GOLGI APPARATUS

Camillo Golgi (1898) discovered a internal reticular apparatus in the nerve cells of the Barn owl as a special cytoplasmic area impregnated with silver nitrate. These stained regions were termed as "**Golgi apparatus or Golgi body**". Under electron microscope it has been observed that these regions show flattened membranous vesicles. These are known as Golgi complex. Golgi complex is a differentiated portion of the endomembrane system, which is morphologically very similar in plant and animal cells. It is specifically and temporally related to the endoplasmic reticulum on one side and to secretory vesicles leading to the plasma membrane on the other. Golgi complex plays as an intermediary in secretory processes. One quality of Golgi complex is lack of attached ribosomes. Most of the Golgi complex is surrounded by a zone from which most ribosomes, glycogen and mitochondria are absent, the so called zone of exclusion. Some free polysomes have been observed at the periphery of the Golgi complex.

ELECTRON MICROSCOPIC STRUCTURE: Dalton and Felix (1954) were first to reveal the electron microscopic structure of the Golgi complex. In general, three membranous components are observed under the electron microscope:

a. Flattened sacs or cisternae,
b. Clusters of tubules and vesicles of about 60 nm and
c. Large vacuoles filled with an amorphous or granular content.

a. Cisternae: The Golgi cisternae are arranged in parallel way to form stacks. Cisternae are separated by a space of 20 to 30 nm which may contain rod like elements or fibers. Often, the cisternae are arranged concentrically with a convex or concave face. There may be from 3 to 7 of cisternae in most animal and

plant cells. In certain algae, there may be as many as 10 or 20 cisternae.

Each stack of cisternae forming a dictyosome is a polarized structure having a proximal or forming face generally convex and closer to the nuclear membrane or the ER and a distal or maturing face of concave shape, which encloses a region of large secretory vesicles. This polarization is often referred to as the cis-trans axis of the Golgi complex. The forming face (cis) is characterized by the presence of small transition vesicles or tubules that converge upon the Golgi cisternae, forming a kind of fenestrated plate. These transition vesicles form blebs from the ER and migrate to the Golgi where, by coalescence, they form new cisternae. New cisternae are formed at the proximal end by mechanism of membrane flow and thus compensate for the loss of released secretory vesicles at the maturing face. Associated with the maturing face there is saccular structure rich in acid phosphatase called as the GERL. GERL has been interpreted as region of smooth ER, near the Golgi involved in the production of lysosomes.

b. Tubules and Vesicles: From the peripheral area of cisternae arise a complex, anastomising flat network of tubules of 30 to 50 nm diameter. The vesicles are small droplet-like sacs which remain attached to tubules at the periphery of the cisternae and may show continuity with the cisternae. The small vesicles arise from the cisternae by budding or pinching off. These are 40 to 80 nm diameter vesicles which are of two types:

1. **Smooth vesicles or secretory vesicles:** The smooth vesicles are of 20 to 80 μm in diameter. They contain secretory material and are budded off from the ends of the cisternal tubules within the net.

2. **Coated vesicles:** The coated vesicles are spherical protuberances about 50 μm in diameter; having a rough surface. They are found at the periphery of the organelle, usually at the ends of single tubules.

c. **Large vacuoles:** The Golgi vacuoles are large, spacious, rounded sac-like
structures occurring at the distal ends of cisternae. They are produced by vesiculation of saccules of cisternae.

FUNCTIONS OF THE GOLGI COMPLEX: Golgi complex plays an important role in the storage, packaging and secretion of certain cell products. It is involved in the formation of lysosomes and other enzyme-containing cellular inclusions. It is also involved in the formation of secretory granules in cells such as those found in the pancreas, the pituitary and mammary glands and in the mucus secreting glands of the intestine and in many other cell types.

The Golgi complex is mainly concerned with formation and packaging of material for export from the cell through the plasma membrane by reverse pinocytosis. In this way, cell wall material is deposited in plants and secretory proteins, digestive enzymes and the matrix of the connective tissue are transported in animal tissues.

The Golgi complex represents a special membranous compartment interposed between ER and the extracellular space. Through this compartment there is continuous traffic of substances which have been synthesized elsewhere but are modified and transformed while transported. This process also involves the flow and differentiation of membranes. Within the membranes of the Golgi complex a vast diversity of materials may be found, varying from simple fluids to macromolecules. Every type of macromolecule is transported

through the Golgi and secreted and there is a continuous and fast turnover of the Golgi membranes.

Some of the most important functions of Golgi complex are described here:

1. Synthesis of Glycosphingolipids and Glycoproteins- Major function of the Golgi complex:

The Golgi complex plays a major role in the glycosidation of lipids and proteins to form glycosphingolipids and glycoproteins. The carbohydrate prosthetic groups of both these complex substances are added in a sequential manner in the Golgi complex by the action of the various glycosyl transferases. The enzymes are responsible for transferring a sugar residue either to an amino acid residue of a protein or to another carbohydrate in a glycoprotein or glycolipid.

From studies using radioactive precursors (eg: galactose, fucose and sialic acid), the following biosynthetic scheme has emerged for the types of secreted glycoproteins. The protein backbone of the glycoprotein is synthesized by ribosomes and then the monosaccharides are added one by one as the protein moves through the channels of the ER and Golgi complex. In this process the glycosyl tranferases that are bound to the Golgi membranes play an important role. The enzymes adding the oligosaccharide core containing N-acetylglucosamine and mannose are in part assembled in the rough ER. The fucosyl-and the dialyl-galactosyl-N-acetyl-glucosamine termini of the prosthetic group are incorporated in the Golgi complex by the corresponding transferases.

There are three main patterns of incorporation of various precursors into glycoproteins. When D-mannose is used as precursor, the rough ER is the first to be marked and then the other components. When sialic acid, L-fucose or D-galactose is

used, the Golgi complex is the first to be labelled. With D-glucosamine both the rough ER and Golgi complex are simultaneously labelled.

Radioautography revealed that H^3-fucose does not enter into mucopolysaccharides and fucose is present in glycoproteins only in the terminal group. In intestinal cells, two minutes after the injection of H^3-fucose the labelling is almost exclusively in the Golgi complex. Then there is migration of the glycoproteins to the sides of the cell and into the apical cell membranes, where it is concentrated four hours after injection. The intracellular migration of the glycoproteins is carried out by small vesicles formed in the Golgi complex.

In liver cells, H^3-fucose is first incorporated into the Golgi and later on is found in lysosomes, in the blood plasma and on the cell membranes. The polypeptide backbone of the glycoprotein is synthesized on the ribosomes and side chains of mannose and N-acetylglucosamine are added in ER, whereas the terminal side chains of galactose, fucose and sialic acid are added in the Golgi complex.

The substrates for glycosyl and sulphate transferases are not the sugar moieties or the sulphate. The true donor molecules are sugar nucleotides, rich in energy, such as guanosine-5' diphosphate fucose or mannose, uridine-5' diphosphate glucose, galactose or N-acetyl glucosamine. The adenosine 3' phosphate 5' phosphosulphate is the donor of the sulphate moiety. All these compounds are synthesized in the cytosol and traverse the membrane to become substrates of the enzymes, which have their active centers at the luminal side of the Golgi vesicle.

2. **Secretion- The main function of the Golgi complex:** ER and the Golgi complex are more directly involved in the synthesis, transport and release of macromolecules from

the cell. Cell secretion is not confined to animal cells, plant cells also secrete polysaccharides and proteins to build their cell walls. The enzymes of lysosomes and peroxisomes of animal and plant cells are produced by a kind of secretory process. Cell secretory activity appears even in the prokaryotic cells, producing the cell wall and secrete a variety of enzymes to the medium.

Secretion may be continuous, the secretion products being discharged without storage, that is glycoproteins by the liver cells, antibodies by the plasma cells. In these cells, the secretion produced is not accumulated into special storage granules and the release of secretory materials is more or less simultaneous with the synthesis and intracellular transport of these substances. Secretion may be discontinuous with storage in secretory or zymogen granules, for example in the pancreas, parotid glands and others. In these cells secretory cycle is specially timed so that the synthesis and intracellular transport are followed by the accumulation of the secretion products in special storage granules which are finally released to the extracellular space. These products may be dense and refractile granules, vacuoles, droplets or other substances having a definite location in the cell and have characteristic histochemical reactions. The dense secretory granules containing enzymes, generally in an inactive form (proenzyme) are called the zymogen granules.

3. Endocytosis and Recycling of Membranes of Secretory Granules: A pancreatic cell in which protein synthesis has been inhibited can go through an entire secretory cycle of transport, concentration, storage and release. This suggests that within the period of time of one cycle (i.e., 60 to 90 minutes), the synthesis of new membrane proteins is not required.

The intracellular membranes have a much longer half-life and are reutilized extensively during the secretory process. The

membrane of the zymogen granules may be regarded as a vacuole that shuttles between the Golgi complex and the cell surface. In the removal of excess membrane from the apical region of the cell, it has been suggested that patches of membranes are invaginated from the surface as small vesicles that move back into the Golgi region, to be re-utilized in the packing of more secretion. Thus, the process of exocytosis is coupled with that of endocytosis. The specificity of this recycling process depends on the formation of coated pits and vesicles, which separate the membrane patches from the plasma membrane by mechanism of selective endocytosis.

The morphological and histochemical evidences indicate a possible heterogeneity of function within the Golgi complex. For example, galactose residues, labelled by a specific lectin complexed to gold particles are localized in the trans region of the Golgi complex, while the cis region is unlabelled. In the same cells thymine pyrophosphatase is localized in similar stacks of Golgi membranes. The co-distribution of these two enzymes suggests the existence of functional compartmentalization in the Golgi complex and favours a model of glycosidation in which two enzymes act in concert. Using monoclonal antibodies and electron microscopy, it has been found that N-acetyl glucosamine transferase I occurs in medial cisternae of the Golgi. Additional evidence indicates that the compartmentalization of the Golgi complex is provided by the presence of a gradient of cholesterol from the cis to the trans stacks.

The Golgi complex have atleast three distinct sets of cisternae, besides the GERL region. If each cisternae has a specific function then the traffic between the cis and trans side would be affected by vesicular carriers that operated from the dilated rims of the cisternae. The Golgi membrane proteins and specific enzymes are in fixed positions within the Golgi complex, but those proteins that enter the cisternae may diffuse throughout the entire

complex by this carrier mechanism. The proteins transported by small vesicles from the ER are received at the cisternae and they exit from the trans cisternae at the opposite end of the stack.

4. **Lipid Packaging and Secretion:** The electron microscopic and autoradiographic studies of Stein and Stein revealed the role of the Golgi complex in lipid secretion. Fatty acids and monoglycerides are used in the synthesis of lipids. The epithelial cells (of intestine) secrete chylomicrons which contain lipids in the form of lipo-proteins. Labelled palmitate and glycerol were injected into fasted and ethanol treated rats. First the labelled material (triglycerides) was seen in ER, then in storage lipid droplets and finally in the Golgi complex (about after 10 minutes). The ER is involved in triglyceride synthesis. The vesicles derived from the Golgi complex is involved in adding the carbohydrate components of chylomicrons. The overall role of the Golgi complex in lipid metabolism is the concentration and modification of secretory material. These changes convert the lipid droplets into chylomicrons. The Golgi complex also provides a membrane for covering of lipid to be released from the cell.

5. **Insulin Biosynthesis:** The role of Golgi complex in insulin biosynthesis has provided an excellent example of the molecular processing of secretion. The many secreted proteins are first synthesized as biologically inactive precursors which are activated later. Activation consists of removal of a portion of the polypeptide chain and occur at different sites. The zymogens secreted by the pancreas are activated extracellularly, i.e., after the release of the secretion. Various polypeptide hormones are produced as inactive prohormones which are then activated intracellularly by the converting enzymes (proteolytic) present in the Golgi complex. Examples of proproteins are: proalbumin, proparathyroid hormone, proglucagon, progastin and proinsulin. The insulin produced by the beta cells of the pancreatic island has a molecular weight of 12000 and two chains, the A chain of 21

amino acids and the B chain of 30 amino acids. The chains are linked by two S-S bonds.

The insulin mRNA with its B and A regions (cistrons) code for the B and A chains. In addition, the mRNA contains a pre-region which codes for the signal peptide, a C segment and a poly A tail. This mRNA contains information coding for a polypeptide chain of 330 amino acids. The complete translation of this mRNA on free ribosomes gives rise to pre-proinsulin. In the ER, the pre-region (i.e., a signal peptide 23 amino acids long) is removed by the signal peptidase. The completed proinsulin chain is then activated in the Golgi through the removal of the C peptide by the converting enzyme and is packaged as active hormone within the secretion granule.

6. **The GERL Region and Lysosome Formation:** Golgi membranes are involved in the formation of the primary lysosomes. This process has the sequence, i.e., synthesis, aggregation, transport and packaging of the enzymes. The ribosomes synthesize lysosomal hydrolases. These hydrolytic enzymes then enter the ER. The ER forms small vesicles of these hydrolases by blebbing, the vesicles are transferred to the Golgi complex. The cisternae of the Golgi complex in turn form vesicles. The primary lysosomes fuse with pinocytic vesicles or with autophagic vesicles and form secondary lysosomes. De Duve suggested that the Golgi vesicles transfer acid hydrolases to food vacuoles, converting them into digestive vacuoles. Lysosomes can also be formed from the ER without the Golgi complex, as in liver cells and in neurons.

Because of the close functional relationships between the Golgi complex, ER and lysosomes, Novikoff has denoted it as the GERL system. In the maturing face of the Golgi is th GERL region, in which acid phosphatase, a characteristic lysosomal enzyme is present. This region has been implicated in the formation of

primary lysosomes. There is some kind of traffic control which exists in the Golgi complex to direct the various products to their final destination, i.e., to the zymogen granules or the lysosomes.

Novikoff suggested that the GERL of the Golgi complex is also involved in the formation of melanin granules, in the processing and packaging of secretory material in endocrine and exocrine cells and in lipid metabolism. GERL (also known as the trans-reticular Golgi) is the site of the cell involved in the sorting out of the proteins.

7. **Acrosome Formation:** There is a close association between the Golgi complex and acrosome formation. The acrosome of a spermatozoon is derived from the Golgi complex of a spermatid. The Golgi complex of an early spermatid consists of a series of membranes arranged concentrically around an aggregation of small vacuoles. During acrosome formation, one or more vacuoles start enlarging and inside the vacuole appear a small dense body, the proacrosomal granule. The contents of vacuole and granule give a positive staining reaction for mucopolysaccharides. The vacuole enlarges in its volume by fusing with other small vacuoles containing proacrosomal granule and become closely applied to the forwarding tip of the elongating nucleus. The granule increases further and becomes the acrosomal granule which forms the core of the acrosome. The vacuole loses its liquid contents and its wall spreads out over the acrosomal granule. Front half of the nucleus, covered with a double membranous sheath (i.e., plasma membrane + membrane of acrosomal vesicle) forms the cap of spermatozoon. The remaining parts of Golgi complex are gradually reduced and ultimately discarded from sperm as 'Golgi rest' together with some cytoplasm.

8. **Plasma Membrane Formation:** It has been shown that secretory granules originating from the Golgi complex fuse with

the plasma membrane during exocytosis. The membrane of the granules become incorporated into the plasma membrane and thus contributes to the renewal of the membrane constituents. The Golgi complex is involved in the synthesis of the carbohydrate components of the plasma membrane. The tritiated sugars first localized at the Golgi complex migrates to the cell surface and in the cell coat. Secretory glycoproteins are released into the extracellular space after fusion of the secretory vesicle membrane with the plasma membrane. The Golgi complex plays an important part in the biogenesis of the plasma membrane by supplying it with glycosidated molecules.

9. **Plant Cell Wall Formation:** Plant cell walls are made up of fibrils which predominantly contain polysaccharides, some lipids and proteins. The polysaccharides are formed in the Golgi complex and transferred to the new cell wall which is being formed. The Golgi complex also contributes the substances, pectins and hemicelluloses which form the matrix of the cell plate.

10. **Neurosecretion:** A study of neurosecretory cells of Invertebrates and Vertebrates has revealed that neurosecretory granules lie close to the Golgi complex. The neurosecretory material is synthesized in the ribosomes and is then transferred to the Golgi complex, where it undergoes packaging to form neurosecretory granules.

11. **Pigment Formation:** The GERL of the Golgi complex is also involved in the formation of melanin granules. In many mammalian and cancer cells, the Golgi complex is involved in origin of pigment granules (melanin). The Golgi complex has also been associated with pigment formation in retinal pigment epithelium of chick embryos, in the test cells of the ovaries of certain tunicates and in the oocytes of the Salamander.

12. **Formation of Yolk Substances and Cortical Granules of Oocytes:** During oogenesis, the Golgi complex is involved in the formation of yolk. In the young ovum, it breaks down into pieces and arrange themselves to form Balbianic Vitelline rings or yolk nucleus. Soon this arrangement is lost and the yolk particles appear in the cytoplasm.

SUMMARY: Golgi apparatus appear to resemble a small stack of flattened sacs. It assembles the protein products made by ribosomes into the usable proteins and these finalized proteins are then packed into special sacs and are sent out to their final destination. Thus Golgi bodies are frequently described as "assembly lines" or "shipping and receiving" facilities.