Origin of Prokaryotic and Eukaryotic Cells

Academic Script: -

1. Introduction

Cells are divided into two main classes, initially defined by whether they contain a nucleus. Prokaryotic cells lack a nuclear envelope; eukaryotic cells have a nucleus in which the genetic material is separated from the cytoplasm. Prokaryotic cells are generally smaller and simpler than eukaryotic cells; in addition to the absence of a nucleus, their genomes are less complex and they do not contain cytoplasmic organelles or a cytoskeleton .The difference between prokaryotic and eukaryotic cells are as, in spite of these differences, the same basic molecular mechanisms govern the lives of both prokaryotes and eukaryotes, indicating that all present-day cells are descended from a single primordial ancestor. How did this first cell develop? and how did the complexity and diversity exhibited by present-day cells evolve?

2. The Origin of Cellular Life

Research on the origin(s) of life is central to biological research. An accurate understanding of the origin(s) of life is necessary if we are to understand our past, present and future in a meaningful manner. We need to know if life originated by several possible mechanisms on Earth during a narrow period of time, if life was transported to Earth or if a combination of events allowed for the rapid evolution and diversification of life on Earth. It is known from the fossil records that life existed as microbial communities on Earth at least 3.5 billion years ago.

There are several theories about the origin of small molecules that could lead to life in an early Earth. One is that they came from meteorites. Another is that they were created at deep-sea vents. A third is that they were synthesized by lightning in a reducing atmosphere (*Miller–Urey experiment*); although it is not clear if Earth had such an atmosphere. There are essentially no experimental data defining what the first self-replicating forms were. RNA is generally assumed the earliest self-replicating molecule, as it is capable of both storing genetic information and catalyzing chemical reactions. But some other entity with the potential to self-replicate could have preceded RNA, like clay or peptide nucleic acid.

When life arose on Earth, the first type of cells to evolve were prokaryotic cells. For approximately 2 billion years, prokaryotic cells were the only form of life on Earth. The oldest known sedimentary rocks found in Greenland are about 3.8 billion years old. The oldest known fossils are prokaryotic cells, 3.5 billion years in age, found in Western Australia and South Africa. The nature of these fossils, and the chemical composition of the rocks in which they are found, indicates that these first cells made use of simple chemical reactions to produce energy for their metabolism and growth.

The current belief is that these cells were heterotrophs. An important characteristic of cells is the cell membrane, composed of a bilayer of lipids. The early cell membranes were probably more simple and permeable than modern ones, with only a single fatty acid chain per lipid. Lipids are known to spontaneously form bi-layered vesicles in water, and could have preceded RNA, but the first cell membranes could also have been produced by catalytic RNA, or even have required structural proteins before they could form.

Possible Origin of Membranes

1. ***Lipid molecules*** spontaneously form membrane vesicles.
2. ***Protobionts*** are aggregates of a biotically produced organic molecules surrounded by a membrane-like structures. The protobionts exhibits properties of life such as simple reproduction, metabolism, and homeostasis.
3. ***Microspheres*** are droplets of thermal protein surrounded by a lipid membrane.
4. ***Liposomes*** *are* Phospholipid molecules in turbulent water, self-assemble into a lipid bilayer forming membrane-bound droplets capable of growth and division.

5. ***Coacervates*** are polypeptides, nucleic acids and polysaccharides combine into a structure with osmotic potential i.e they are simple droplets of liquid and enzymes surrounded by the lipid membrane.

3. Possible Origin of Prokaryotic Cells

- Random collections of organic molecules do not qualify as living material.
- Life organized as cells requires both organization and stability over time cellular structure allows for compartmentalization.
- Protobionts such as liposomes form compartments, which in turn might contain molecules such as RNA capable of reactions, catalysis and replication.
- Selection would favour the most successful protobionts in terms of stability/survivorship and replication/progeny.
- Genetic material, probably RNA, would be needed as information for control, which could be copied to progeny.

RNA World Hypothesis

RNA World describes the hypothetical time of the earliest life-forms when genes were simply strands of RNA. A critical step in understanding molecular evolution was thus reached in the early 1980s, when it was discovered in the laboratories of Sid Altman and Tom Cech that RNA is capable of catalyzing a number of chemical reactions, including the polymerization of nucleotides. RNA is thus uniquely able both to serve as a template for and to catalyze its own replication. Consequently, RNA is generally believed to have been the initial genetic system, and an early stage of chemical evolution is thought to have been based on self-replicating RNA molecules - a period of evolution known as the RNA world. Ordered interactions between RNA and amino acids then evolved into the present-day genetic code, and DNA eventually replaced RNA as the genetic material. (Self-replication of RNA, complementary pairing between nucleotides, adenine [A] with uracil [U] and guanine [G] with cytosine [C]) allows one strand of RNA to serve as a template for the synthesis of a new strand with the complementary sequence).

The first cell is presumed to have arisen by the enclosure of self-replicating RNA in a membrane composed of phospholipids (Enclosure of self-replicating RNA in a phospholipids membrane. The first cell is thought to have arisen by the enclosure of self-replicating RNA and associated molecules in a membrane composed of phospholipids). Phospholipids are the basic components of all present-day biological membranes, including the plasma membranes of both prokaryotic and eukaryotic cells.

The enclosure of self-replicating RNA and associated molecules in a phospholipids membrane would thus have maintained them as a unit, capable of self-reproduction and further evolution. RNA-directed protein synthesis may already have evolved by this time, in which case the first cell would have consisted of self-replicating RNA and its encoded proteins.

The primitive earth atmospheric gases, such as Ammonia (NH_3), Hydrogen (H_2) and Hydrogen Sulfide (H_2S) could be oxidized to produce energy that allowed conversion of CO_2 to cellular organic material. As organic material developed, it became the substrate to support the growth and metabolism of other cells that use simple organic compounds as their source of energy. An important group of archaea that were involved in this process were the Methanogens, which grow by using H_2 as an energy source and CO_2 as a carbon source, resulting in the production of the simplest of all organic molecules, methane (CH_4). Archaea and bacteria probably arose from a universal ancestor but are thought have split early during the evolution of cellular life into the two groups of prokaryotes that we recognize today.

Photosynthesis - metabolism, which uses of light as an energy source developed in bacteria about 3.2 billion years ago. The first type of photosynthesis to appear is called anoxygenic photosynthesis because it does not produce O_2. Anoxygenic photosynthesis preceded oxygenic photosynthesis i.e. plant-type photosynthesis, which produces atmospheric O_2. However, oxygenic photosynthesis also arose in prokaryotes, specifically in a group of bacteria called cyanobacteria, and existed for millions of years before the evolution of plants.

As molecular oxygen (O_2) began to appear in the atmosphere, organisms that could use O_2 for respiration began their evolution, and "aerobic" respiration became a prevalent form of metabolism among bacteria and some archaea.

Prokaryotes are thus assumed to be the life source that first performed photosynthesis, which then contaminated the atmosphere with oxygen, which selected against anaerobic metabolic pathways and caused one of the greatest mass extinctions.

4. Origin of Eukaryotic Cells

Cells from eukaryotic organisms (e.g. Animals, Plants, Fungi) differ from those of the prokaryotes (*Bacteria* and *Archaea*) in a large number of characteristics. These differences are so vast that the evolution of the eukaryotic cell from prokaryotic ancestors is widely regarded as a major evolutionary discontinuity. Although there are no clear intermediates in this transition, the available evidence strongly indicates that eukaryotic cells have evolved much later (only about 1-1.5 billion years ago) in comparison to the prokaryotic organisms, which existed as far back as 3.5-3.8 billion years ago. The question thus arises how the transition did from prokaryotic to eukaryotic cell come about and who are the progenitors of the ancestral eukaryotic cell?

Fossil records indicate that eukaryotes evolved from prokaryotes somewhere between 1.5 to 2 billion years ago. Two proposed theories describe the invasion of prokaryote cells by two smaller prokaryote cells. They subsequently became part of a now much larger cell with additional structures and capable of additional functions.

Theories on the Origin of Eukaryotic Organelles

Endosymbiotic Theory

Endosymbiosis is the name given to processes wherein one cell lives inside of another cell in a mutualistic fashion.

This is the most popular scientific theory was first attributed to Lynn Margulis, though related concepts by others (i.e. Mereschkowsky) have been around for years.

It is theorized that a larger anaerobic prokaryotic cell “swallowed” a smaller aerobic one, and the aerobic prokaryote became an organelle a mitochondrion of the larger.

In fact, possibly all eukaryotes membranous structures may have arisen from prokaryotes cells through independent processes of endosymbiosis.

A critical step in the evolution of eukaryotic cells was the acquisition of membrane-enclosed sub cellular organelles, allowing the development of the complexity characteristic of these cells. The organelles are thought to have been acquired as a result of the association of prokaryotic cells with the ancestor of eukaryotes.

The hypothesis that eukaryotic cells evolved from a symbiotic association of prokaryotes i.e. endosymbiosis - is particularly well supported by studies of mitochondria and chloroplasts, which are thought to have evolved from bacteria living in large cells.

About 1.5 -2 billion years ago, oxygenic photosynthesis and aerobic respiration were predominant types of metabolism in the bacteria. Cyanobacteria produced all of the earth's atmospheric O_2, and respiratory bacteria had developed sophisticated membrane systems allowing them to reduce O_2 and generate relatively large amounts of energy. If these prokaryotes invaded or were captured by primitive eukaryotes cells, which had only sluggish modes of chemoheterotrophic metabolism, they could provide new ways to produce energy from light or during aerobic respiration. In return, the eukaryotic cell could provide nutrients and a protected habitat for its invader or prey. Hence, the two organisms were able to enter into a mutually beneficial and stable relationship, and thus, microbiologists believe that the origin of eukaryotes chloroplasts (organelles for photosynthesis) and mitochondria (organelles for aerobic respiration) are in cyanobacteria and respiratory bacteria that entered into a partnership with eukaryotes cells in the evolutionary past.

Hence an endosymbiotic origin for these organelles is now generally accepted, with mitochondria thought to have evolved from aerobic bacteria and chloroplasts from photosynthetic bacteria, such as the cyanobacteria. The acquisition of aerobic bacteria would have provided an anaerobic cell with the ability to carry out oxidative metabolism. The acquisition of photosynthetic bacteria would have provided the nutritional independence afforded by the ability to perform photosynthesis. Thus, these endosymbiotic associations were highly advantageous to their partners and were selected for in the course of evolution. Through time, most of the genes originally present in these bacteria apparently became incorporated into the nuclear genome of the cell, so only a few components of mitochondria and chloroplasts are still encoded by the organelle genomes.

Eukaryotic cells appear to have arisen from prokaryotic cells, specifically out of the Archaea. Indeed, there are many similarities in molecular biology of contemporary archaea and eukaryotes. However, the origin of the eukaryotes organelles, specifically chloroplasts and mitochondria, is explained by evolutionary associations between primitive nucleated cells and certain respiratory and photosynthetic bacteria, which led to the development of these organelles and the associated explosion of eukaryotic diversity.

Studies of their DNA sequences indicate that the archaebacteria and eubacteria are as different from each other as either is from present-day eukaryotes. Therefore, a very early event in evolution appears to have been the divergence of three lines of descended from a common ancestor, giving rise to present-day archaebacteria, eubacteria, and eukaryotes. Interestingly, many archaebacterial genes are more similar to those of eukaryotes than to those of eubacteria, indicating that the archaebacteria and eukaryotes share a common line of evolutionary descent and are more closely related to each other than either is to the eubacteria. Present-day cells evolved from a common prokaryotic ancestor along three lines of descent, giving rise to archaebacteria, eubacteria, and eukaryotes.

Evidence for endosymbiotic origin of eukaryotic cells

- If mitochondria and chloroplasts are evolutionary remnants of bacteria, there ought to be some similarities between contemporary eukaryotes organelles and the bacteria from which they arose, and indeed, there are Mitochondria & chloroplasts both have double membrane.It is known that in modern-day eukaryotes, the inner membrane of both the mitochondria and chloroplast contain structures more similar to prokaryotes than eukaryotes, whereas the outer membrane retains eukaryote characteristics!

- Mitochondria & chloroplasts both have a loop of naked DNA lacking histone proteins, as do prokaryotes

- Mitochondria & chloroplasts both divide by binary fission independent of nuclear division.
- Mitochondria & chloroplasts both have smaller 70S ribosomes similar to prokaryotes, & different from 80S eukaryotic ribosomes.

- The protein synthesis of these organelles is semi-independent of that occurring in the cytoplasm and it is inhibited by the same antibiotic that works on prokaryotes.
- Chloroplast thylakoids are similar to cyanobacterial photosynthetic structures.
- Chlorophyll a is the main photosynthetic pigment for both chloroplasts and prokaryotes.
- Mitochondrial cristae are similar to bacterial mesosomes.
- Mitochondria and chloroplasts divide by fission, not mitosis.

- Chloroplasts have the same type of chlorophyll, enzymes, and metabolism as cyanobacteria, and mitochondria have the same type of metabolism as respiratory bacteria such as*Pseudomonas*. and other "proteobacteria". Interestingly, on the basis of RNA analysis, the closest relatives of mitochondria are the rickettsia bacteria, which are modern-day intracellular parasites of Eukaryotic cells!

Autogenous Theory

It is also known as membrane infolding theory. Eukaryotes arose directly from a single prokaryote ancestor by compartmentalization of functions brought about by infoldings of the prokaryotic plasma membrane.

This model is usually accepted for the endoplasmic reticulum, Golgi, and the nuclear membrane, and of organelles enclosed by a single membrane (such as lysosomes).

According to the autogenous hypothesis, mitochondria and chloroplasts have evolved within the protoeukaryote cell by compartmentalizing plasmids or vesicles of DNA within a pinched off invagination of the cell membrane.

It is also suggested that continued membrane infolding created the endomembrane system. It can be said that possibly the first eukaryotic cell type was miraculously born from prokaryotic, symbiotic, multicell interactions!

5. Other Theories for Eukaryotic Cell origin

1 **Serial endosymbiosis theory or exogenous, or xenogenous hypothesis**. Within the idea of endosybiosis, there are different theories as to the exact type and sequence of evolution, proposed by: Mereschkowsky and Sagan et.al.

The elements of this theory are as follows:

- Mitochondria of eukaryotes evolved from aerobic bacteria living within their host cell.
- The chloroplasts of eukaryotes evolved from endosymbiotic cyanobacteria (autotrophic prokaryotes).
- Eukaryotic cilia and flagella may have arisen from endosymbiotic spirochetes. The basal bodies from which eukaryotic cilia and flagella develop would have been able to create the mitotic spindle and thus made mitosis possible.

2 ***Thermoreduction model***: Eukaryotes came first, and prokaryotes evolved (reductive evolution) from them; focuses more on gene and genome organization.

3 ***Ox-tox model***: the ancestor of mitochondria was an aerobic proteobacterium; the host was an anaerobic, primitively amitochondriate eukaryote; addresses the origin of mitochondria, not the complete eukaryote cell

4 ***Panspermia* (or Cosmozoan):** cells came from somewhere else (outer space) and seeded Earth.

5 ***Biblical* (or Scientific Creationism)**: both types of cells came from a Creator

Amongst all the theories of origin of eukaryotic cell, the endosymbiotic theory is widely accepted.

Summary

Today prokaryotes are found everywhere on Earth and greatly outnumber all eukaryotes combined. Prokaryotes contribute as decomposers and recyclers to such an extent that without them, eukaryotes would die off. However, prokaryotes could survive without eukaryotes as they have already demonstrated for about 2 billion years ago.