Gas Exchange is critical to all organisms

- It is of vital importance that a source of clean, oxygen-rich air is available 24 hours a day.
- Like Robert gets when he sleeps at night.....
Avoid breathing contaminated air while you sleep.
• What, exactly, do you need oxygen for? And where, exactly does that carbon dioxide come from?
The source of oxygen, the respiratory medium, is air for terrestrial animals and water for aquatic animals.

- The atmosphere is about 21% O\textsubscript{2} (by volume).
- Much less for water.
- Even less as the water warms up, right?
• The part of an animal where gases are exchanged with the environment is the respiratory surface.

• Movements of CO\textsubscript{2} and O\textsubscript{2} across the respiratory surface occurs entirely by ???????.

• Diffusion is very slow.

• So respiratory surfaces tend to be thin.

• And how do you get lots of surface area?

• And to keep cells alive, they must be WET, and thus gases must first dissolve in water.

• THIN and WET is what ALL respiratory surfaces are.
• If you are an amoeba, how would you exchange gases? A jellyfish? Flatworm?

• However, most animals are just too thick.

• Their respiratory surface is a thin, moist epithelium, with the respiratory medium on one side and the blood or capillaries on the other.

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Animals like flatworms, earthworms, and some amphibians that use their moist skin as their only respiratory organ are usually small and are either long and thin or flat in shape, with a high ratio of surface area to volume.

For most other animals, the solution is a respiratory organ that is extensively folded or branched, enlarging the surface area for gas exchange.

- Gills, tracheae, and lungs.
2. Gills are respiratory adaptation of most aquatic animals

• **Gills** are outfoldings of the body surface that are suspended in water. (Lungs are infoldings).

• The total surface area of gills is often much greater than that of the rest of the body.
• Look at some of this variety. Common ancestry?

![Diagram of sea star, marine worm, clam, and crayfish with labeled parts: Gills, Coelom, Tube foot, Parapodia, and Gill.](image)
• Ventilation, which increases the flow of the respiratory medium over the respiratory surface, ensures that there is a strong diffusion gradient between the gill surface and the environment.

• Keep moving, or keep the water flowing!!!

• Crayfish and lobsters have paddlelike appendages that drive a current of water over their gills.
• Fish gills are ventilated by a current of water that enters the mouth, passes through slits in the pharynx, flows over the gills, and exits the body.

• It helps to have the blood and water moving in opposite directions.
Fig. 42.20
• This flow pattern (water and blood in opposite directions) makes **countercurrent exchange**.
3. Adaptations to dry land...

- Air has many advantages over water.
  - Higher concentration of oxygen.
  - When a terrestrial animal does ventilate, less energy is needed because air is far lighter and much easier to pump than water and much less volume needs to be breathed to obtain an equal amount of $O_2$. 
• But the flipside is that

DRY = DEATH

• This problem is greatly reduced by a respiratory surface folded inside the body to prevent evaporation.
• Remember how insects breathe?
Unlike branching tracheal systems, *lungs* are restricted to one location.

- Lungs have a dense net of capillaries just under the epithelium that forms the respiratory surface.
- Lungs have evolved in spiders, terrestrial snails, and vertebrates.
• What breathes with lungs, gills and skin??

• In contrast, most reptiles and all birds and mammals rely entirely on lungs for gas exchange.

• Lungs and air-breathing have evolved in a few fish species as adaptations to living on oxygen-poor water or to spending time exposed to air.
• Nasal cavity to pharynx to larynx goes the air…

• The wall of the larynx is reinforced by ???????.

• In most mammals, the larynx is adapted as a voicebox in which vibrations of a pair of vocal cords produce sounds.

• This develops from one of those gill arches in an embryo.
• Trachea to bronchi to bronchioles. Branching abounds, BUT, no gas exchange yet; walls of these tubes are TOO THICK, like arteries and veins.

• The epithelium lining the major branches of the respiratory tree is covered by cilia and a thin film of mucus.

• The mucus traps dust, pollen, and other stuff Johnny in the 3rd row just sneezed out, and the beating cilia move the mucus upward to the pharynx, where it is swallowed. Yummy!!!
• At their tips, the tiniest bronchioles dead-end as a cluster of air sacs called **alveoli**.

• Now the walls are thin enough for gas exchange.

• These have a total surface area of about 100 m² in humans, about half a tennis court!!!

• Surrounding each alveolus would be??????
• Mammals **ventilate** their lungs by **negative pressure breathing**.

• This works like a suction pump, pulling air into the lungs.

• Muscle action changes the volume of the rib cage and the chest cavity, and the lungs follow suit.

Here’s a good summary

And the diaphragm...
• The volume of air an animal inhales and exhales with each breath is called **tidal volume** (kind of like stroke volume is for the heart).

• The maximum tidal volume during forced breathing is the **vital capacity**.

  • The lungs hold more air than the vital capacity, but some air remains in the lungs, the **residual volume**, because the alveoli do not completely collapse.

• Sounds like time for a lab!!!
• Oxygen concentration in the air is 21%.

• What do you think it would be in the alveoli right after taking a big breath?
New technology to test effect of things you breath in

- The stretching of the alveoli when inhaling affects how particles enter and affect the cells.
- This includes drugs that might be delivered by an inhaler, drugs that have been shown to act differently on cells when they are stretched.
- See the clip here: [Lung on a chip](#) 3:30
• Ventilation is much more complex in birds than in mammals. Check this out...1:00
• The entire system - lungs and air sacs - is ventilated when the bird breathes.

• Air flow is one-way.

• Instead of alveoli, which are dead ends, the sites of gas exchange in bird lungs are tiny channels called parabronchi.
• This system completely exchanges the air in the lungs with every breath.

• Therefore, the maximum lung oxygen concentrations are higher in birds than in mammals.

• Partly because of this efficiency advantage, birds perform much better than mammals at high altitude.
4. Control centers in the brain regulate the rate and depth of breathing

- While we can voluntarily hold our breath or breathe faster and deeper, most of the time autonomic mechanisms regulate our breathing.
- This ensures that the work of the respiratory system is coordinated with that of the cardiovascular system, and with the body’s metabolic demands for gas exchange.
• Our breathing control centers are located in two brain regions, the medulla oblongata and the pons; both are in the brain stem, which controls many basic functions.

• Aided by the control center in the pons, the medulla’s center sets basic breathing rhythm, triggering contraction of the diaphragm and rib muscles.
• The medulla’s “air-o-stat” monitors which gas??

  • Its main cues about CO$_2$ concentration come from slight changes in the pH of the blood and cerebrospinal fluid bathing the brain.

  • Carbon dioxide reacts with water to form carbonic acid, which lowers the pH.

  • When the control center registers a slight drop in pH, it increases the depth and rate of breathing, and the excess CO$_2$ is eliminated in exhaled air.

  • Pretty neat control mechanism, eh?
Oxygen concentrations in the blood have little effect on the breathing control centers.

However, when the O₂ level is severely depressed - at high altitudes, for example, O₂ sensors in the aorta and carotid arteries in the neck send alarm signals to the breathing control centers, which respond by increasing breathing rate.

A rise in CO₂ concentration is a good indicator of a fall in O₂ concentrations, because these are linked by the same process - cellular respiration.

However, deep, rapid breathing purges the blood of so much CO₂ that the breathing center temporarily ceases to send impulses to the rib muscles and diaphragm (hyperventilation).
• To match the air intake system to the air distribution system during, for instance, exercise, heart rate increase is matched to the increased breathing rate, which enhances \( O_2 \) uptake and \( CO_2 \) removal as blood flows through the lungs.

• Good example of coordination between systems. AP question?
6. Respiratory pigments transport gases and help buffer the blood

- The low solubility of oxygen in water is a fundamental problem for animals that rely on the circulatory systems for oxygen delivery.
  - If all your cells could receive was the oxygen dissolved in the blood, they wouldn’t get enough.
A diversity of respiratory pigments have evolved.

One example, **hemocyanin**, found in the hemolymph of arthropods and many mollusks, has copper as its oxygen-binding component, coloring the blood bluish.

Tell me all you know about hemoglobin…
• This is neat, and not a surprise that it works this way…
  
  • The binding of $O_2$ to one subunit induces the remaining subunits to change their shape slightly such that their affinity for oxygen increases.
  
  • When one subunit releases $O_2$, the other three quickly follow suit as a conformational change lowers their affinity for oxygen.
• Cooperative oxygen binding and release is evident in the **dissociation curve** for hemoglobin.

• Where the dissociation curve has a steep slope, even a slight change in $P_{O_2}$ causes hemoglobin to load or unload a substantial amount of $O_2$.

• This steep part corresponds to the range of partial pressures found in body tissues.

![Dissociation curve for hemoglobin](image)

*Fig. 42.28a*
Look at the **Bohr shift**.

- Because CO$_2$ reacts with water to form carbonic acid, an active tissue will lower the pH of its surroundings and induce hemoglobin to release more oxygen.

![Graph showing O$_2$ saturation of hemoglobin vs. P$_O_2$](image)

Fig. 42.28b
In addition to oxygen transport, hemoglobin also helps transport carbon dioxide and assists in buffering blood pH.

- About 7% of the CO$_2$ released by respiring cells is transported in solution.
- Another 23% binds to amino groups of hemoglobin.
- About 70% (MOST) is transported as bicarbonate ions.
- This fact is very often a test question, so let’s check it out.
Fig. 42.29

CO₂ transport from tissues

Tissue cell

CO₂ produced

Interstitial fluid

CO₂

Blood plasma within capillary

CO₂

Capillary wall

Red blood cell

H₂O

H₂CO₃

Carbonic acid

H₂CO₃⁻ + H⁺

Bicarbonate

HCO₃⁻

HCO₃⁻

To lungs

Hemoglobin picks up CO₂ and H⁺
Fig. 42.29, continued
7. Deep-diving air-breathers stockpile oxygen and deplete it slowly

• When an air-breathing animal swims underwater, it lacks access to the normal respiratory medium.
  • Most humans can only hold their breath for 2 to 3 minutes and swim to depths of 20 m or so. Contest?
  • However, a variety of seals, sea turtles, and whales can stay submerged for much longer times and reach much greater depths.

Fig. 42.30
One adaptation of these deep-divers, such as the Weddell seal, is an ability to store large amounts of O₂ in the tissues.

- Compared to a human, a seal can store about twice as much O₂ per kilogram of body weight, mostly in the blood and muscles.
- About 36% of our total O₂ is in our lungs and 51% in our blood.
- In contrast, the Weddell seal holds only about 5% of its O₂ in its small lungs and stockpiles 70% in the blood.
Several adaptations create these physiological differences between the seal and other deep-divers in comparison to humans.

- First, the seal has about twice the volume of blood per kilogram of body weight as a human.
- Second, the seal can store a large quantity of oxygenated blood in its huge spleen, releasing this blood after the dive begins.
- Third, diving mammals have a high concentration of an oxygen-storing protein called **myoglobin** in their muscles.
  - This enables a Weddell seal to store 25% of its $\text{O}_2$ in muscle, compared to only 13% in humans.
• Diving vertebrates also have adaptations that conserve O$_2$.
  
  • They swim with little muscular effort and often use buoyancy changes to glide passively upward or downward.
  
  • Their heart rate and O$_2$ consumption rate decreases during the dive and most blood is routed to the brain, spinal cord, eyes, adrenal glands, and placenta (in pregnant seals). This is called the dive reflex.
  
  • Blood supply is restricted or even shut off to the muscles, and the muscles can continue to derive ATP from fermentation after their internal O$_2$ stores are depleted.