

Gas exchange systems and gas transport

All animals must exchange oxygen and carbon dioxide with their environments. Several physical and biological principles are universally important:

- All animals (aquatic or terrestrial) use these gases in a **dissolved** state.
- Movement of gases across membranes is by **diffusion (no active transport of gases)**. The **rate** of diffusion depends on:

-- the diffusion **distance** (rate $\sim 1/\text{distance}^2$)
-- the **area** for diffusion (rate $\sim \text{area}$)
-- the **concentration gradient** (rate $\sim \text{gradient}$)

- Diffusion is **much** faster in air than in water, and...
- Air contains **much more oxygen per liter** (about 210 ml of O₂/liter) than does water (5-10 ml of dissolved O₂/liter *at most*)

Gas exchange organs

Gas exchange **without** specialized exchange organs is possible in animals that are small, thin, and have low MR.

- can manage by diffusion across skin

For larger, more active animals, cells are too far from the surface for diffusion to be fast enough.

Solution: **gas exchange organs**, usually connected to the **circulatory system** (**bulk flow** much faster than diffusion)

Gas exchange organs:

- are moist (even in air-breathers)
- have **large surface area**
- are **thin** (to reduce diffusion distance)
- usually are **ventilated** (by breathing)
 - keeps concentration gradients across surface *high*

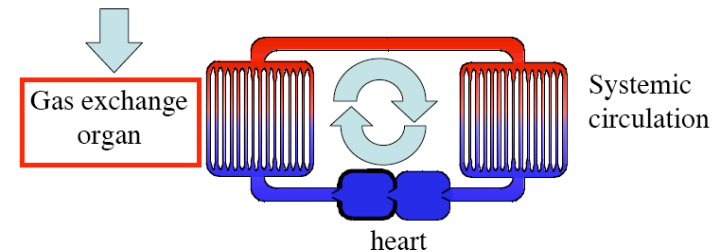
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Gas exchange organs

Simplest gas exchange organ is the **skin**:

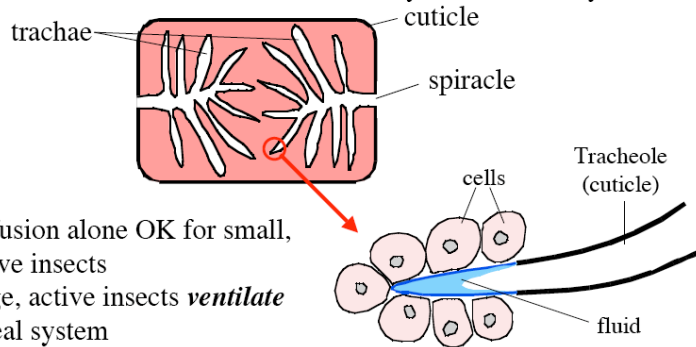
- usually highly vascularized (connection to circulation)
- needs to be moist (water loss problem for air-breathers)
- needs to be thin (precludes protective coverings, which would block gas exchange)

Gas exchange organs

Tracheal systems (insects)

Network of hollow, air-filled tubes inside the cuticle, collected to the outside through spiracles (controllable)

- primarily diffusion -- but through **gas**, not liquid (faster)
- trachae & tracheoles near every cell in the body



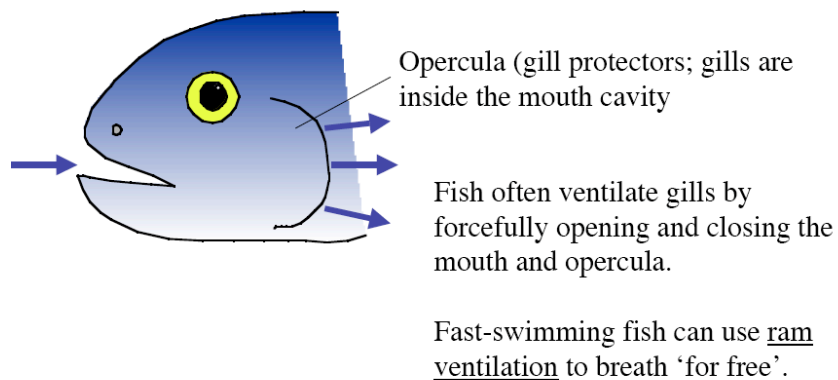
- diffusion alone OK for small, inactive insects
- large, active insects **ventilate** tracheal system

Gas exchange organs

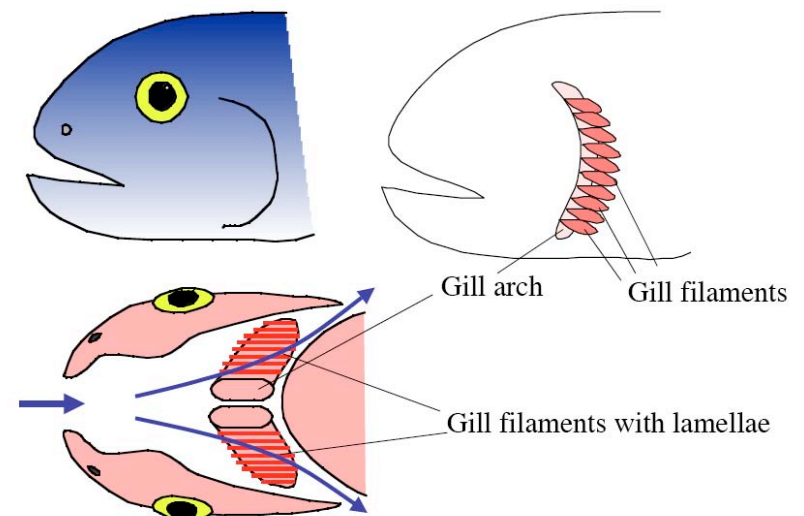
Aquatic animals usually exchange gases through **gills**:

- lots of surface area
- extensive blood supply
- usually, **must** be actively ventilated
 - O₂ content low in water; need to keep water near exchange surface refreshed
 - water is heavy and viscous: **expensive to pump** (especially since O₂ content low)
 - selection to maximize efficiency of exchange (amount of O₂ extracted from breathed water)

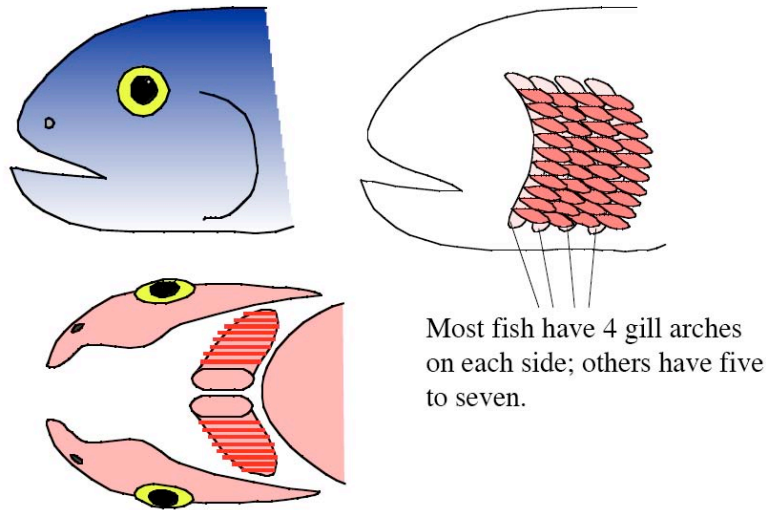
Gas exchange organs: fish gills



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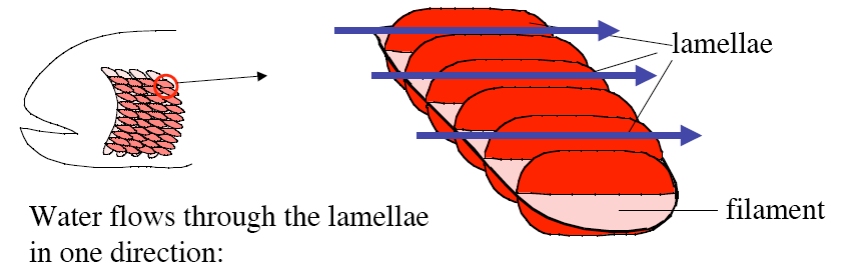


Gas exchange organs: fish gills



Gas exchange organs: fish gills

A closer look at gill filaments and lamellae:



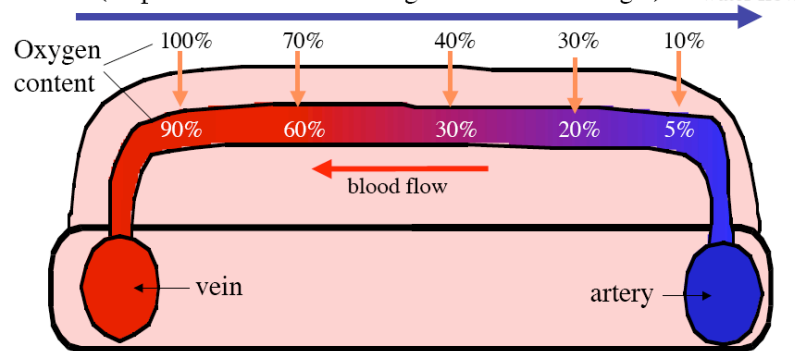
Gas exchange organs: fish gills

A closer look at a single lamella:

2 fluid streams in close proximity, moving in opposite directions:

Countercurrent exchanger

(helps maintain continuous gradient for exchange:)

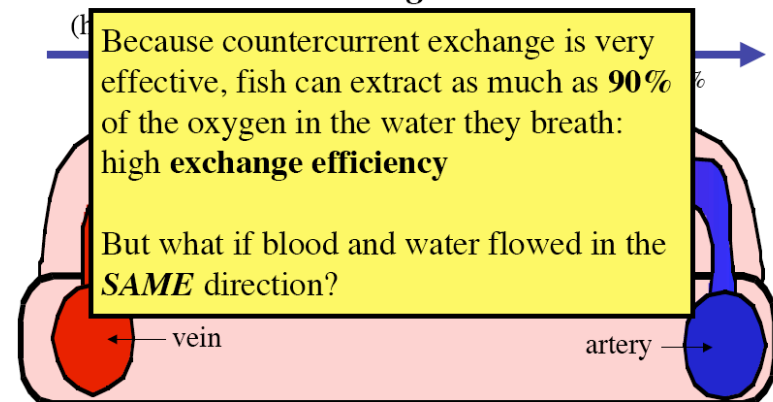


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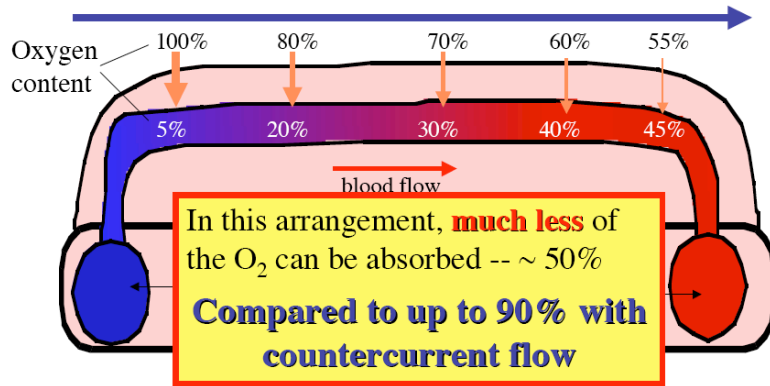
2 fluid streams in close proximity, moving in opposite directions:

Countercurrent exchanger



Gas exchange organs: fish gills

If flow is *not* countercurrent (opposite directions), exchange is ***much less complete***:



Gas exchange organs: lungs

Air breathing has several advantages over water breathing:

- Air contains a lot of oxygen (about 21% by volume)
- Air is ***much*** easier to pump (ventilate) than water
- Diffusion is faster in air than in water

But air breathing has a serious disadvantage: Respiratory surface must be wet and air is often very dry --> water loss, organ collapse (not supported by surrounding water)

Solution: place exchange organs (lungs) inside a protective cavity

Gas exchange organs: fish gills

Even though countercurrent exchange allows fish to extract most of the oxygen in the water they breath, they are limited in how much O₂ they can acquire:

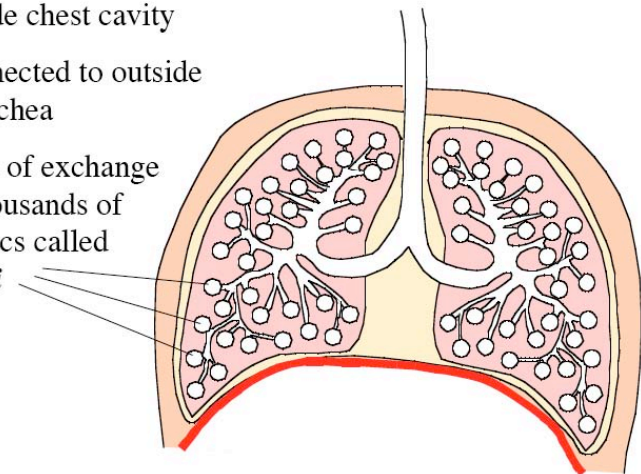
- water is very expensive to pump (heavy and viscous) -- high energy cost
- water doesn't contain large amounts of O₂, so even if a fish gets 90% of it, there isn't much
- in warm, stagnant water, there is even less O₂ available.

Low oxygen availability is another reason fish are usually ***ectotherms!***

Gas exchange organs: lungs

Typical mammal lungs:

- inside chest cavity
- connected to outside via trachea
- sites of exchange are thousands of tiny sacs called ***alveoli***

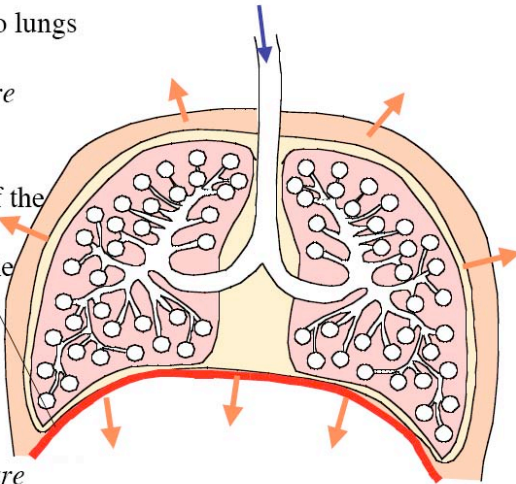


Gas exchange organs: lungs

Ventilation occurs when air is pushed into lungs under pressure
(positive pressure breathing)

Or, expansion of the chest cavity by chest wall muscle and **diaphragm** create a partial vacuum

(negative pressure breathing)

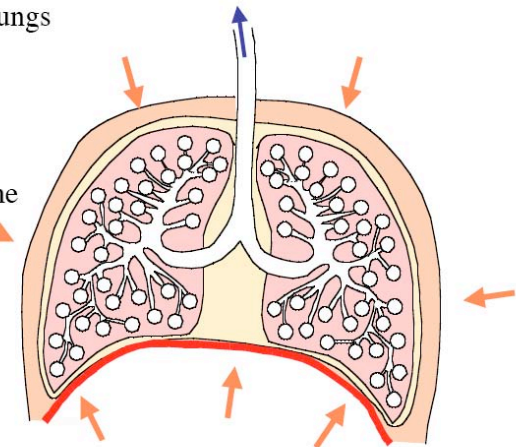


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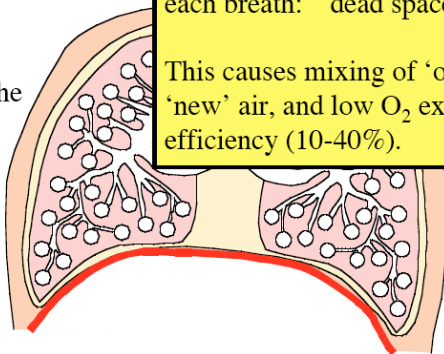
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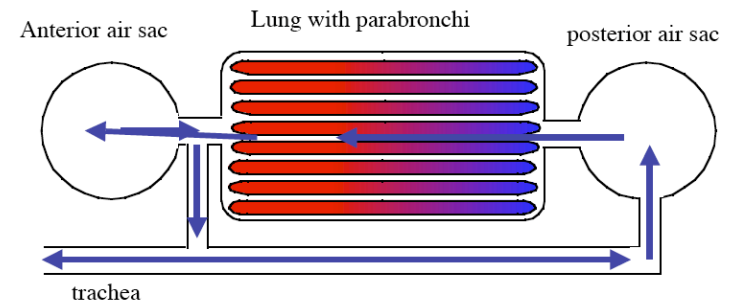
Tidal ventilation

Because ventilation is **tidal** and alveoli are blind sacs, not all of the alveolar air is exchanged with each breath: "dead space".

This causes mixing of 'old' and 'new' air, and low O₂ exchange efficiency (10-40%).

Gas exchange organs: lungs

Bird lungs avoid the problem of poor mixing in tidal systems by having *one way flow* in the lung:



One-way flow permits smaller lungs, higher extraction (>50%) and is one reason birds do much better than mammals at high altitude.

Gas exchange organs: ventilation control

Gas exchange varies with metabolic rate; ventilation has to be matched. **What controls breathing rate?**

O₂ content (pO₂; *partial pressure* of O₂) of body?

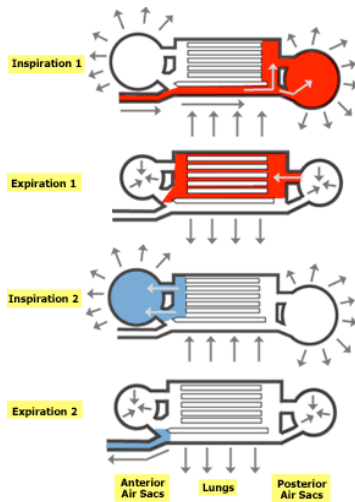
CO₂ content (pCO₂; *partial pressure* of CO₂) of body? ←

BOTH have an effect, but normally pCO₂ -- sensed as **pH** in body fluids (dissolved CO₂ forms **carbonic acid**) -- drives breathing:

excess CO₂ → low pH → increased breathing

Forced hyperventilation → high pH → reduced breathing ('blows off' CO₂)

Very low pO₂ will result in increased breathing



Transport of oxygen in blood

Most animals use circulatory systems to move oxygen between the gas exchange organs and the tissues; this **bulk flow** is much better than diffusion over long distances.... but there are serious problems due to the low solubility of O₂ in water.

Consider an exercising human consuming 4 **liters** of O₂/min:

- at 37 °C, only about 4-5 **ml** O₂/liter can dissolve into blood
- assuming 4 ml O₂/liter is transferred to the tissues, the heart would need to pump **one thousand** liters/minute (**one ton** of blood/min) -- clearly impossible!

Solution: most (~98%) of O₂ is *not* transported in the dissolved state. Instead, it is bound to **respiratory pigments**:

O₂ in solution: ~ 4 ml/liter O₂ bound to pigment: ~**200 ml/liter**

Transport of oxygen in blood: Respiratory pigments

Respiratory pigments (so-called because they are usually visibly colored) are modified proteins.

In vertebrates the 'standard' respiratory pigment is **hemoglobin**; contained within erythrocytes.

Each hemoglobin can bind 4 oxygen molecules (O₂) when fully **saturated** (none when completely **unsaturated**)

Like all respiratory pigments, hemoglobin must do two things:

- **bind** oxygen in the respiratory organ
- **release** oxygen to the tissues

--> **reversible oxygen binding**

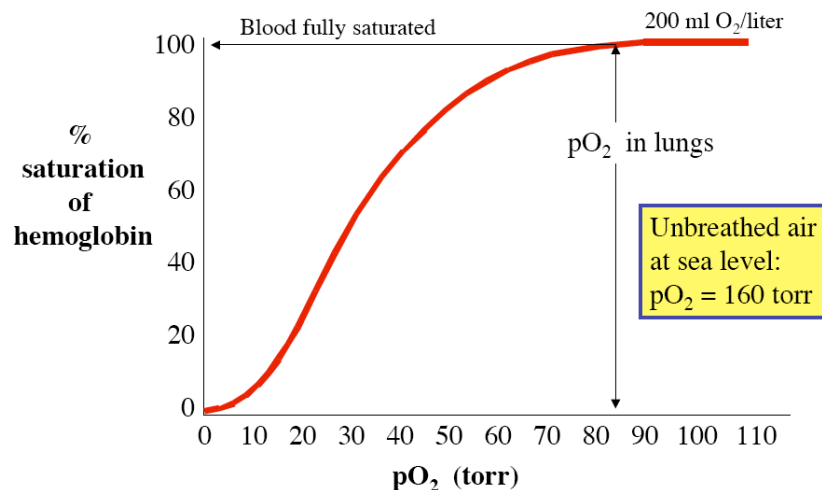
Transport of oxygen in blood: Respiratory pigments

Reversible oxygen binding by hemoglobin is a function of the availability of oxygen in the vicinity

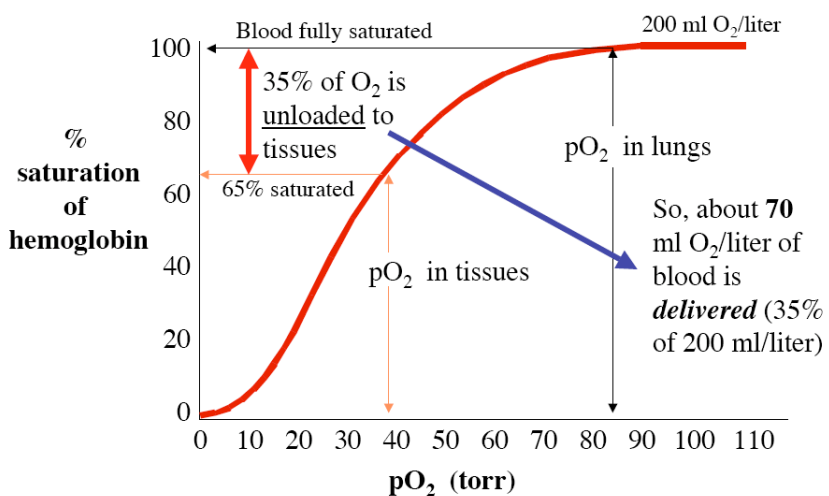
- measured as pO_2 (partial pressure of O_2)
- pO_2 is high in the air (and lungs) and low in the tissues
- since there is no active transport of O_2 , it must move 'down' a pO_2 gradient as it travels from the air to the cells where it is used
- the relationship between the amount of O_2 bound to hemoglobin and pO_2 is **non-linear**:

the hemoglobin-oxygen *dissociation curve*

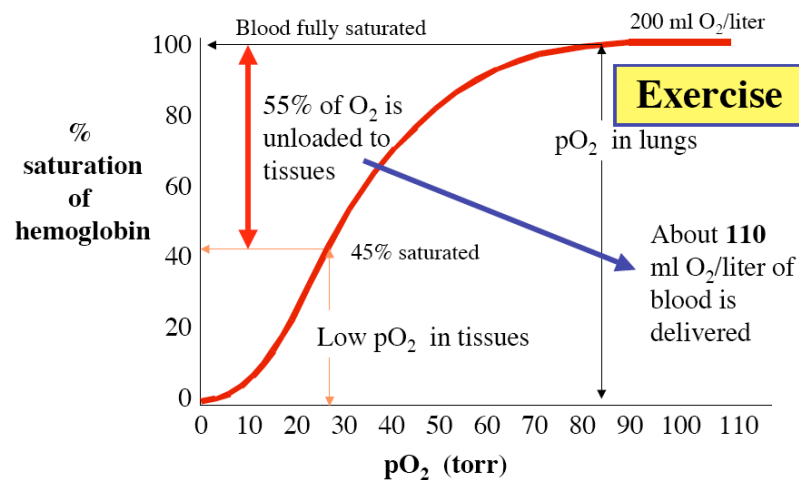
Transport of oxygen in blood: Dissociation curve



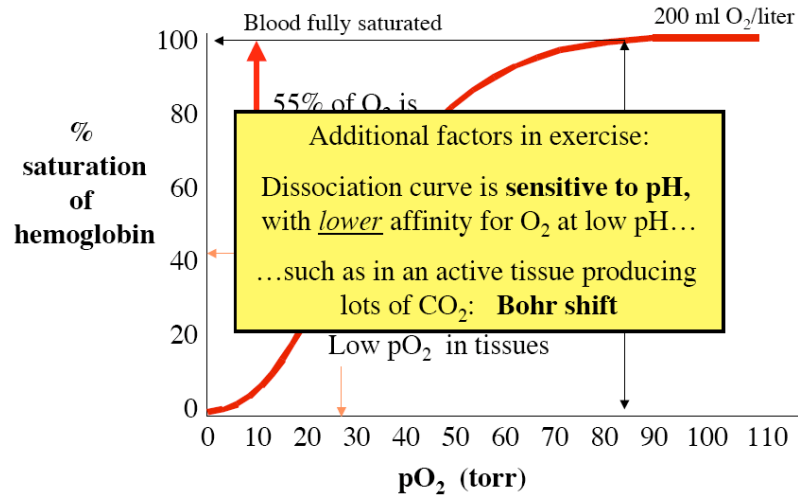
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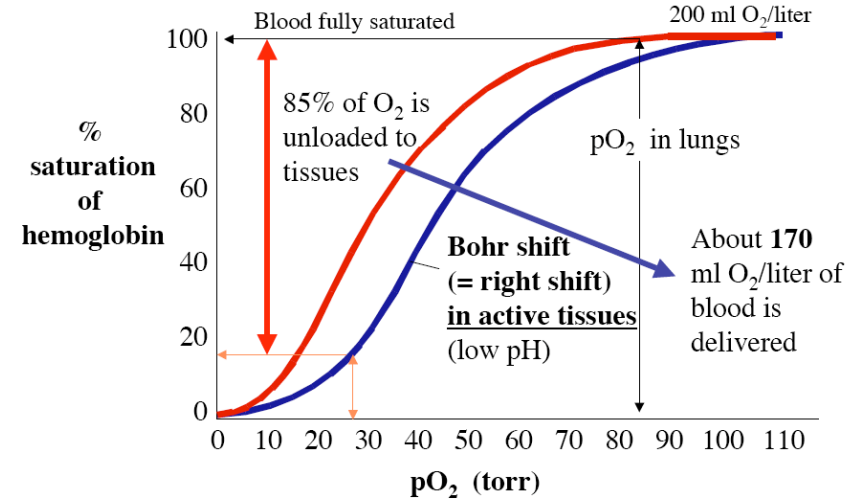
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