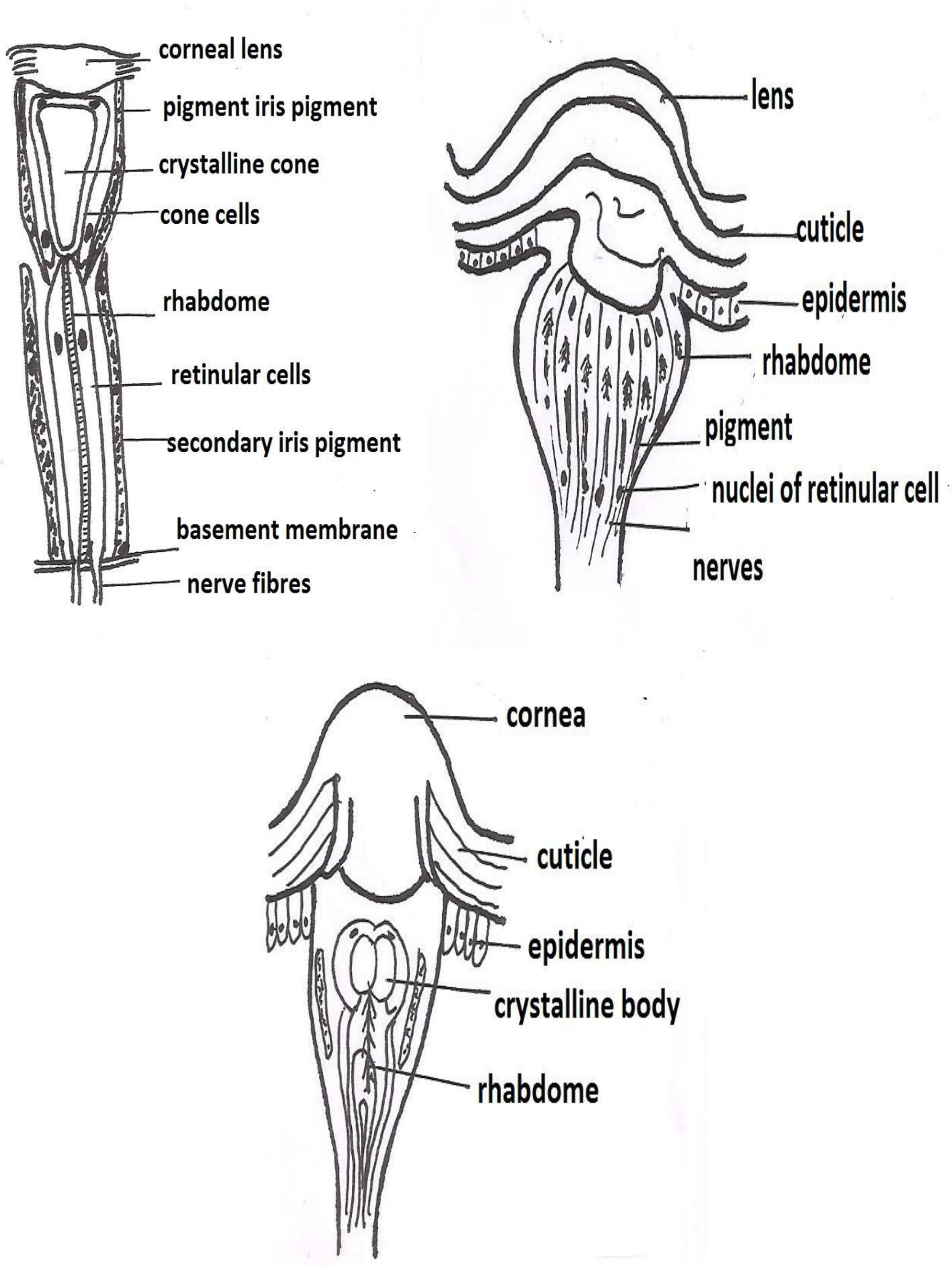


FIG 6.7: A) Ommatidium B) Ocellus (Hemiptera) C) Stemmata (Lepidoptera)

6.4.6 Physiology of vision

Insects have binocular vision and sensitive to UV and blue green light of electromagnetic spectrum. Bees are attracted towards yellow flower as flower reflects UV rays. They are also red color blind except butterflies which can recognize red flower. Two types of images are formed (apposition and superposition) and on this basis ommatidium is also differentiated into two types (photopic and scotopic).

1. **Apposition image/ photopic ommatidium**- In these pigment cells get extended and isolates ommatidium so that light rays can pass through the central axis. The other light rays get absorbed. This type of image is formed in diurnal insects (FIG 6.8).
2. **Superposition image/ scotopic ommatidium-** Pigment cells are in contracted state so that each rhabdom receives various light rays from many lenses. This type of image is formed in nocturnal insects (FIG 6.9).

The sharpness of image depends upon the number of ommatidia per unit surface area of the eye. Since the surface of the eye is curved, insect can detect the distance to their prey or predator from them.

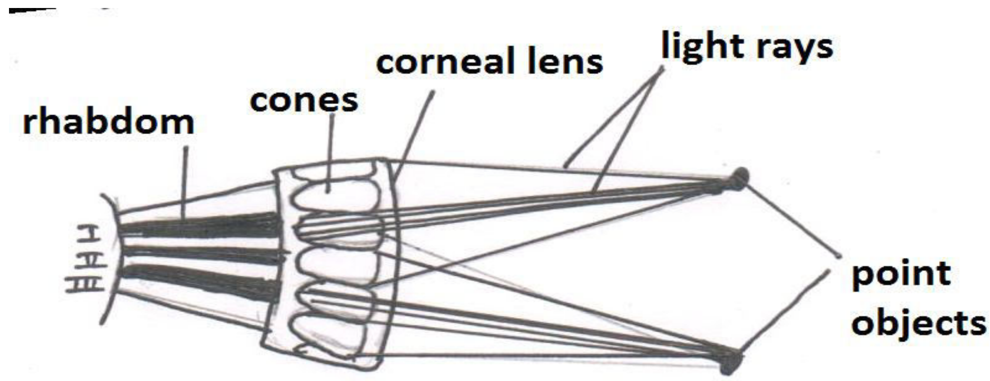


FIG 6.8: Apposition image

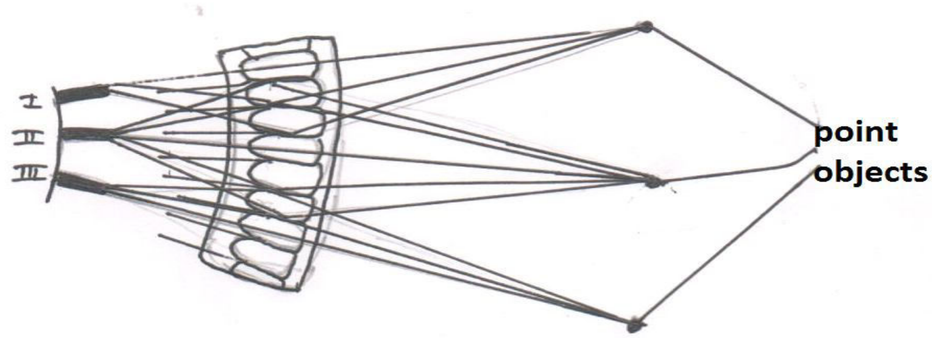


FIG 6.9: Superposition image

6.5 Reproductive systems

Insects have a high rate of reproductive rate and a short generation time, so that they evolve faster and can adapt to environmental changes much faster than other slower breeding animals. There remains a basic design and function for each reproductive part as all the animals have like gonads, accessory gland and external genitalia.

Reproductive system is meant for mating and reproduces young ones. Although sexual reproduction is common to insects but there are many insects which have special type of development like parthenogenesis, polyembryony or paedogenesis. The two individual male and female shows sexual dimorphism in many insects but in some by examining the external features one is not able to differentiate between them. In some insects male and female reproductive organs are found in same individual, phenomenon called **hermaphroditism** as in case of *Drosophila* and scale insect. Reproductive organ produces ova and sperms like that of vertebrates with common character as they are unicellular, haploid, ova larger than sperm.

6.5.1 Structure and Physiology

Female Reproductive System

A pair of ovaries present on either side of the abdomen. Each ovary is divided into many functional units named ovarioles. Ovariole lies parallel to each other and are the site of production of ova. Ovarioles in Diptera and young ones of many insects covered with layer of peritoneum called peritoneum sheath. This sheath disappear with growth and are absent in adults. The number of ovarioles may vary from one insect to another for example, 1 in tse-tse fly, dung beetle and beetles to 2,000 in termite queen. Ovariole is divided into three parts terminal filaments, egg tube and pedicel. Terminal filament is the topmost part of ovariole with egg tube in middle and pedicel at the end (FIG 6.10). Egg tube further divided into germarium containing germ cells and vitellarium where egg grows in size. Germarium produces two types of cells cystocytes give rise to follicle cell and trophocyte giving nurse cells. During active oogenesis, new oocytes are produced within each ovariole and migrate toward the basal end of the ovariole. Each oocyte undergoes meiosis yielding one egg and three polar bodies which may disintegrate. As the developing egg grow in size by absorbing yolk (produced by nurse cells) move down the ovariole. Each ovariole contains a linear series of eggs in progressive stages of maturation. By the time an egg reaches the base of ovariole pedicel it becomes fully mature and up to 100,000 times larger than the original oocyte. A mass of follicle cells plugs the pedicle and get dissolved when egg is laid.

Function: The female insect's main reproductive function

- is the production of eggs,
- to protect egg by covering them with egg's protective coating,
- to store the male gametes until egg is ready for fertilization

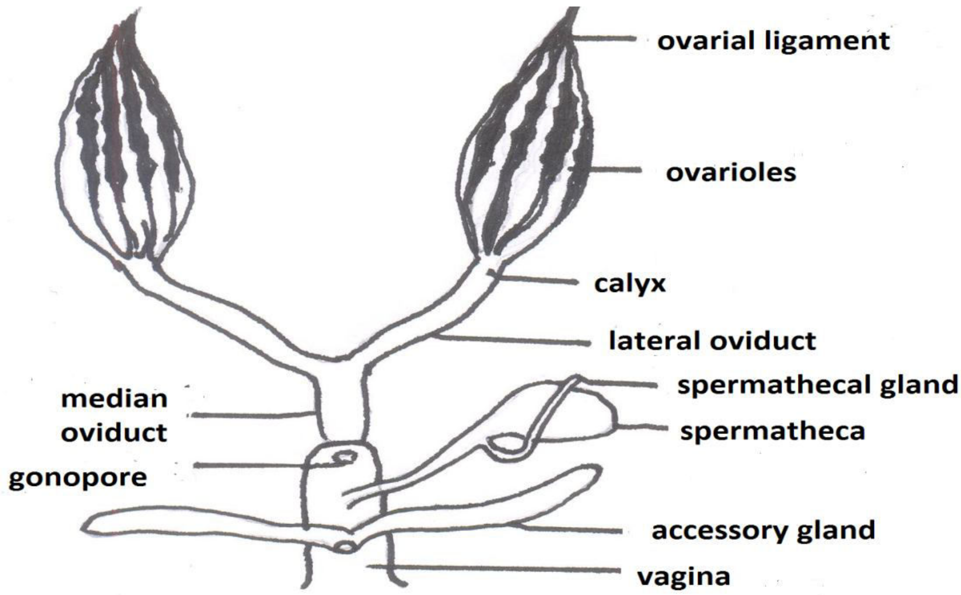


FiG 6.10: Female reproductive system of an insect.

Types of egg tube:

- **Panoistic type-** In these nutritive cells is absent and nutrition is directly absorbed by the follicular cells. Example, Apterygota, Odonata, Orthoptera, Isoptera (crickets, grasshoppers, termites, dragonflies, stoneflies and fleas, FIG 6.12, A).
- **Meroistic type-** Nutritive nurse cells are present.
  - **a) Polytrophic type-** Nurse cells are present in succession with the oocytes. Example: Neuroptera, Coleoptera, Lepidoptera, Hymenoptera, Diptera (antlions, moths, butterflies, wasp, bees, flies, FIG 6.12,C).
  - **b) Acrotophic/telotrophic-** Nurse cells are confined to the top of the egg tube and oocytes get their nutrition by nutritive cords. Example: Hemiptera, Coleoptera (bugs, most beetles, FIG 6.12,B).

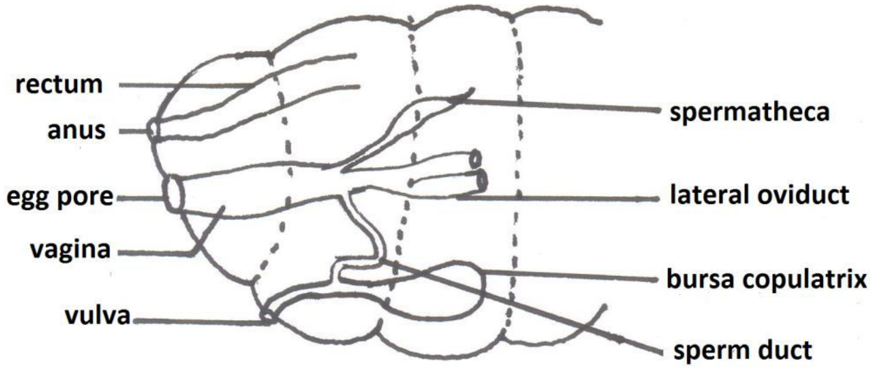


FIG 6.11: Lepidoptera female reproductive system

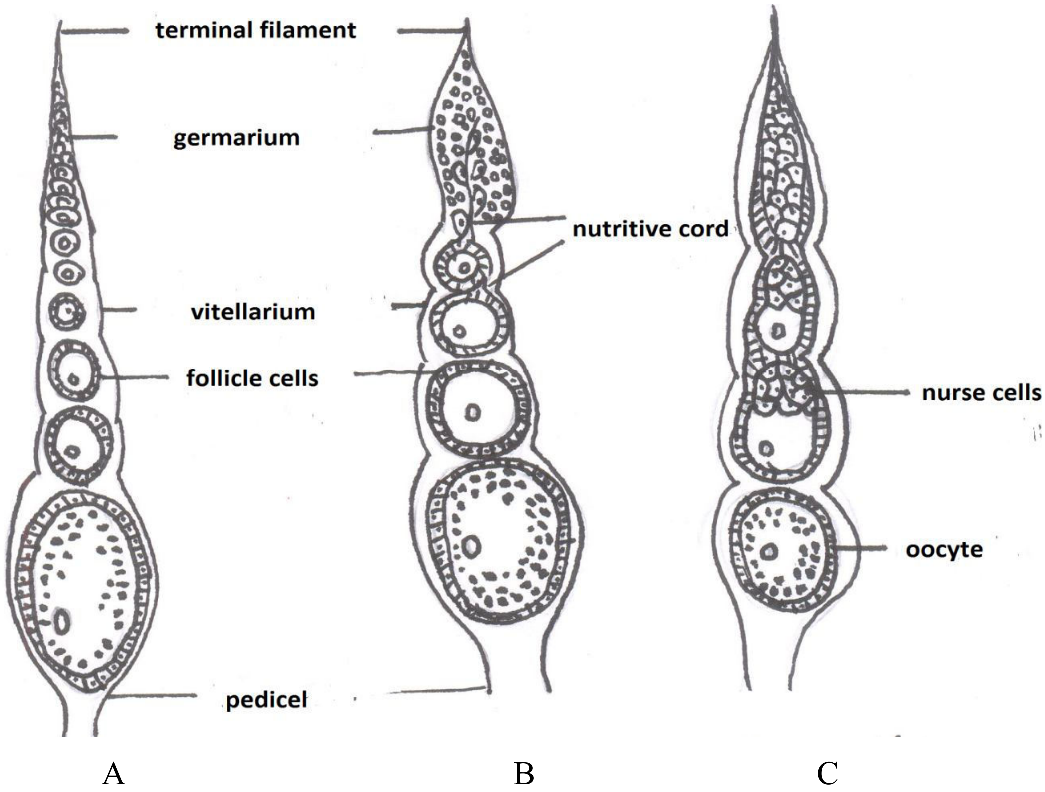


FIG 6.12: Types of ovariole A) panoistic B) telotrophic C) polytrophic

Mature eggs leave the ovarioles passing through the calyx and move towards short lateral oviducts. It is mesodermal in origin and muscular due to the presence of circular and longitudinal fibres. These lateral oviducts join to form a common median oviduct ectodermal in origin and muscular which opens into a genital chamber called the bursa copulatrix. Female accessory glands/collateral gland are also associated which supplies lubricants for the reproductive system and secrete a protein rich egg shell/chorion that surrounds the entire egg. It also forms ootheca. Poison gland in Hymenoptera is modification of these accessory glands. These glands are usually connected by small ducts to the common oviduct or the bursa copulatrix. Bursa copulatrix is a pouch like chamber meant for storage of sperms. During copulation, the male deposits his spermatophore in the bursa copulatrix. The protein coat of the spermatophore is digested by the enzymes secreted by spermathecal gland and nutrients for nourishing the sperm. Sperm may live in the spermatheca for weeks, months, or even years.

With some exceptions like flesh flies are viviparous and in them genital chambers enlarges to form uterus. In Lepidoptera and certain water beetles there are two openings one is oviporus where egg is discharged and vulva is a copulatory opening (FIG 6.11). In Ephemeroptera lateral oviducts opens independently to the exterior.

Male Reproductive System

Sperm development usually takes place by the time the insect reaches adulthood. Male reproductive system contains a pair of testes, vasa deferen, paired ejaculatory duct and accessory glands. Testes are usually paired except in Lepidopetra (locust and moth) where they are fused to form a single median organ. Each testis is subdivided into parallel arranged functional units called tubular follicles bounded by connective tissue sheath. The number of testicular follicle may vary as 1 in certain beetle, 2 in lice and upto 100 in grasshoppers. Spermatocytes formed in testicular follicles migrate toward the basal end of the follicle undergoes meiosis and yields four haploid spermatids which mature to form spermatozoa/sperms. Mature sperm pass out of the testes through short ducts called vas deferns to the seminal vesicles where they are stored. Vas deferns join one another near the midline of the body, and form a single ejaculatory duct that leads out of the body through the male's copulatory organ (called an aedeagus).

One or more pairs of accessory glands are connected with the male reproductive system through short ducts. They open near the testes or seminal vesicles or sometimes ejaculatory duct. The glands have function of manufacture of liquid seminal fluid that sustains and nourishes mature sperm while they are in the male's genital system (FIG 6.13). Vas deferens is mesodermal, ejaculatory duct is ectodermal and accessory glands may be ecto or mesodermal in origin. In Ephemeroptera vas deferens opens directly to outside without forming ejaculatory duct.

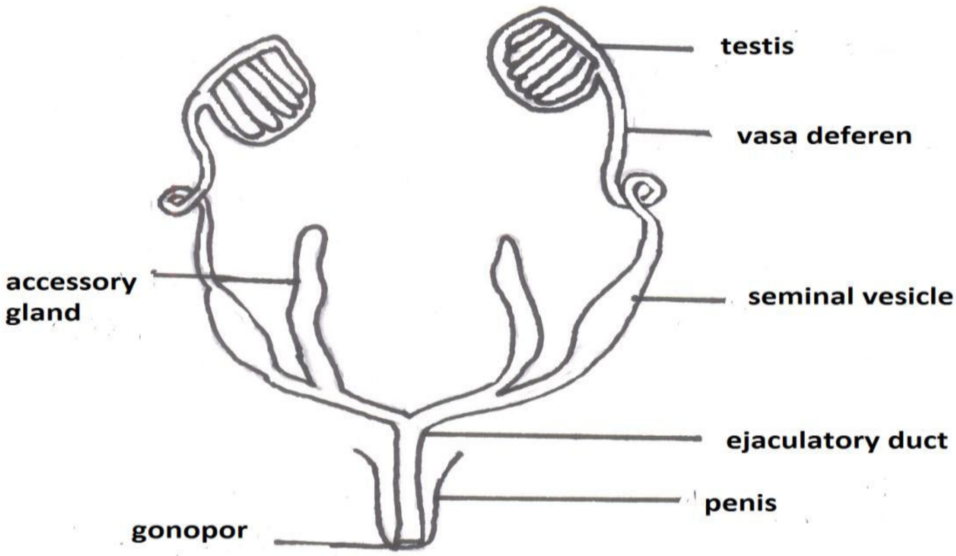


FIG 6.13: Male reproductive system of insect.

Spermatophores are pouch-like structures made up of protein that encase the sperms and protect them while delivering to the female's body during copulation.

Function:

The male's main reproductive function

- is formation of male gametes ;
- storage of spermatozoa and;
- to provide transport of the sperms to the reproductive tract of the female.

6.4.2- Role of pheromones in reproduction

The sexual maturation is effected by quantity, quality of food, population density, mating, temperature, humidity and also photoperiod. The two endocrine glands are also influencing the reproduction corpora allata producing hormones from ovaries in some insects; it also has both ganadotrophic and metabolic effect. In various insects different pheromones are secreted which are specific in their function.

- **Maturation accelerating pheromones**-In locust, *Schistocerca gregaria* if females are abundant, their egg matures faster than the isolated females due to their increase in endocrine activity. Here in the presence of mature male's egg development in females is promoted due to maturation accelerating pheromones. Greyish brown color of newly emerged insect changes to yellow color in mature males is identified in Acrididae.

- **Maturation inhibiting pheromones**-In social insects such as in honey bees there is only one queen per bee hive. This is due to the fact that queen secretes maturation inhibiting pheromones (9-oxodecenoic acid from her mandibular glands) that prevents the development of reproductive system in other workers.
- **Pheromones producing gland**- During sexual maturation certain changes may also occur in males as they develop characteristics behavior pattern and coloration.
- **Sex pheromones/ aphrodisiac**- Pheromones are also responsible for locating mate by producing signals. This signal or chemical or pheromone can be secreted by either by male or female or both. For example, *Bombyx mori* secretes bombykol, musculure from *Musca domestica,* male cockroach secretes seducing. Sex attractants pheromones used to locate mate from a distance followed by courtship pheromones used before mating. Butterfly *Danus gilippus* have several abdominal hair pencils produces pheromones that dusted on antenna of male while both are flying. Female then folds her wings and allows copulation. This pheromone is named as danaidone which is a pyrrolizidine alkaloid.
- **Fecundity enhancing pheromones**- In Diptera and Orthoptera these pheromones are likely to be produced in semen which stimulate female to produce oviposition hormone.
- **Spacing pheromones**- These are produced by some immature and adults that may be tactile or olfactory, may release to oviposition. *Rhagoletis pomonella* (apple maggot fly) females produces these chemicals to deter oviposition by other females. *Oecophylla longinoda* (African weaver ant) secretes for even dispersal of colonies. *Pieris brassica* larva secretes to inhibit egg laying of adult females in same place.

6.5- Summary

Neuro-endocrine system comprises of neurosecretory cells and hormones produced by endocrine glands. Different glands are prothoracic glands, corpora cardiac, corpora allata and neurosecretory cells of the brain. The hormones secreted by these glands are JH, ecdysone which are involved with the metamorphosis and moulting. Corpora allata are responsible for polymorphism in insects. Pheromones are trail making, territory making, sex pheromones, aggregation, alarm and caste differentiating pheromones. Sense organs are specialized structures which receive external stimuli and pass information to the central nervous system. Sense organs are mechanoreceptors, chemoreceptor, tactoreceptors, audio and visual receptors. Reproductive system is meant for mating and reproduces young ones. Although sexual reproduction is common to insects but there are many insects which have special type of development like parthenogenesis, polyembryony or paedogenesis. Male and female shows sexual dimorphism in many insects.

The female reproductive organs include, paired ovaries, and paired lateral oviducts that join to form the common oviduct. The external opening gonopore from common oviduct is concealed in a cavity called the genital chamber which serves as a copulatory pouch during mating. The spermatheca and accessory glands are meant for nourishing the spermatozoa in the vagina.

The male reproductive system contains two testes, consisting of follicles in which the spermatozoa are produced. Testes open individually into the vas deferens meant posteriorly for storage of the sperm. The vas deferents unite at posterior end to form a centrally placed ejaculatory duct, opens outside in the form of aedeagus or a penis. Accessory glands function to secrete fluid in the spermatophore which carry sperms and nourishes them.

6.7 Glossary

- **Hormones:** These are the chemicals which are secreted by endocrine glands and its function is to regulate internal environment of body.
- **Pheromones:** They are the chemical that triggers a natural behavioral response in another member of the same species.
- **Discontinuous polymorphism:** Termites and aphids shows discontinuous polymorphism as the forms are totally different to each other.
- **Continuous polymorphism:** Locust shows continuous polymorphism as the forms are slightly different.
- **Mechanoreceptors:** They are sense organs sensitive to physical touch.

- **Chemoreceptors:** They are the receptors deal with taste (gustatory) and smell (olfactory).
- **Audioreceptors:** They are sense organs sensitive to sound.
- **Hermaphroditism:** Male and female reproductive organs are found in same individual.
- **Panoistic type-** In these nutritive cells is absent and nutrition is directly absorbed by the follicular cells.
- **Meroistic type-** Nutritive nurse cells are present.
- **Moulting:** Insects have rigid exoskeleton and can grow only by periodically shedding their exoskeleton called moulting.

6.8 Self learning exercise

Section -A (Very Short Answer Type)

1. Where is brain hormone stored in insect body?
2. Which germ layer gives two prothoracic glands/ecdysial gland?
3. Two small glandular bodies named corpora allata present on either side of ………………..on sides of the oesophagus
4. The word hormone was given by which scientist?
5. Give the synonym of Prothoracicotropic Hormone (PTTH)?
6. What is composition of JH?
7. The term *pheromone* was introduced by …………………………?
8. Write other name of pheromones?
9. How many cycles beat in a second that produces sound in mosquitoes?

Section -B (Short Answer Type)

1. Define ectohormones and hormones?
2. What is Johnston's organ?
3. Name some examples of sound producing organs?
4. What is difference between compound eye, stemmata and ocelli?
5. Define bioluminescence phenomenon?
6. What is the mechanism and function of light production?

Section -C (Long Answer Type)

1. Briefly explain male and female reproductive organs in insects?
2. Write a short note on mechanoreceptors and chemoreceptors?
3. What are different images formed by compound eye?

4. Write a note on sense organs?
5. What is the role of pheromones in reproduction?
6. How Endocrine control Polymorphism in insects?
7. What are ovarioles and its types?

Answer Key of Section-A

1. Neuro-haemal organs
2. Ectodermal layer
3. Corpora cardiac
4. C. M. Williams
5. Ecdysone
6. Non sterolic compound generally terpenoid
7. Peter Karlson and Martin Lüscher (1959)
8. Ectohormones
9. 280-340 c/sec

6.9 References

- Cedric Gillot: Entomolgy
- Kachhwaha N.: Principles of Entomology- Basic and Applied