Few processes are as vital for life as respiration.
Acquisition of oxygen from the atmosphere is the primary purpose of respiration.
Oxygen is the most important molecule contracted from the external environment.
It is an important factor for aerobic metabolism and a necessary resource for growth and development.
Animals will generally live for weeks without food, days without water, but only minutes without oxygen.
Almost four billion years ago, living beings that inhabited the earth were very primitive microorganisms, perhaps methanogenic bacteria, living in absolute anaerobiosis. These organisms still exist in our days and are included in the Archae domain, and for this reason are central to the paleoenvironment and paleobiology studies.
ANEROBIC TO AEROBIC TRANSFORMATION

- Oxygen has been incorporated in aerobic metabolism some 2 billion years ago, since than no other molecule has been as consequential in shaping life and as paradoxical in its operation as oxygen.

- However, the respiratory system has been evolved from the cell membrane of unicellular organism and Despite the striking morphological diversification of the respiratory organs, oxygen is still transported through simple diffusion processes.

- The alternate method of acquisition of oxygen would have been by an active process. This strategy seems to have been rejected very early in the evolution of life, if it was ever attempted.

- Transfer of oxygen in organs and tissues such as the lung, liver, placenta, and muscle may be facilitated: hemoglobin, myoglobin, and a specific carrier (cytochrome P450) have been implicated.
AEROBIC TO AEROBIC TRANSFORMATION

- Life started in an anaerobic environment in the so-called ‘primordial broth’ (a mixture of organic molecules).
- Anaerobic fermentation, the metabolic process that prevailed for the first about 2 billion years of the evolution of life, was a very inefficient way of extracting energy from organic molecules.
- The rise of an oxygenic environment was a momentous event in the diversification of life that dramatically shifted from inefficient to sophisticated oxygen dependent oxidizing ecosystems.
- A molecule of glucose, e.g., produces only two molecules of ATP (‘15 kCal) compared with 36 ATP molecules (‘263 kCal) in oxygenic respiration.
There are two widely accepted views of aerobic metabolism:

- First, that it was only possible after oxygen release by photosynthesis became abundant.
- Second, that it developed independently in diverse evolutionary lines.

Molecular evidence shows that aerobic respiration evolved before oxygenic photosynthesis, or, in other words, cytochrome oxidase appeared before the water-splitting system.

Denitrification (NO reductase) is the probable origin of aerobic respiration.
AEROBIC TO AEROBIC TRANSFORMATION

- This new and more profitable method of extracting energy, aerobic respiration, should have led to a domain of aerobic organisms in the biological community, and probably even leading to the extinction of some anaerobic organisms.

- The respiratory systems from different groups of animals, although morphologically different, have in common two characteristics:
  - They have a large capillary network, with free movement of blood.
  - The gas exchange surfaces are thin and moist; with constant renewal of oxygen-rich fluid (air or water) in order to provide oxygen and remove carbon dioxide.
AEROBIC TO AEROBIC TRANSFORMATION

- Oxygen absorption from the environment can be carried out by:
  1. Cutaneous diffusion (earthworm and some amphibians).
  2. By thin tubes called tracheae (some insects).
  3. By gills, the respiratory system of fish.
  4. By diffusion through the lungs, respiratory organs present in amphibians, reptiles, birds and mammals.
Simple diffusion can not satisfy the oxygen demands of organisms much larger than 1mm.

Oxygen absorption affected by the shape of organism.

Giant land planarians (Terricola) may be 50cm long but they have flat elongated bodies result very large surface to mass ratio.

Colentrates and sponges often reach even larger size with modest metabolic demands and relatively short diffusion distance.
Cutaneous Respiration

- Cutaneous respiration can only be successful if the surfaces are well vascularized, moist, thin and readily permeable.
- This imposes a serious restriction in many habitat.
- Smaller organisms like earthworm, leeches obtain their oxygen supply through this mechanism.
- Even larger organisms like amphibians and fishes may rely on cutaneous respiration during emergencies or may utilize it as add to up lungs and gills.
- Cutaneous respiration is important in all amphibians.
GILLS

- Some of the external cutaneous folds have specialized for gaseous exchange.
- Become highly vascularized and folded.

- External Gills

- Internal Gills
**EXTERNAL GILLS**

- External gills are expansion of specific areas of highly vascular epithelia, to provide gaseous exchange.
- Found in many fish and amphibian larvae and neotenic forms (axolot).
- The ventilation occur by movement or by water currents.
- One of the disadvantages of external gills is that they must constantly be moved or the surrounding water becomes depleted in oxygen as the oxygen diffuses from the water to the blood of the gills. The highly branched gills, however, offer significant resistance to movement, making this form of respiration ineffective except in smaller animals.
- Another disadvantage is that external gills are easily damaged. The thin epithelium required for gas exchange is not consistent with a protective external layer of skin.
EXTERNAL GILLS

- Other types of aquatic animals evolved specialized branchial chambers, which provide a means of pumping water past stationary gills.
- Mollusks, have an internal mantle cavity that opens to the outside and contains the gills. Contraction of the muscular walls of the mantle cavity draws water in and then expels it.
- In crustaceans, the branchial chamber lies between the bulk of the body and the hard exoskeleton of the animal. This chamber contains gills and opens to the surface beneath a limb.
- Movement of the limb draws water through the branchial chamber, thus creating currents over the gills.
INTERNAL GILLS

- The gills of bony fishes are located between the buccal (mouth) cavity and the opercular cavities. The buccal cavity can be opened and closed by opening and closing the mouth, and the opercular cavity can be opened and closed by movements of the operculum, or gill cover.

- The two sets of cavities function as pumps that expand alternately to move water into the mouth, through the gills, and out of the fish through the open operculum.
INTERNAL GILLS
INTERNAL GILLS

- There are four **gill arches on each side of the fish head**.
- Each gill arch is composed of two rows of **gill filaments**.
- Each gill filament contains thin membranous plates, or **lamellae**, that project out into the flow of water
INTERNAL GILLS

- Water flows past the lamellae in one direction only. Within each lamella, blood flows in a direction that is opposite the direction of water movement. This arrangement is called **countercurrent flow**, and it acts to maximize the oxygenation of the blood by increasing the concentration gradient of oxygen along the pathway for diffusion,
INTERNAL GILLS

- Water & blood flow opposite directions.
- This maximizes the concentration gradient & speeds up diffusion.
- Equilibrium is never reached.
INTERNAL GILLS

Countercurrent exchange
Blood (85% O₂ saturation) → Water (100% O₂ saturation)
- 85%
- 80%
- 70%
- 60%
- 50%
- 40%
- 30%
- 20%
- 10%
- 0%

Blood (0% O₂ saturation)

Concurrent exchange
Blood (50% O₂ saturation) → Water (50% O₂ saturation)
- 50%
- 40%
- 30%
- 20%
- 10%
- 0%

Blood (0% O₂ saturation)

No further net diffusion
- 50%
- 60%
- 70%
- 80%
- 90%

Water (100% O₂ saturation)
INTERNAL GILLS

- The epithelial surface of a gill arch is structurally and functionally zoned.
- Filaments are covered by two distinct epithelial surfaces,
  - filament (primary) epithelia
  - lamellar (secondary) epithelia
- Gas exchange occurs through the secondary lamellae, and the non-respiratory functions of the gills take place in the primary epithelium.
INTERNAL GILLS

- The primary epithelium contains the chloride cells, which vary in morphology and number according to the milieu where the fish lives.
- Chloride cells are sites of active chloride secretion and high ionic permeability, performing an integral role in acid-base regulation.

1. primary lamella; 2. secondary lamella; 3. epithelial cell; 4. mucous cell; 5. pillar cell; 6. lacuna (capillary lumen); 7. erythrocyte within capillary lumen; 8. chloride cell; 9. rodlet cell; 10. undifferentiated basal cell.
INTERNAL GILLS

- The secondary epithelium that covers the free part of the secondary lamellae has an exclusive relationship with the arterioarterial vasculature, i.e., the pillar cells.
- In contrast to the primary epithelium, the secondary epithelium does not exhibit any obvious differences between freshwater and seawater fish.

1. primary lamella; 2. secondary lamella; 3. epithelial cell; 4. mucous cell; 5. pillar cell; 6. lacuna (capillary lumen); 7. erythrocyte within capillary lumen; 8. chloride cell; 9. rodlet cell; 10. undifferentiated basal cell.
Lungfish

- Air is richer source of oxygen (210ml/L) as compared with fresh water (5-10ml/L).
- The first air-breathing vertebrates were fishes.
- The fish-tetrapod transition was one of the greatest events in the vertebrate evolution.
- Tetrapods first appeared about 360 million years ago, but appear to have been primarily aquatic animals.
Lungfish

In our days the lungfish are represented by three genera,

- Australian lungfish, *Neoceratodus forsteri*.
- African lungfish (Protopterus)
- American lungfish (Lepidosiren)
Lungfish

- Air is richer in oxygen but Carbon dioxide and ammonia are readily removed in water.
- Lung fishes rely for elimination on skin.
- Keeping their skin moist with mucus like secretions.

- Terrestrial environment forced skin dryness and toughness.
- Lungs made moist.
- Breathing become active

- The advantages of tetrapod gill loss included
  - Head mobility
  - Development of hearing
  - Origin of different ventilatory and feeding mechanisms
Lungfish

- Australian lungfish, *Neoceratodus forsteri*
- considered the most primitive
- They have efficient gills and possess only a single lung
- breathe air for short periods and for this reason the lung is an accessory organ which is only used during periods of high activity in its natural habitat.
- cannot survive complete desiccation like African and South American lungfishes.

- African lungfish (Protopterus)
- possess two lungs
- obligate air breathers.
- Young *Protopterus* possess external gills, which are usually lost as the fish ages.
- can survive prolonged periods of desiccation by burrowing into the mud and creating a mucus cocoon.
### Actinistia

*Actinista, coelacanths*, is a subclass of mostly fossil lobe-finned fishes. This subclass contains the coelacanths, including the two living coelacanths, the West Indian Ocean coelacanth and the Indonesian Coelacanth.

![West Indian Ocean coelacanth](image)

### Dipnoi

*Dipnoi, lungfish, also known as salamanderfish,*[15] is a subclass of freshwater fish. Lungfish are best known for retaining characteristics primitive within the bony fishes, including the ability to breathe air, and structures primitive within the lobe-finned fishes, including the presence of lobed fins with a well-developed internal skeleton. Today, lungfish live only in Africa, South America and Australia. While vicariance would suggest this represents an ancient distribution limited to the Mesozoic supercontinent Gondwana, the fossil record suggests advanced lungfish had a widespread freshwater distribution and the current distribution of modern lungfish species reflects extinction of many lineages following the breakup of Pangaea, Gondwana and Laurasia.

![Queensland lungfish](image)

### Tetrapodomorpha

*Tetrapodomorpha, tetrapods and their extinct relatives, is a clade of vertebrates, consisting of tetrapods (four-limbed vertebrates) and their closest sarcopterygian relatives that are more closely related to living tetrapods than to living lungfish. Advanced forms transitional between fish and the early labyrinthodonts, like *Tiktaalik*, have been referred to as “fishapods” by their discoverers, being half-fish half-tetrapods, in appearance and limb morphology. Tetrapodomorpha contains the crown group tetrapods (the last common ancestor of living tetrapods and all of its descendants) and several groups of early stem tetrapods. Tetrapodomorpha contains several groups of related lobe-finned fishes, collectively known as the osteolepiforms. The Tetrapodomorpha minus the crown group Tetrapoda is the Stem Tetrapoda, a paraphyletic unit encompassing the fish to tetrapod transition. Among the characters defining tetrapodomorphs are modifications to the fins, notably a humerus with convex head articulating with the glenoid fossa (the socket of the shoulder joint). Tetrapodomorph fossils are known from the early Devonian onwards, and include *Osteolepis, Panderichthys, Kenichthys* and *Tungisia.*[16]

![Advanced tetrapodomorph Tiktaalik](image)
**AMPHIBIANS**

- Having simplest lungs, that are adequate for ectothermic and low aerobic metabolism animals.
- The paired lungs are unicameral.
- In various amphibian species the lungs differ greatly in size, their extension and the dimension of exchange surface by the development of interconnected folds with highly varying number of subdivisions and height of their folds.
- Due to the absence of an individualized chest well, with no ribs or diaphragm, the amphibian’s pulmonary ventilation is mainly accomplished at the expense of swallowing air, carried out by rising of the oral cavity floor.
- Skin still used for respiration.
- Aquatic larvae having gills.
Reptilians & Mammals

- Reptilians are the first vertebrates adequately adapted for terrestrial habitation and utilization of lungs as a sole pathway for acquisition of oxygen.

- The skin that was no longer necessary for gas exchange, became an armor to protect against dehydration, being waterproof, dry and keratinized.

- Lungs of both reptiles and mammals are multicameral (with few exceptions). Division of the lumen of the lung into a number of chambers, by septation, enlarges the exchange area.
**Reptilians & Mammals**

- Generally, the pattern of organization of the respiratory system of reptiles is identical to mammals, with the lungs coated externally by a serosa.
- The conducting portions are supported by complete cartilaginous rings, which continue through the extra and intrapulmonary bronchi.
- The epithelial cells lining the respiratory surface of reptilian lungs are differentiated into type I and type II cells (secreting the surfactant).
- Active inspiration, expiration passive (can be active).
BIRDS

- Birds’ respiratory system, the lung – air sac system, is the most complex and efficient gas exchanger that has evolved in air-breathing vertebrates.
The pair of lungs of the birds are relatively small, noncompliant, localized in the dorsal thorax region and with little moving during breathing, as air is driven unidirectionally though the lung, via the system of air sacs.
BIRDS

- Alveoli replaced by air capillaries providing greater exchange surface area.
- Very thing blood gas barrier.
Insects, being arthropods, have a relatively inefficient, open circulatory system with no vessels to carry oxygen to different parts of their body. Because of the inefficiency of the circulatory system, a centralized respiratory system, such as lungs, would not meet the respiratory demands of the insect's cells. Instead, insects have evolved a very simple **tracheal system** that relies on a network of small tubes that channel $O_2$ directly to the different parts of the body.
The tracheal system is composed of chitin-ring tubes called tracheae that connect directly to the air through openings in the body wall called spiracles. The tracheae are reinforced with rings of chitin, the same material that makes up the arthropod exoskeleton.
The tracheae branch into smaller and smaller tubes, called **tracheoles**, that eventually terminate on the plasma membrane of every cell in the insect's body. The tips of the tracheoles are closed and contain fluid. Air enters the tracheae through the spiracles and travels through the tracheoles to the fluid-filled tips, where oxygen diffuses directly from the tracheoles into the cells, and CO$_2$ diffuses from the cells into the tracheoles.
RESPIRATORY PIGMENTS

- The simplest way to carry gases in the blood is by dissolution.
- The quantities of gas that can be moved around in this manner will be limited by the solubility coefficients of the gas.
- The blood of a marine animal, having roughly the ionic composition of sea water, will hold about 5.5 ml l⁻¹ of oxygen at 20°C when exposed to normal air. Under the same conditions this blood will hold 159 ml l⁻¹ of carbon dioxide, a gas with much greater solubility.
- Oxygen limitation will therefore become a serious problem for larger animals with a high metabolic rate, especially where raised body temperature further compromises the blood plasma’s ability to hold oxygen.
- Therefore in nearly all of the more complex animals there are special components of the blood that enhance its oxygen carrying capacity the **blood pigments, or respiratory pigments.**
**Respiratory Pigments**

- These are metalloproteins, containing metallic ions bound to one or more polypeptide groups.
- The partial changes in valency of metal component confers varying color on the pigment as a whole.

<table>
<thead>
<tr>
<th>Pigment</th>
<th>Structure</th>
<th>Color (+ change)</th>
<th>Oxygen capacity (ml g⁻¹)</th>
<th>Molecular weight (kDa)</th>
<th>Cells or solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hemocyanin</td>
<td>Protein + Cu²⁺</td>
<td>Blue (colorless)</td>
<td>0.3–0.5</td>
<td>25–7000</td>
<td>Solution</td>
</tr>
<tr>
<td>Hemoglobin</td>
<td>Protein + heme + Fe²⁺</td>
<td>Red (purple/blue)</td>
<td>1.2–1.4</td>
<td>16–2000</td>
<td>Either</td>
</tr>
<tr>
<td>Chlorocruorin</td>
<td>Protein + heme + Fe²⁺</td>
<td>Green</td>
<td>0.6–0.9</td>
<td>3000</td>
<td>Solution</td>
</tr>
<tr>
<td>Hemerythrin</td>
<td>Protein + Fe²⁺</td>
<td>Violet (colorless)</td>
<td>1.6–1.8</td>
<td>16–125</td>
<td>Either</td>
</tr>
</tbody>
</table>
**Respiratory Pigments**

**Hemoglobin**

- This is most familiar, the most widespread and most efficient of the respiratory pigments.
- Found in human, most of the major animal phyla, some protozoans and even in some plants.

- They all have iron as their metallic component, in its ferrous state (Fe2+), and bound in the center of a porphyrin ring, forming a functional heme group.
- Heme, associated with a protein globin.
- Prophyrin composed of four pyrrol rings.
**Respiratory Pigments**

**Hemoglobin**

- Heme compound is a constant structural feature of all Hbs.
- But the globin portion varies in different species.
- Variety of globin may occur in the same specie, in different tissue, developmental stage or environmental conditions.

<table>
<thead>
<tr>
<th>Hb</th>
<th>No. of unit</th>
<th>Mol.wt</th>
<th>Muscles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Myoglobin</td>
<td>1</td>
<td>17000</td>
<td>Muscles</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Hb type</th>
<th>No. of units</th>
<th>Mol. Wt.</th>
<th>Muscles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Myoglobin</td>
<td>1</td>
<td>17000</td>
<td>VertebrateMuscles</td>
</tr>
<tr>
<td>Oxyhemoglobin</td>
<td>1</td>
<td>17000</td>
<td>Cyclostomes blood</td>
</tr>
</tbody>
</table>
Figure 28-8  Hemoglobin switching during embryonic, fetal, and adult development. The \( \zeta \) and \( \epsilon \) genes are transcribed during embryonic development and are soon replaced by the fetal \( \gamma \)- and adult \( \alpha \)-globin gene. At birth, fetal hemoglobin forms about 75% and hemoglobin A forms 25% of the total. Transcription of the \( \gamma \) gene begins to fall before birth, and by 6 months of age, this gene is expressed only at very low levels. Expression of the \( \delta \)-globin gene begins near birth. In adults, hemoglobin A makes up about 97%, hemoglobin A2 about 2.5%, and fetal hemoglobin less than 1% of the total. (From Steinberg MH: Hemoglobinopathies and thalassemias. In Stein JH [ed]: Internal Medicine, 4th ed. St. Louis, Mosby-Year Book, 1994, p 852.)
**Respiratory Pigments**

**Hemerythrin**

- A less common type of respiratory pigment, occurring in three phyla only (sipunculids, priapulids, and brachiopods), as well as in one family of marine annelids.

- Having no iron-prophyrin ring.

- Monomeric unit consist of a polypeptide thrown into four interconnected helical with two Fe2+ binding sites.

- Two iron hold a single molecule of oxygen.

- Like low molecular weight Hbs occurs intracellularly and occur in various forms. Most common forms are trimeric or octomeric.
RESPIRATORY PIGMENTS

CHLOROCRURIN (CLOROHEMOGLOBIN)

- An extracellular green color pigment that confined to four families of polychaete worms.
- Biochemically similar to Hb, having chloroheme, prophyrin ring having a functional group substitution (formyl – vinyl) from prophyrin of Hb.
- It has high molecular wt. (about 3000000), sharing many of the Hb properties, with similar oxygen capacity.
- Resulted by a mutation in Hb gene which somehow survived.
Respiratory Pigments

Chlorocruorin (CloroHemoglobin)

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- Resulted by a mutation in Hb gene which some how survived.
**RESPIRATORY PIGMENTS**

**Hemocyanin**

- Hemocyanin is the respiratory pigments of many Molluscs and some arthropode.
- An extracellular, non heme (glycoprotein in arthropod), high molecular weight protein (3000000 – 13000000 in molluscs and 40000 – 1000000 in arthropods).
- Contains Cu2+ instead of iron.
- Two Cu2+ atom bind with a single oxygen atom.
- Some member of both phyla rely on Hb, while some of them have myoglobin in their muscles (Buccinum).
**BOHR EFFECT**

The oxyhemoglobin dissociation curve. Hemoglobin combines with O2 in the lungs, and this oxygenated blood is carried by arteries to the body cells. After oxygen is removed from the blood to support cell respiration, the blood entering the veins contains less oxygen. The difference in O2 content between arteries and veins during rest and exercise shows how much O2 was unloaded to the tissues.
The effect of pH and temperature on the oxyhemoglobin dissociation curve. Lower blood pH (a) and higher blood temperatures (b) shift the oxyhemoglobin dissociation curve to the right, facilitating oxygen unloading. This can be seen as a lowering of the oxyhemoglobin percent saturation from 60 to 40% in the example shown, indicating that the difference of 20% more oxygen is unloaded to the tissues.