

Module 1 Lecture 9

Cell locomotion (amoeboid, flagella, cilia)

Cell Movement

Cell movement; is both internal, referred to as cytoplasmic streaming, and external, referred to as motility. Internal movements of organelles are governed by actin filaments and other components of the cytoskeleton. These filaments make an area in which organelles such as chloroplasts can move. Internal movement is known as cytoplasmic streaming. External movement of cells is determined by special organelles for locomotion. These could be pseudopodia, cilia and flagella.

Elements of cell movement

Cell movement is brought about by the cytoskeleton which is a network of connected filaments and tubules. It extends from the nucleus to the plasma membrane. Electron microscopic studies showed the presence of an organized cytoplasm. Immunofluorescence microscopy identifies protein fibers as a major part of this cellular feature. The cytoskeleton components maintain cell shape and allow the cell and its organelles to move. The cytoskeleton is composed of actin and microtubules. Actin filaments are thoroughly described in later lectures. In short, they are long, thin fibers approximately seven nm in diameter. These filaments occur in bundles or meshlike networks. These filaments are polar, meaning there are differences between the ends of the strand. An actin filament consists of two chains of globular actin monomers twisted to form a helix. Actin filaments play a structural role, forming a dense complex web just under the plasma membrane. Actin filaments in microvilli of intestinal cells act to shorten the cell and thus to pull it out of the intestinal lumen. Likewise, the filaments can extend the cell into intestine when food is to be absorbed. In plant cells, actin filaments form tracts along which chloroplasts circulate. Actin filaments move by interacting with myosin. The myosin combines with and splits ATP, thus binding to actin and changing the configuration to pull the actin filament forward. Similar action accounts for pinching off cells during cell division and for amoeboid movement.

Other components are the intermediate filaments which are between eight and eleven nm in diameter. They are between actin filaments and microtubules in size. The intermediate fibers are rope-like assemblies of fibrous polypeptides. Some of them support the nuclear envelope, while others support the plasma membrane, form cell-to-cell junctions. Similarly, microtubules are small hollow cylinders (25 nm in diameter and from 200 nm-25 μ m in length). These microtubules are composed of a globular protein tubulin. Assembly brings the two types of tubulin (α and β) together as dimers, which arrange themselves in rows.

Cilia and Flagella

Cilia and flagella are micro tubular projections of the plasma membrane responsible for movement of a variety of eukaryotic cells. Many bacteria also have flagella, but these prokaryotic flagella are quite different from those of eukaryotes. Bacterial flagella are protein filaments projecting from the cell surface, rather than projections of the plasma membrane supported by microtubules. Cilia are short, usually numerous, hairlike projections that can move in an undulating fashion (e.g., the protzoan *Paramecium*, the cells lining the human upper respiratory tract). Flagella are longer, usually fewer in number, projections that move in whip-like fashion (e.g., sperm cells). Cilia and flagella grow by the addition of tubulin dimers to their tips.

Eukaryotic cilia and flagella are very similar structures, each with a diameter of approximately 0.25 μ m. Many cells are covered by numerous cilia, which are about 10 μ m in length. Cilia beat in a coordinated back-and-forth motion. For example, the cilia of some protozoans (such as *Paramecium*) are responsible both for cell motility and for sweeping food organisms over the cell surface and into the oral cavity. In animals, an important function of cilia is to move fluid or mucus over the surface of epithelial cell sheets. A good example is provided by the ciliated cells lining the respiratory tract, which clear mucus and dust from the respiratory passages. Flagella differ from cilia in their length (they can be as long as 200 μ m) and in their wavelike pattern of beating. Cells usually have only one or two flagella, which are responsible for the locomotion of a variety of protozoans and of sperm.

Occurrence:

The flagella occur in the protozoans of the class Flagellata, choanocyte cells of the sponges, spermatozoa of the Metazoa and among plants in the algae and gamete cells. The cilia occur in the protozoans of the class Ciliata and members of other classes and ciliated epithelium of the Metazoa. The cilia may occur on external body surface and may help in the locomotion of such animals as the larvae of certain Platyhelminthes, Nemertines, Echinodermata, Mollusca and Annelida. The cilia may line the internal cavities or passages of the metazoan bodies as air passage of the respiratory system and reproductive tracts. The nematode worms and arthropods have no cilia. Except for sperm, the cilia in mammalian systems are not organelles of locomotion. But their effect is the same, that is, to move the environment with respect to the cell surface.

Arrangement:

Different species of bacteria have different numbers and arrangements of flagella. Monotrichous bacteria have a single flagellum. Lophotrichous bacteria have multiple flagella located at the same spot on the bacteria's surfaces. Amphitrichous bacteria have a single flagellum on each of two opposite ends. Peritrichous bacteria have flagella projecting in all directions.

Structure

Cilia and flagella is made of the axoneme (**Figure 1**) which is composed of microtubules and their associated proteins. The microtubules are arranged in a characteristic "9 + 2" pattern in which a central pair of microtubules is surrounded by nine outer microtubule doublets (Figure 1). The two fused microtubules of each outer doublet are distinct: One (called the A tubule) is a complete microtubule consisting of 13 protofilaments; the other (the B tubule) is incomplete, containing only 10 or 11 protofilaments fused to the A tubule. The outer microtubule doublets are connected to the central pair by radial spokes and to each other by links of a protein called nexin. In addition, two arms of dynein are attached to each A tubule. It is the motor activity of these axonemal dyneins that drives the beating of cilia and flagella. The minus ends of the microtubules of cilia and flagella are anchored in a basal body, which is similar in structure to a centriole and contains nine triplets of microtubules. Basal bodies thus serve to

initiate the growth of axonemal microtubules as well as anchoring cilia and flagella to the surface of the cell.

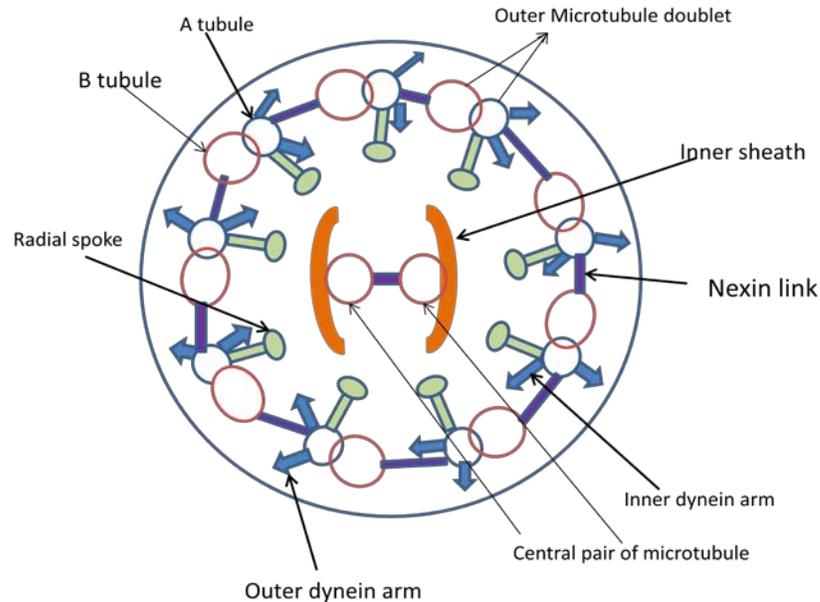


Figure 1: Structure of axoneme of cilia and flagella

Movement:

Generally speaking flagella work as whips pulling (as in *Chlamydomonas* or *Halosphaera*) or pushing (dinoflagellates, a group of single-celled Protista) the organism through the water. Cilia work like oars on a viking longship (*Paramecium* has 17,000 such oars covering its outer surface). Figure 1 illustrates the movement of cilia and flagella. More precisely the movements of cilia and flagella result from the sliding of outer microtubule doublets relative to one another, powered by the motor activity of the axonemal dyneins. The dynein bases bind to the A tubules while the dynein head groups bind to the B tubules of adjacent doublets. Movement of the dynein head groups in the minus end direction then causes the A tubule of one doublet to slide toward the basal end of the adjacent B tubule. Because the microtubule doublets in an axoneme are connected by nexin links, the sliding of one doublet along another causes them to bend, forming the basis of the beating movements of cilia and flagella. It is apparent, however, that the activities of dynein molecules in different regions of the axoneme must be carefully regulated to produce the coordinated beating of cilia and the wavelike oscillations of flagella—a process about which little is currently understood. Another important thing is

that counterclockwise rotation of monotrichous polar flagella pushes the cell forward with the flagella trailing behind, much like a corkscrew moving inside cork. Indeed water in the microscopic scale is highly viscous, very different from our daily experience of water. The flagella are left-handed helices, and bundle and rotate together only when rotating counterclockwise. When some of the rotors reverse direction, the flagella unwind and the cell starts "tumbling" (see Figure 2).

The beating of cilia or flagella is caused by the intraciliary excitation which is followed by the interciliary conduction. Recent studies have shown that cytoplasm is necessary for the ciliary movements. The ATP provides necessary amount of energy for the motion of the cilia and flagella. Four types of ciliary movements have been recognized which are as follows :

- 1. The pendulus ciliary movement:** The pendulus type of ciliary movement is carried out in a single plane. It occurs in the ciliated protozoans which have rigid cilia.
- 2. The unciform ciliary movement:** The unciform (hook-like) ciliary movement occurs commonly in the metazoan cells.
- 3. The infundibuliform ciliary movement:** The infundibuliform ciliary movement occurs due to the rotary movement of the cilium and flagellum.
- 4. The undulant movement:** The undulant movement is the characteristic of the flagellum. In undulant movement the waves of the contraction proceed from the site of implantation and pass to the border.

Each beat of cilium or flagellum involves the same pattern of microtubule movement. Each cilium moves with a whip-like motion and its beat may be divided into two phases:

1. The fast effective stroke (or forward active stroke or power stroke) in which the cilium is fully extended and beating against the surrounding liquid.
2. The slow recovery stroke, in which the cilium returns to its original position with an unrolling movement that minimizes viscous drag.

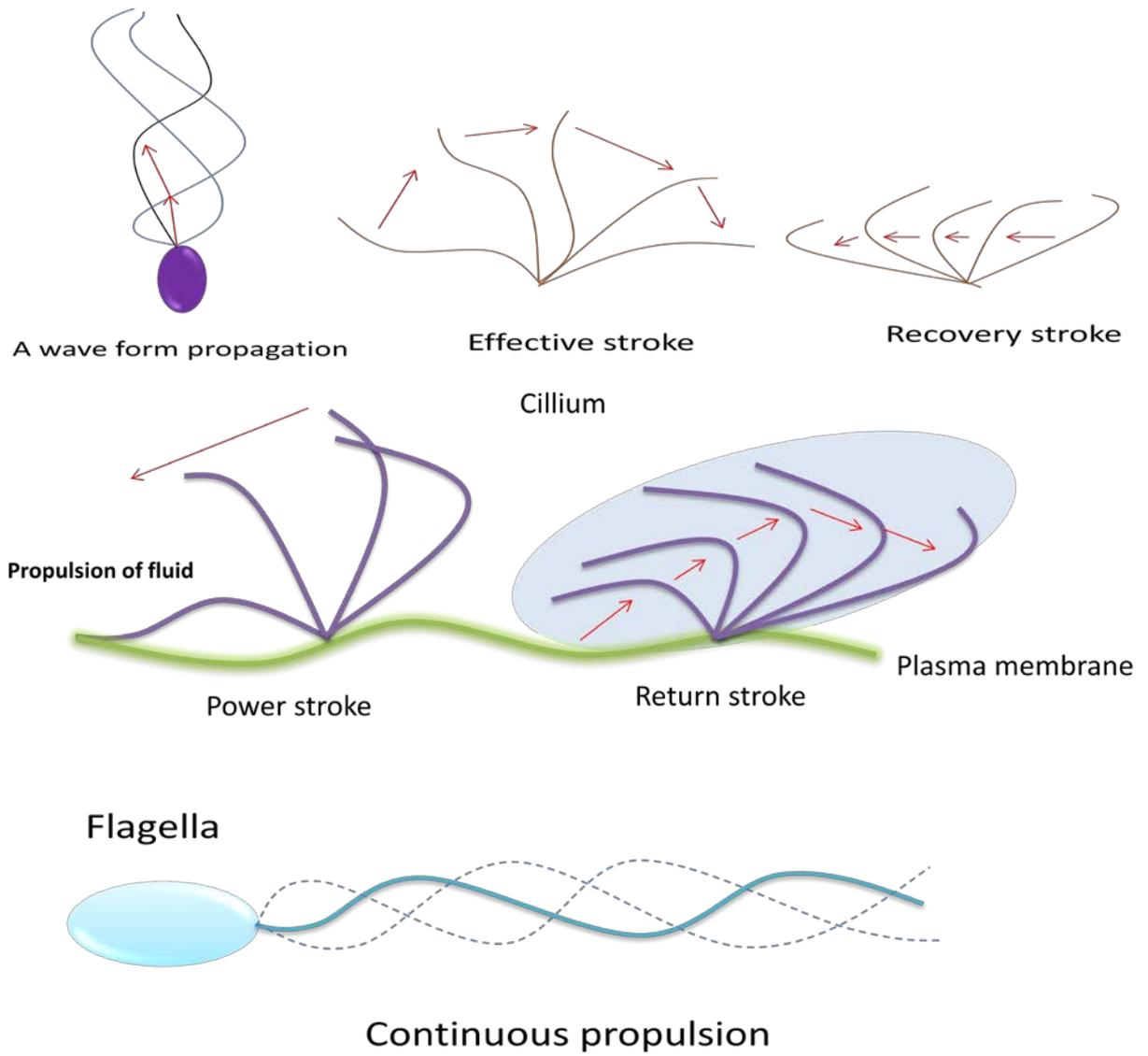


Figure 2: Ciliary and flagellar movement

The mechanism of force and movement (bending) by the flagellum has recently been studied extensively. It is well established now that the ciliary movement is generated by the microtubules and the associated structures of the flagellum. It was shown that the cell free flagella can be caused to move by adding an energy source such as ATP. Even broken pieces of cilia or isolated axoneme itself continue to beat, suggesting the role of microtubules in the movement. The contractile axostyle of some microorganisms such as *Metamonadida*. Bending force is produced by the sliding of microtubules.

Recent experimental work on ciliary motion has shown notable similarities with the sliding mechanism involved in the interaction of actin and myosin in muscle. The dynein arms attached to subfibre A have been compared with the cross bridges of myosin and it has been postulated that they form intermittent attachments, by which one doublet (N1) is able to push the adjacent one (N1 + 1) toward the tip of the axoneme. Under normal conditions, the attachment of subfibre A of N to subfibre B of N + 1 by dynein arms is not observed in an intact cilium. Only when the ciliary membrane is extracted with a detergent, the axoneme enters in a state of rigor in which the attachment is produced. Addition of ATP to axonemes in the state of rigor restores motility and causes release of the dynein arm. In this mechano-chemical cycle, the next step would be reextension of the dynein arm. In this mechano-chemical cycle, the next step would be reextension of the dynein arm and its rebinding at an angle, with a new, more proximal site on subfibre B. This step involves the hydrolysis of ATP to ADP + Pi. In the last step, the arm returns to the rigor position and displacement of the doublets results. Force is generated when dynein arms move. The movement of sliding is converted to bending by virtue of radial spokes that bridge each other doublet to the inner pair of microtubules (Figure 3).

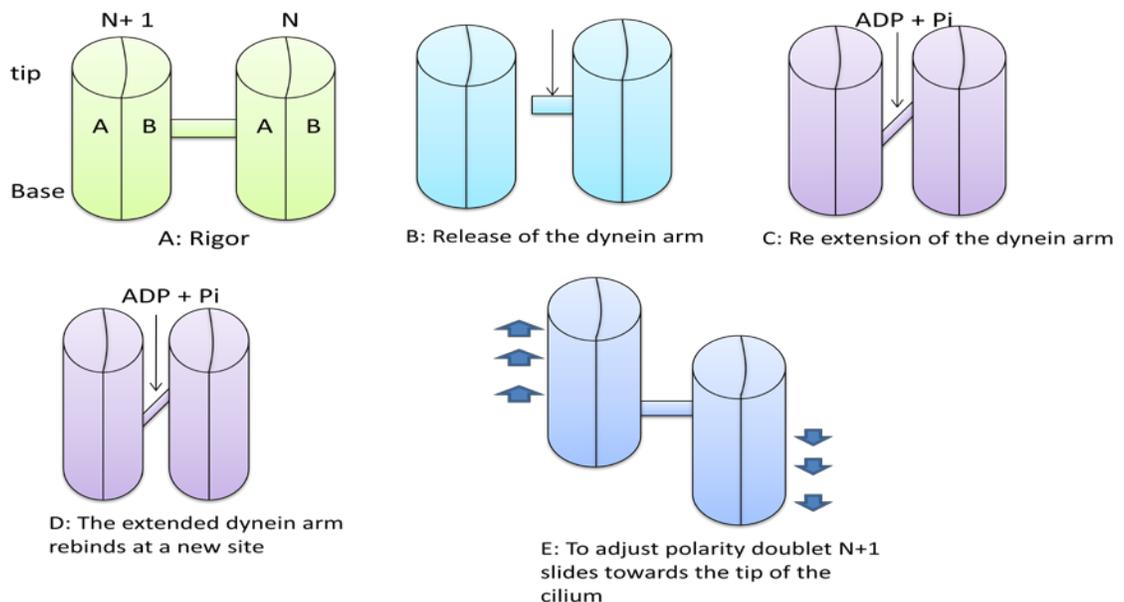


Figure 3: Schematic representation of the mechanochemical cycle involved in sliding of filament in ciliary movement.

The overall structure of bacterial flagella

The bacterial flagellum (Figure 4) is made up of the protein flagellin. Its shape is a 20 nanometer thick hollow tube. It is helical and has a sharp bend just outside the outer membrane which is called the hook. It allows the axis of the helix to point directly away from the cell. A shaft runs between the hook and the basal body, passing through protein rings in the cell's membrane that act as bearings. Gram-positive organisms have 2 of these basal body rings, one in the peptidoglycan layer and one in the plasma membrane. Gram-negative organisms have 4 such rings: the L ring associates with the lipopolysaccharides, the P ring associates with peptidoglycan layer, the M ring is embedded in the plasma membrane, and the S ring is directly attached to the plasma membrane. The filament ends with a capping protein. The bacterial flagellum is driven by a rotary engine (the Mot complex) made up of protein, located at the flagellum's anchor point on the inner cell membrane. The engine is powered by proton motive force, i.e., by the flow of protons (hydrogen ions) across the bacterial cell membrane due to a concentration gradient set up by the cell's metabolism. The rotor transports protons across the membrane, and is turned in the process.

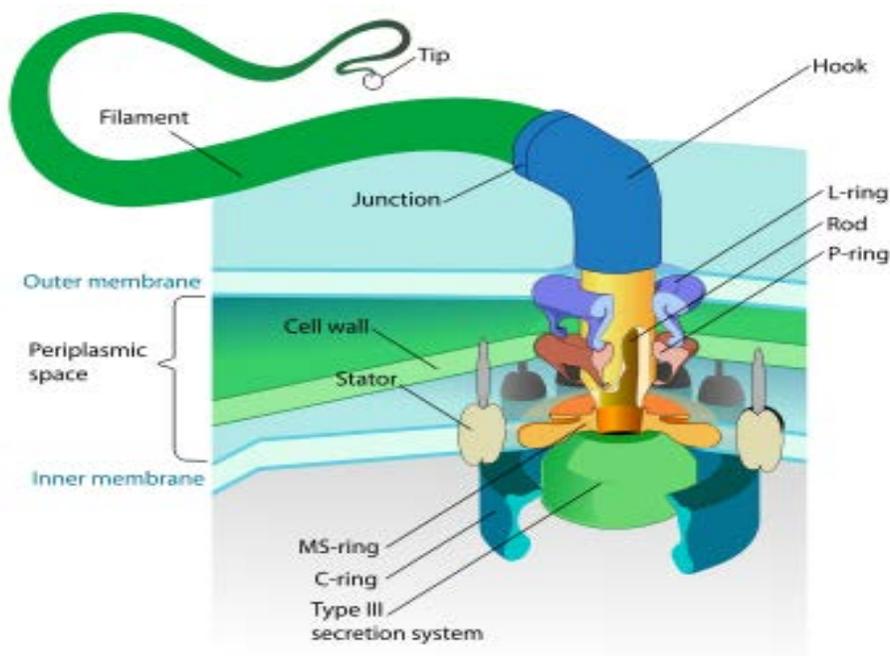


Figure 4: Flagellum of gram negative bacteria

During flagellar assembly, components of the flagellum pass through the hollow cores of the basal body and the nascent filament. During assembly, protein components are added at the flagellar tip rather than at the base. In vitro, flagellar filaments assemble spontaneously in a solution containing purified flagellin as the sole protein.

The flagellar filament is the long helical screw that propels the bacterium when rotated by the motor, through the hook. In most bacteria that have been studied, including the Gram negative *Escherichia coli*, *Salmonella typhimurium*, *Caulobacter crescentus*, and *Vibrio alginolyticus*, the filament is made up of eleven protofilaments approximately parallel to the filament axis. Each protofilament is a series of tandem protein chains. However in *Campylobacter jejuni*, there are seven protofilaments. The basal body has several traits in common with some types of secretory pores, such as the hollow rod-like "plug" in their centers extending out through the plasma membrane. Given the structural similarities between bacterial flagella and bacterial secretory systems, it is thought that bacterial flagella may have evolved from the type three secretion system; however, it is not known for certain whether these pores are derived from the bacterial flagella or the bacterial secretory system.

Other Functions:

1. The ciliary or flagellar movement provides the locomotion to the cell or organism.
2. The cilia create food currents in lower aquatic animals.
3. In the respiratory tract, the ciliary movements help in the elimination of the solid particles from it.
4. The eggs of amphibians and mammals are driven out from the oviduct by the aid of vibratile cilia of the latter.

Thus, the cilia and flagella serve many physiological processes of the cell, such as locomotion, alimentation, circulation, respiration, excretion and perception of sense.

Amoeboid movement

Amoeboid movement is a type of movement accomplished by protrusion of cytoplasm of the cell involving the formation of pseudopodia. The cytoplasm slides and forms a pseudopodium in front to move the cell forward. This type of movement has been linked to changes in action potential; the exact mechanism is still unknown. This type of movement is observed in amoeboids, slime molds and some protozoans, as well as some cells in humans such as leukocytes. Sarcomas, or cancers arising from connective tissue cells, are particularly adept at amoeboid movement, thus leading to their high rate of metastasis. Locomotion of amoeba occurs due the sol-gel conversion of the cytoplasm within its cell. The ectoplasm is called the plasma gel and the endoplasm the plasma sol. The conversion of the endoplasm to ecto and vice versa is called sol-gel conversion.

Pseudopodia

All cells do not use cilia or flagella for movement. Some, such as *Amoeba*, *Chaos* (*Pelomyxa*) and human leukocytes (white blood cells), employ pseudopodia to move the cell. Unlike cilia and flagella, pseudopodia are not structures, but rather are associated with actin near the moving edge of the cell. They are temporary projections of eukaryotic cells. Pseudopodia extend and contract by the reversible assembly of actin subunits into microfilaments. Filaments near the cell's end interact with myosin which causes contraction. The pseudopodium extends itself until the actin reassembles itself into a network. This is how amoebas move, as well as some cells found in animals, such as white blood cells.

Pseudopods can be classified into several types:

1. Lobopodia is bulbous, short and blunt in form as in *Amoebosoa*. These finger-like, tubular pseudopodia contain both ectoplasm and endoplasm.
2. Filopodia is more slender and filiform with pointed ends, consisting mainly of ectoplasm. These formations are supported by microfilaments as in *Euglypha*.
3. Reticulopodia is complex formations where individual pseudopods are blended together and form irregular nets. The primary function of reticulopodia, also known as myxopodia, is the ingestion of food, and the secondary function is locomotion.
4. Axopodia are thin pseudopods of complex arrays of microtubules enveloped by cytoplasm. They are mostly responsible for phagocytosis by rapidly retracting in response to physical contacts.

Interesting Facts:

- The first detailed chemical analysis of the protein components of the cilia of *Tetrahymena pyriformis* was conducted by I. R. Gibbons in 1963.
- In *Chlamydomonas* several mutational defects have been studied in the axoneme of flagellum which may lead to paralysis of the flagellar function.
- The cilia are modified into a variety of structures such as the rods and cones of the retina, crown cell of saccus vasculosus of third ventricle of fishes, primitive sensory cells of the pineal eye and cnidocil of the nematocysts of the coelenterates.