Respiratory system

Respiratory regulation during exercise

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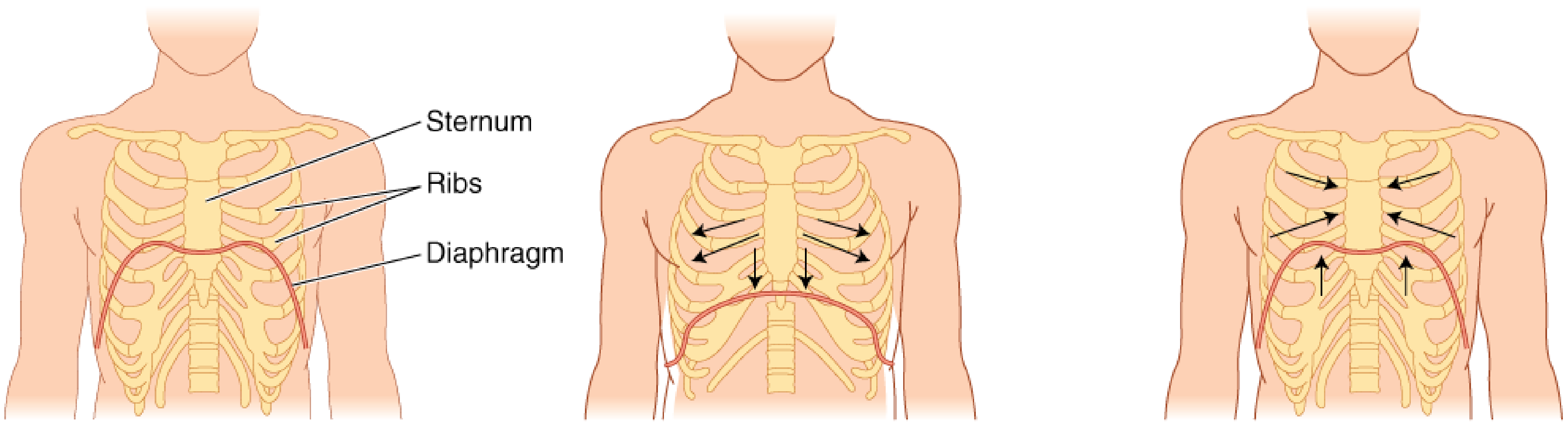
Respiration

- **Respiration - delivery of oxygen to and removal of carbon dioxide from the tissue**
- **External respiration**—ventilation and exchange of gases in the lung
  - **Pulmonary ventilation** – movement of air into and out of the lungs—inspiration and expiration
  - **Pulmonary diffusion** – exchange of oxygen and carbon dioxide between the lungs and blood
- **Internal respiration**—exchange of gases at the tissue level (between blood and tissues)

External respiration



a — Rest

b — Inspiration

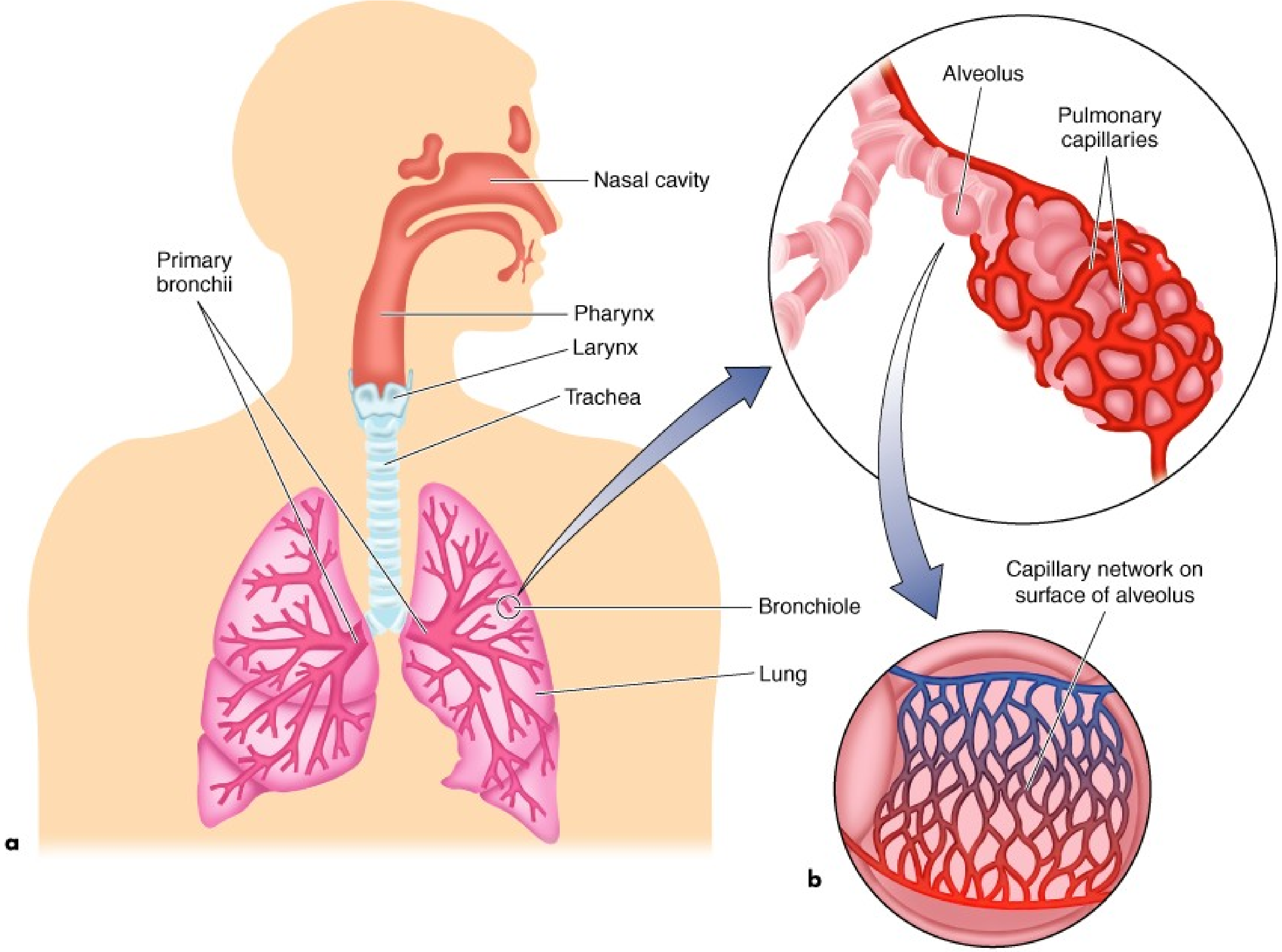
The diaphragm contracts to pull downwards and chest muscles contract to pull open the chest

c — Expiration

The diaphragm and the chest muscles relax allowing the lungs to spring back to normal relaxed size – this pushes the air out

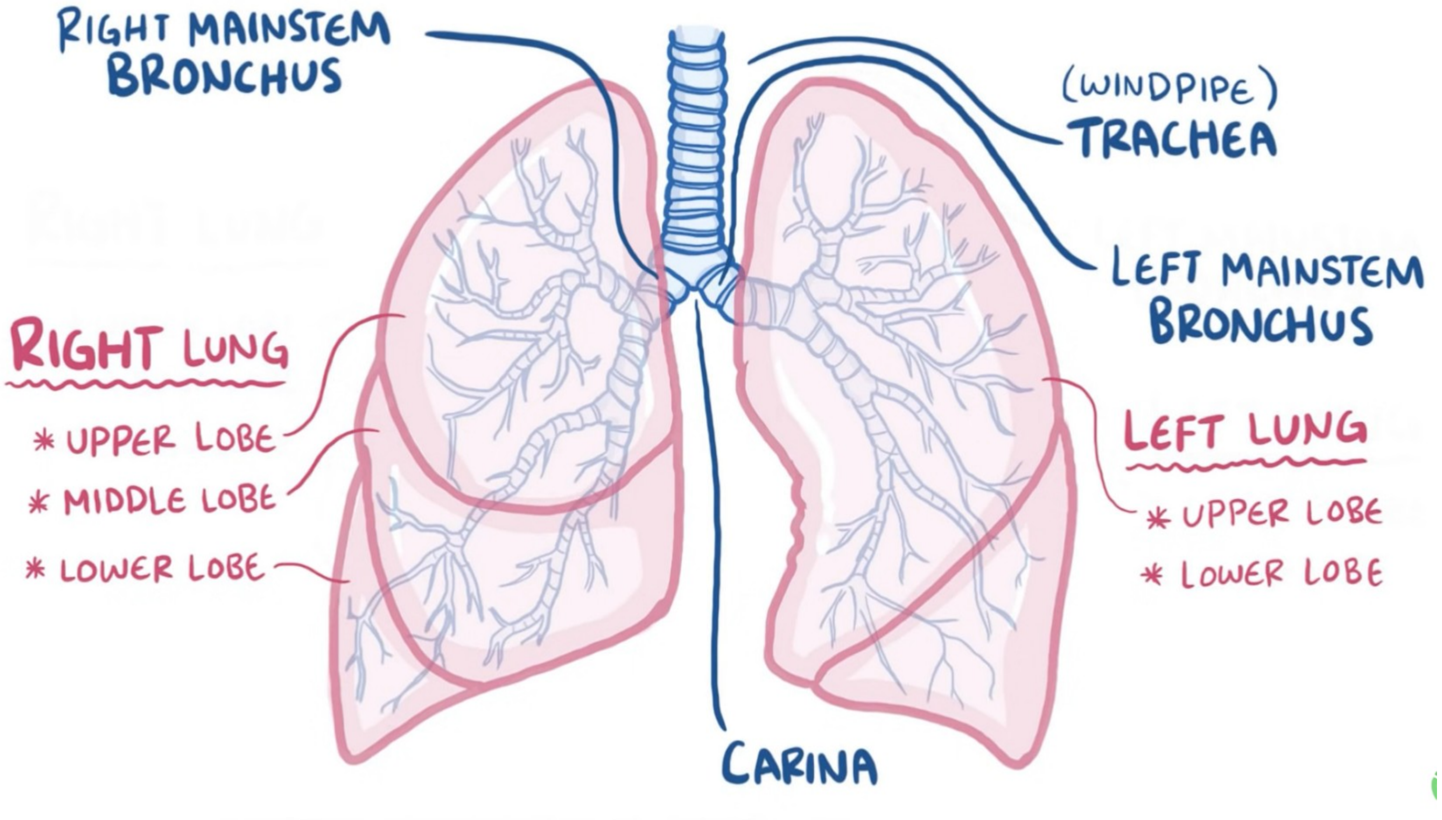
Pulmonary ventilation

- Nasal cavity – lined by cells that release mucus
- **Mucus** – sticky and salty, contains lysozymes
- Nasal hair covered in mucus catch large particles, dust, pollen etc.
- **Paranasal sinuses** – help the air to circulate to get warm and moist
- Air flow

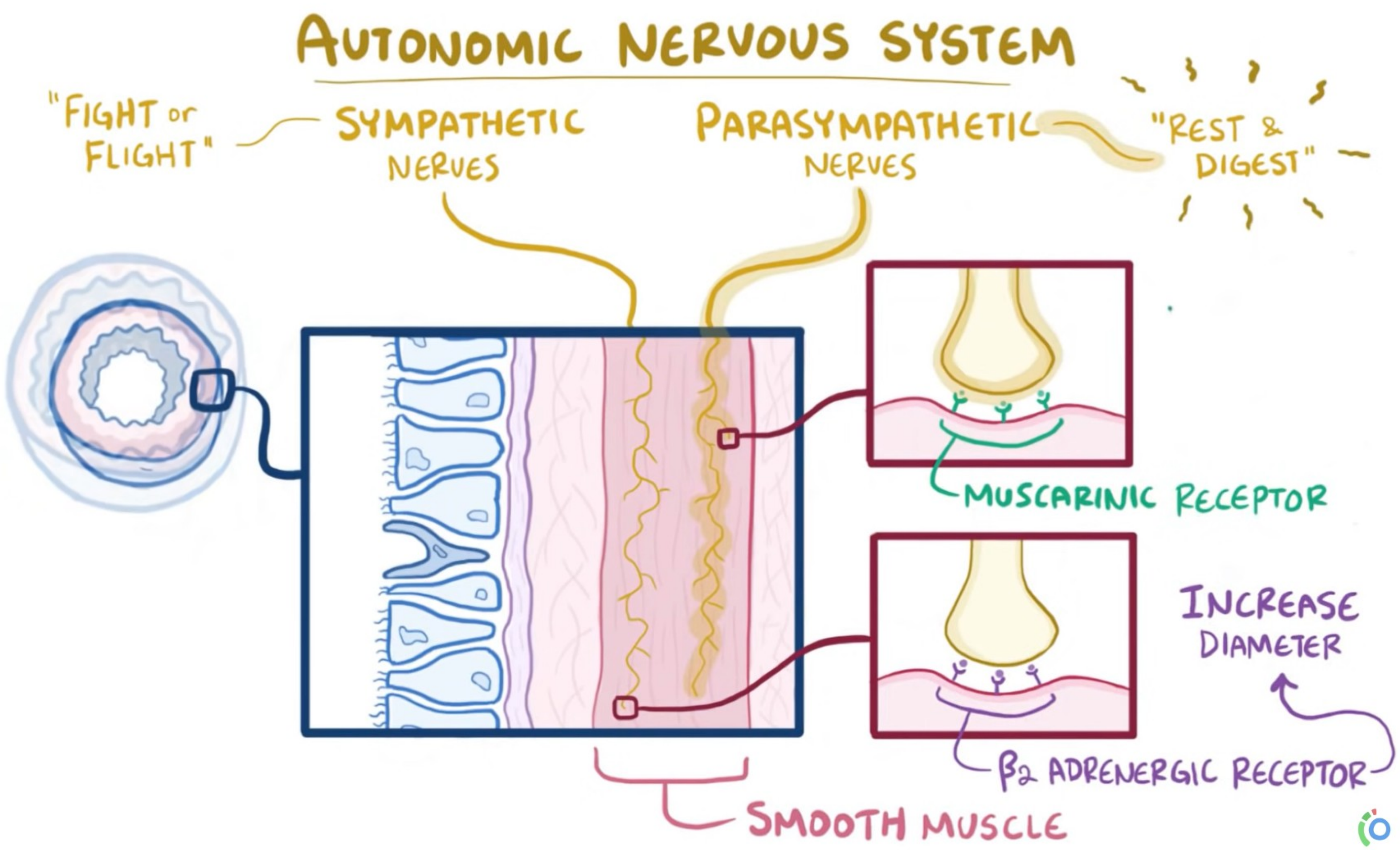


Pulmonary ventilation

- **Lungs' lobes**
- **Trachea** and the first three generations of **bronchi** use **cartilage rings** for support
- Then the bronchi narrow down to **bronchioles**
  - No cartilage
  - 15-20 generations

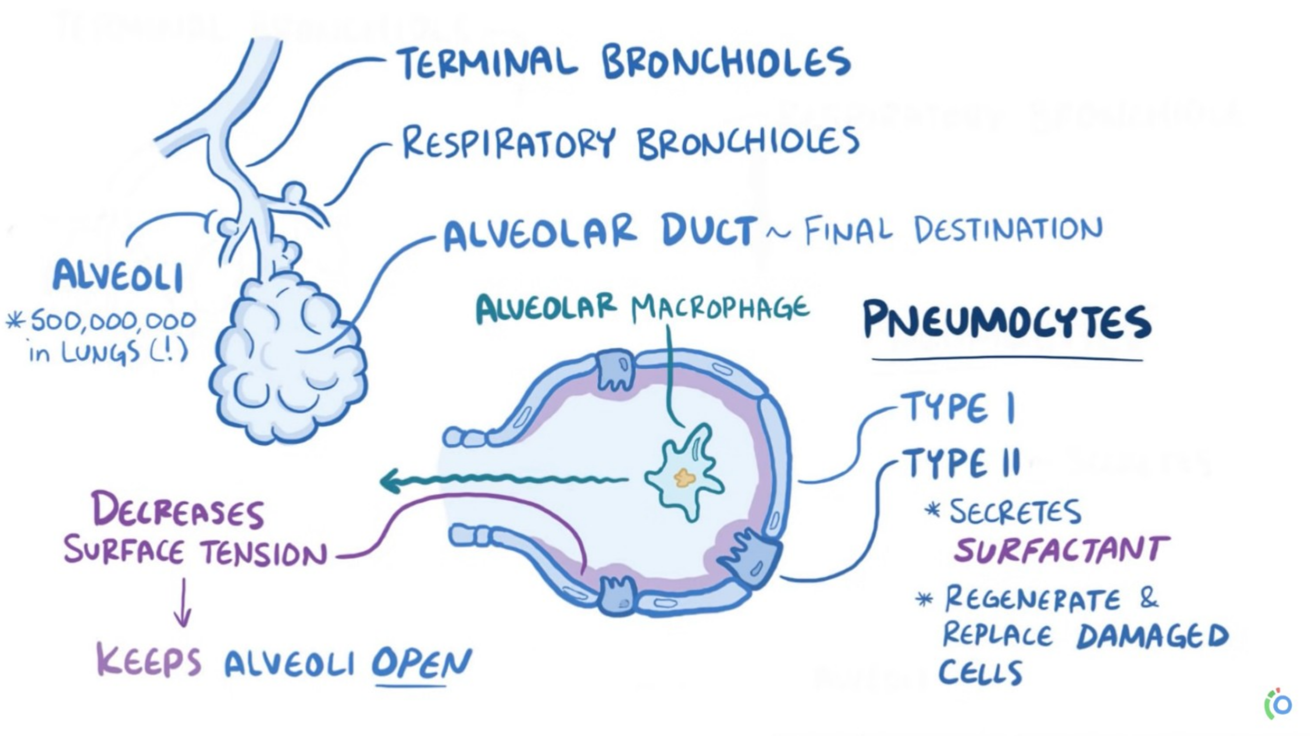


Respiration



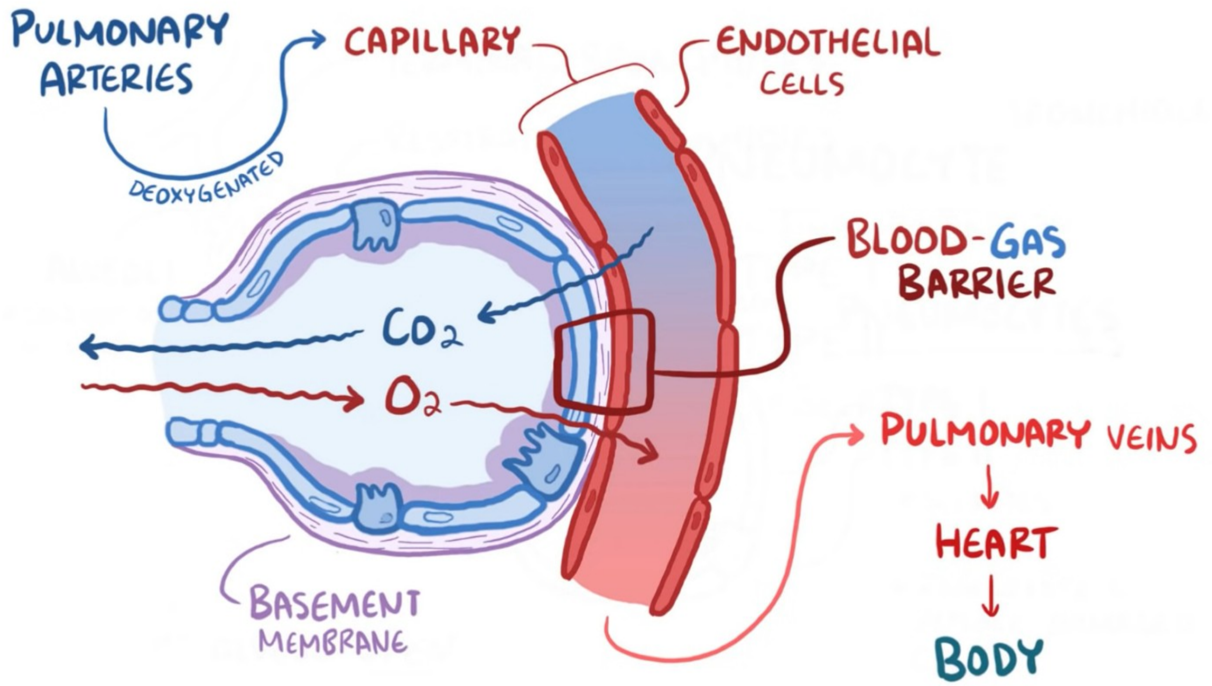
Pulmonary ventilation

- **Terminal bronchioles**
- **Respiratory bronchioles**
- **Alveoli** – about 500 000 000 in the lungs
- **Alveolar duct** – the destination of the inhaled air
- **Pneumocytes**
  - Type I
  - Type II - surfactant



Pulmonary diffusion

- **BLOOD-GAS barrier**: pneumocytes, endothelial cells and basement membrane
- **Deoxygenated blood** arrives via pulmonary arteries
- Replenishes blood's **oxygen supply** that has been depleted for oxidative energy production
- **Carbon dioxide** is removed and breathed out
- **Oxygenated blood** via pulmonary veins – to the heart – to the body



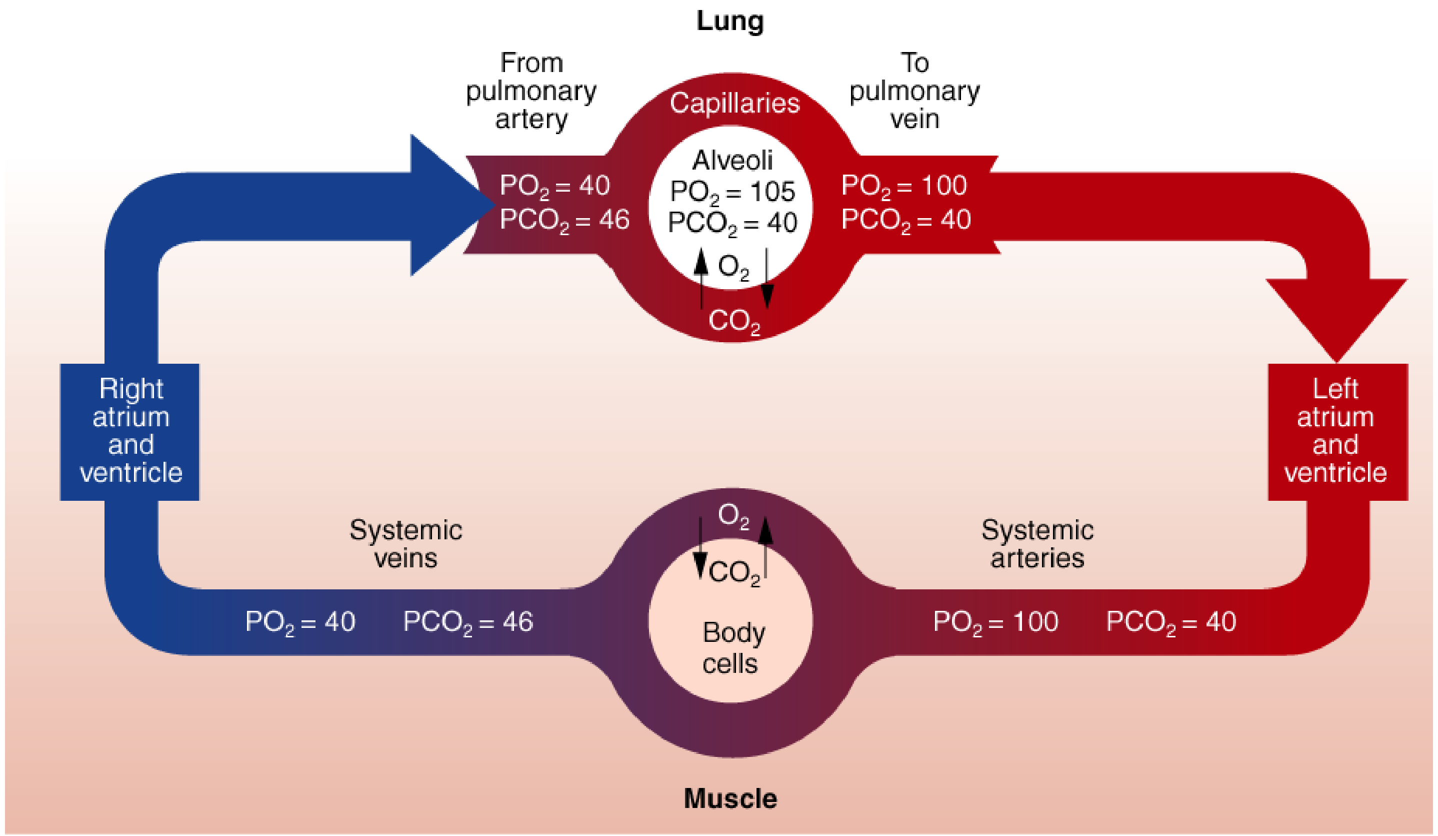
Gases – partial pressure and exchange

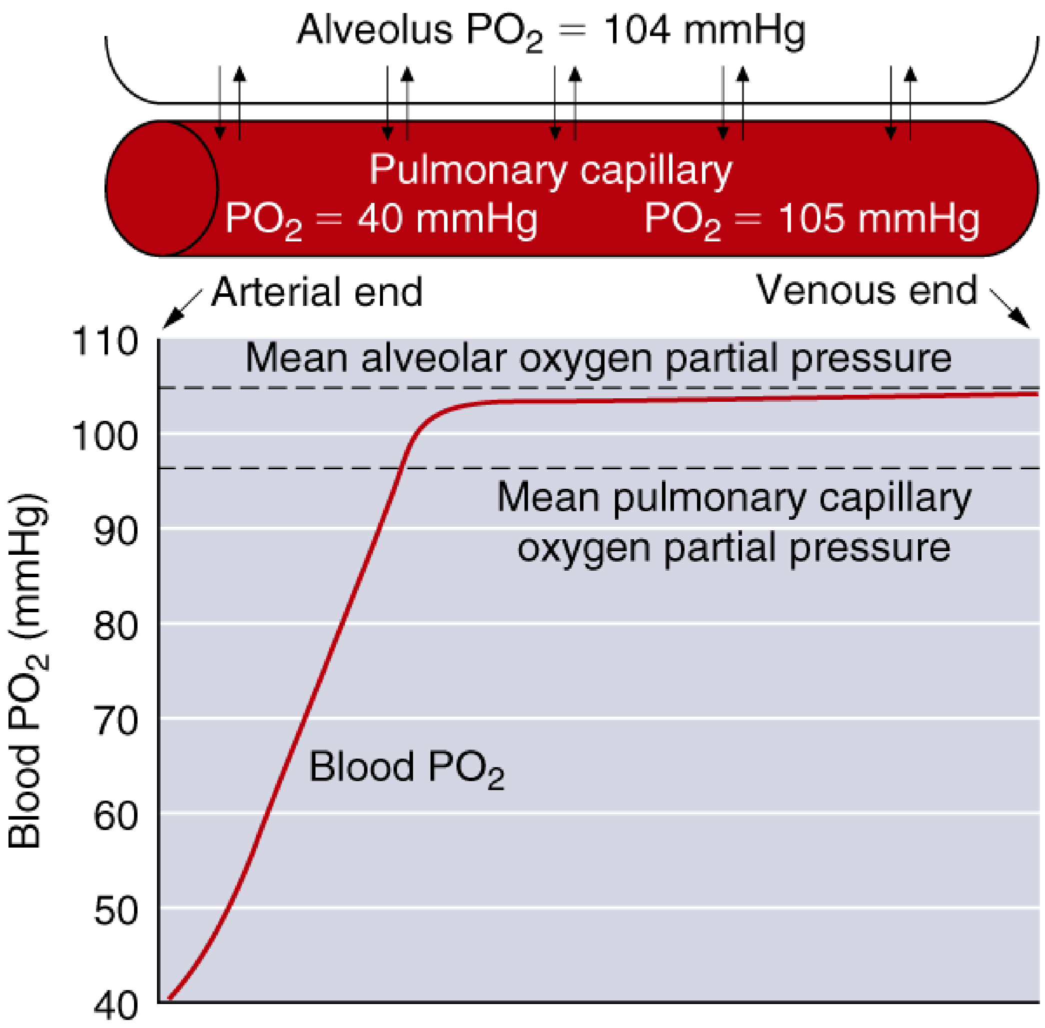
- **Atmospheric air** is a mixture of gases – each gas with its own **partial pressure** contributes to the total atmospheric pressure
- **Alveolar air** differs from atmospheric air
- The **gas exchange** occurs between the alveolar air and the blood in capillaries by **diffusion** – the flow down their **concentration gradient** or **partial pressure gradient**
- The composition of alveolar air is closely monitored
- Gas exchange depends on:
    - **The magnitude of partial pressure gradient** (influenced also by altitude)
    - **Solubility** (nitrogen is plentiful in the air but does not diffuse into the blood)
    - **Thickness** of the pulmonary membrane

KEY POINTS – Pulmonary diffusion

- **Pulmonary diffusion** is the process by which **gases are exchanged** across the respiratory membrane in the alveoli to the blood and vice versa
- The amount of gas exchange depends on **the partial pressure** of each gas, its **solubility**, and **temperature**
- Gases diffuse along a **pressure gradient**, moving from an area of higher pressure to lower pressure
- **Oxygen diffusion capacity increases as you move from rest to exercise**
- The pressure gradient for CO2 exchange is less than for O2 exchange, but **carbon dioxide's diffusion coefficient** is 20 times greater than that of oxygen's, so CO2 crosses the membrane easily

PO_2 AND PCO_2 IN BLOOD





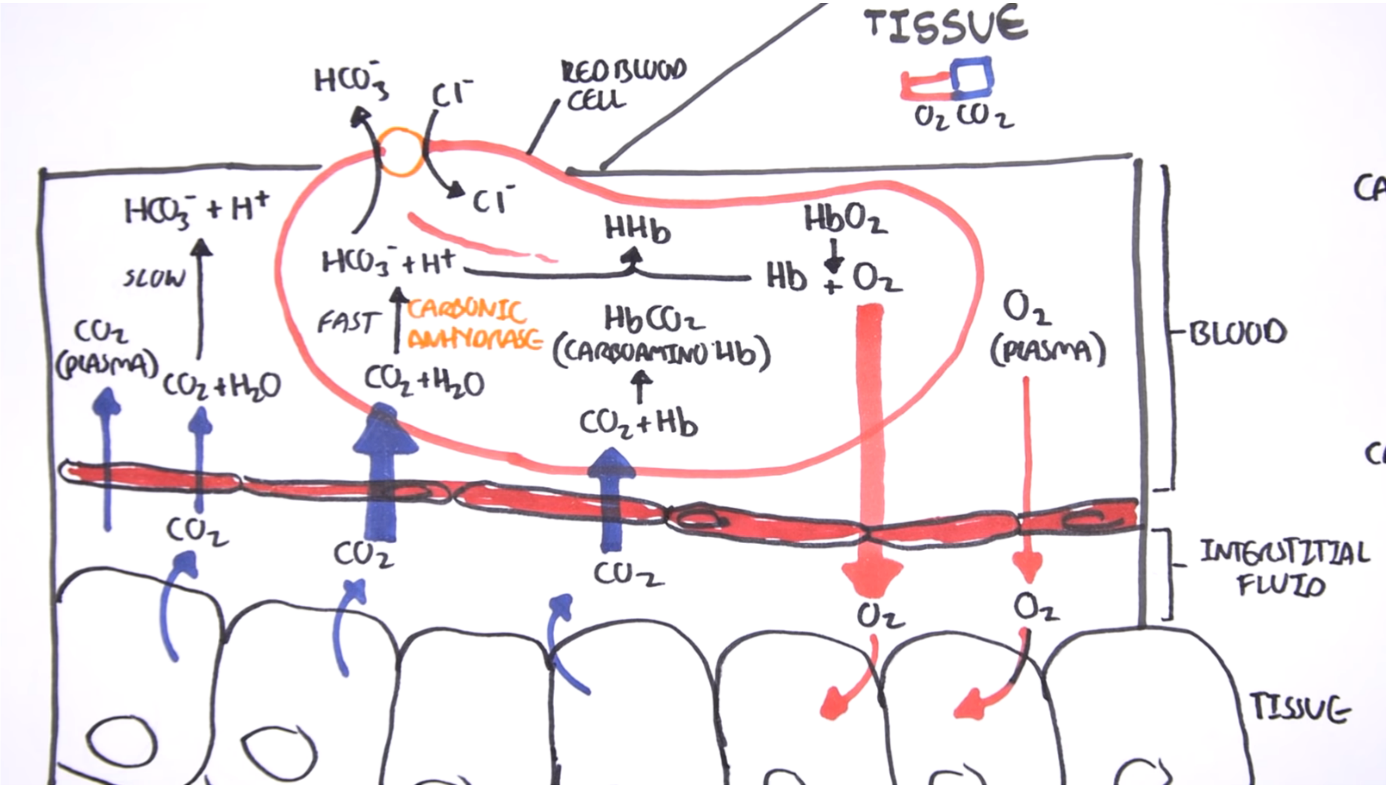
Partial pressures in the blood do not change during exercise!

Partial Pressures of Respiratory Gases at Sea Level

		Partial pressure (mmHg)				
Gas	% in dry air	Dry air	Alveolar air	Arterial blood	Venous blood	Diffusion gradient
Total	100.00	760.0	760	760	706	0
H_2O	0.00	0.0	47	47	47	0
O_2	20.93	159.1	105	100	40	60
CO_2	0.03	0.2	40	40	46	6
N_2	79.04	600.7	568	573	573	0

Oxygen Transport

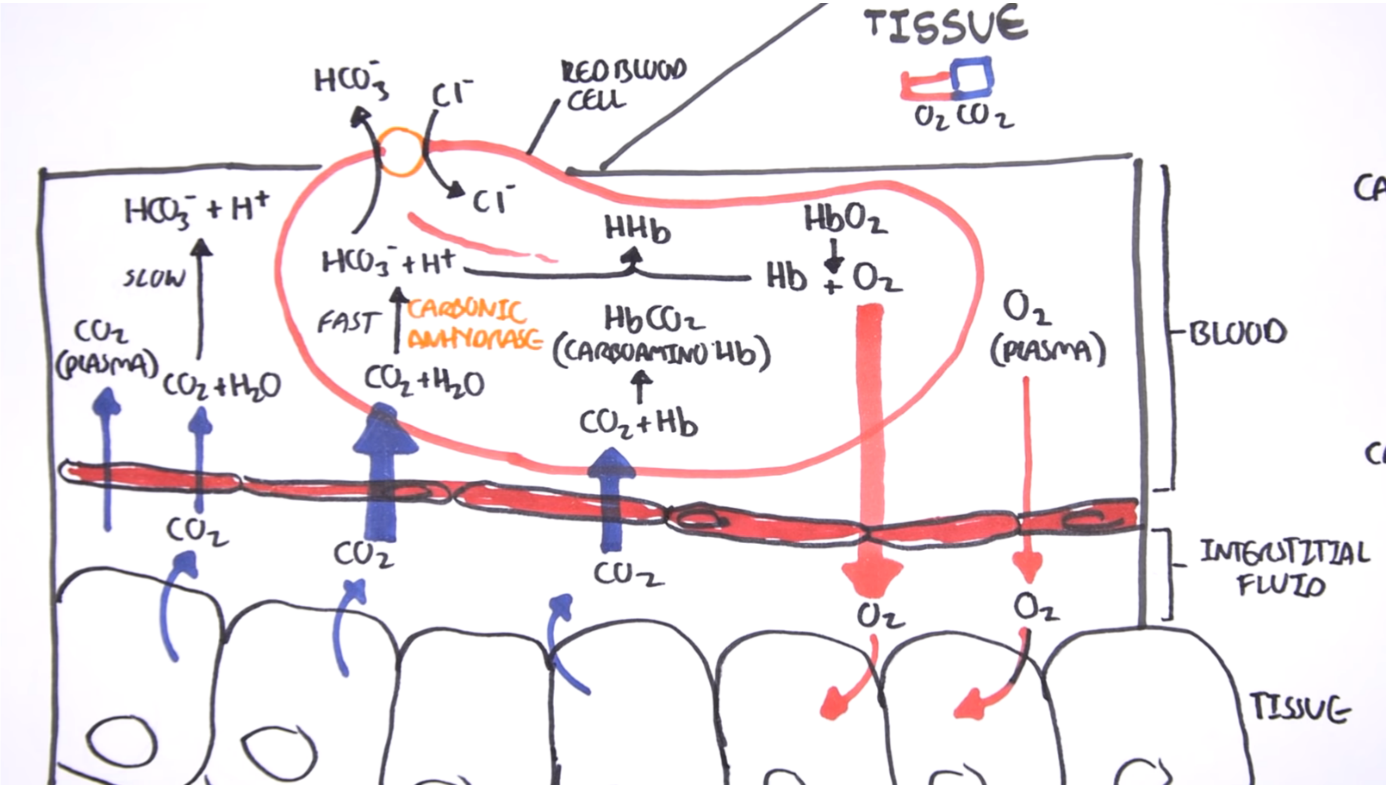
- Hemoglobin concentration largely determines the oxygen-carrying capacity of blood (>98% of oxygen transported)
- Increased H+ (acidity) and temperature of a muscle allows more oxygen to be unloaded there
- Training affects oxygen transport in muscle

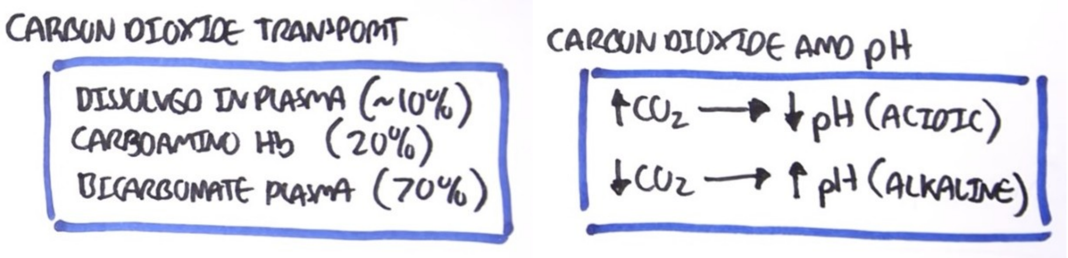


Oxygen uptake and delivery is influenced by oxygen content of the blood, amount of blood flow and conditions in the tissue.

Carbon Dioxide Transport

- Dissolved in blood plasma (7% to 10%)
- As bicarbonate ions resulting from the dissociation of carbonic acid (60% to 70%)
- Bound to hemoglobin (carbaminohemoglobin) (20% to 33%)





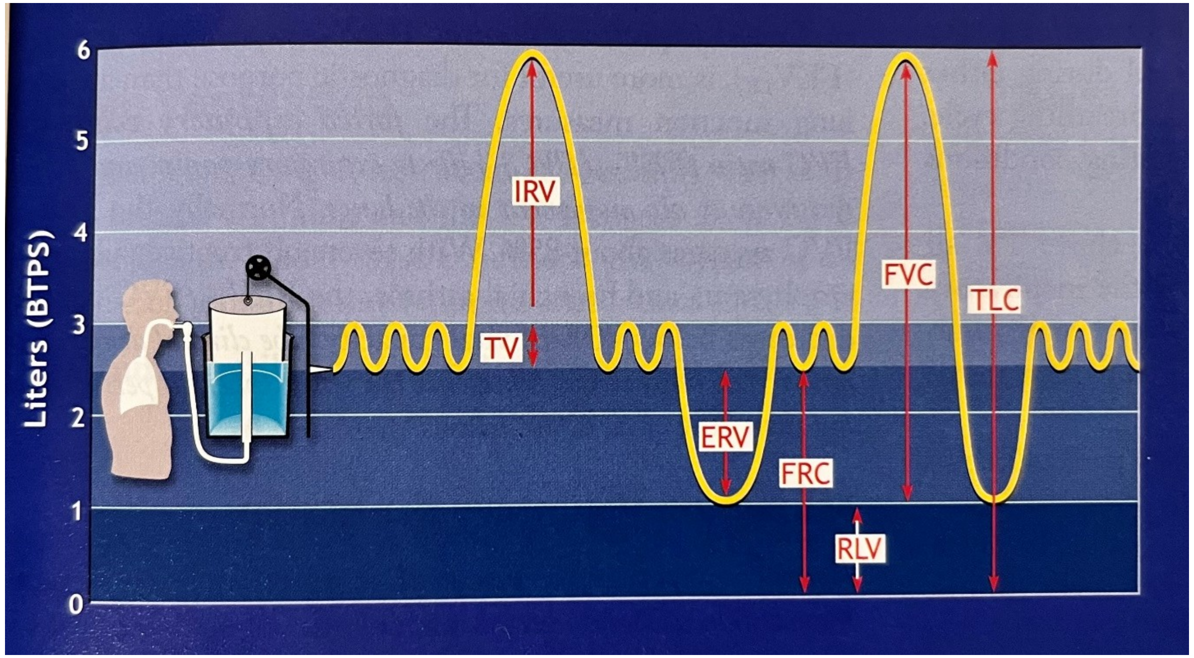
Vital Capacity

- Vital capacity is the maximum amount of air that can be forcefully expired after a maximum inspiration

  VC females = 3-4 l

  VC males = 4-5.5 l

- From the pulmonary function test the vital capacity testing is the most frequently used. It could be performed „slowly“ (VC) and/or as fast and forced as possible (forced vital capacity, FVC)



Lung volume/capacity	Definition	Average values (mL) Men	Women
Tidal Volume (TV)	Volume inspired or expired per breath	600	500
Inspiratory Reserve Volume (IRV)	Maximum inspiration at end of tidal inspiration	3000	1900
Expiratory Reserve Volume (ERV)	Maximum expiration at end of tidal expiration	1200	800
Total Lung Capacity (TLC)	Volume in lungs after maximum inspiration	6000	4200
Residual Lung Volume (RLV)	Volume in lungs after maximum expiration	1200	1000
Forced Vital Capacity (FVC)	Maximum volume expired after maximum inspiration	4800	3200
Inspiratory Capacity (IC)	Maximum volume inspired following tidal expiration	3600	2400
Functional Residual Capacity (FRC)	Volume in lungs after tidal expiration	2400	1800

Vital Capacity

Calcultae your predicted value of the vital capacity:

Males:

Predict. **VC (ml) = [27.63 – (0.112 x age (yrs)] x height (cm)**

Females:

Predict. **VC (ml) = [21.78 – (0.101 x age (yrs)] x height (cm)**

Compare your measured values with the predicted values and express them as a percentage of the predicted values

Respiration and Exercise

1. More **OXYGEN is needed** in active muscles
2. More **CARBON DIOXIDE needs to be removed** from the active muscles

1. An increase of **breathing rate**
2. The depth of breathing increase up to our **vital capacity**
3. **Alveolar ventilation** increases with increased metabolic demands
4. An increase of **blood flow** through the lungs (cardiac output increase)
5. An increase in **oxygen consumption** (metabolic reactions) – up to 20 times higher compared with resting oxygen uptake
6. The arterial **Po_2 and Pco_2** remail almost unchanged!

Signals for Ventilation Increase

The brain sends signals to active muscles, along with that it send signal to the brain stem to excite the respiratory system

1. **An increase in ventilation occurs even before an increase of H+ in blood**
2. **Partial pressures of Po_2 and Pco_2 in the blood**
3. **Proprioceptors in joints**
4. **Increases in temperature (hypothalamus)**
5. **Stress (Adrenalin release)**
6. **Learned responses ***

Respiratory control center (brain stem)

Ventilatory muscles

* With repeated exercise the brain becomes more accurate at providing the right signal to keep Pco_2 at normal level.

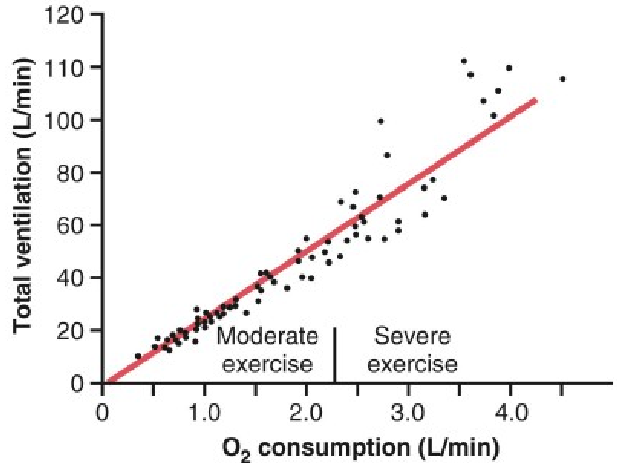


Figure 42-9. Effect of exercise on oxygen consumption and ventilatory rate. *(From Gray JS: Pulmonary Ventilation and Its Physiological Regulation. Springfield, Ill: Charles C Thomas, 1950.)*

Pulmonary Ventilation Control

- The respiratory centres in **pons and medulla oblongata** control the movements of primary breathing muslces and set the rate and depth of breathing (involuntary breathing control)
- **Chemoreceptors** respond to increases in CO2 and H+ concentrations or to decreases in blood oxygen levels by increasing respiration
- Ventilation increases at the initiation of exercise due to inspiratory stimulation from muscle activity. As exercise progresses, increase in muscle temperature and chemical changes in the arterial blood further increase ventilation

Signals for Ventilation Increase

- The diffusing capacity for oxygen increases almost three fold during exercise – mainly due to an increased number of active capillaries
- Blood flow at rest – blood stays in the capillaries longer than necessary – shortened time during exercise in sufficient for oxygenation

	O_2 Diffusing Capacity	CO_2 Diffusing Capacity	O_2 Consumption
AT REST	21 ml/min/mmHg	21x**20** ml/min/mmHg	250 ml/min on average
DURING EXERCISE	65 ml/min/mmHg *	65x**20** ml/min/mmHg	3600 ml/min untrained up to 5000 ml/min marathon runner

* Due to increased number of open pulmonary capillaries (increased surface area for diffusion), increased alveolar ventilation

A) Breathing frequency (BF) or Respiratory Rate (RR)

Breathing frequency is the number of breaths taken within a set amount of minute:

BF rest = 16 (breaths per minute) (10 in endurance) (12-15 on average)

BF (light exercise) = 20-30

BF (moderate exercise) = 30-40

BF (heavy exercise) = 50-60

B) Tidal volume (TV)

Tidal volume (TV [l]) is the amount of air inspired or expired during normal quiet respiration.

V_T rest = 0,5 l (1 l in endurance)

V_T (light exercise) = 1-1,5 l

V_T (moderate exercise) = 1,5-2 l

V_T (heavy exercise) = 2-3 l

C) Pulmonary ventilation (Minute Ventilation)

Minute Ventilation (V_E) is the product of tidal volume (TV) and breathing frequency (f):

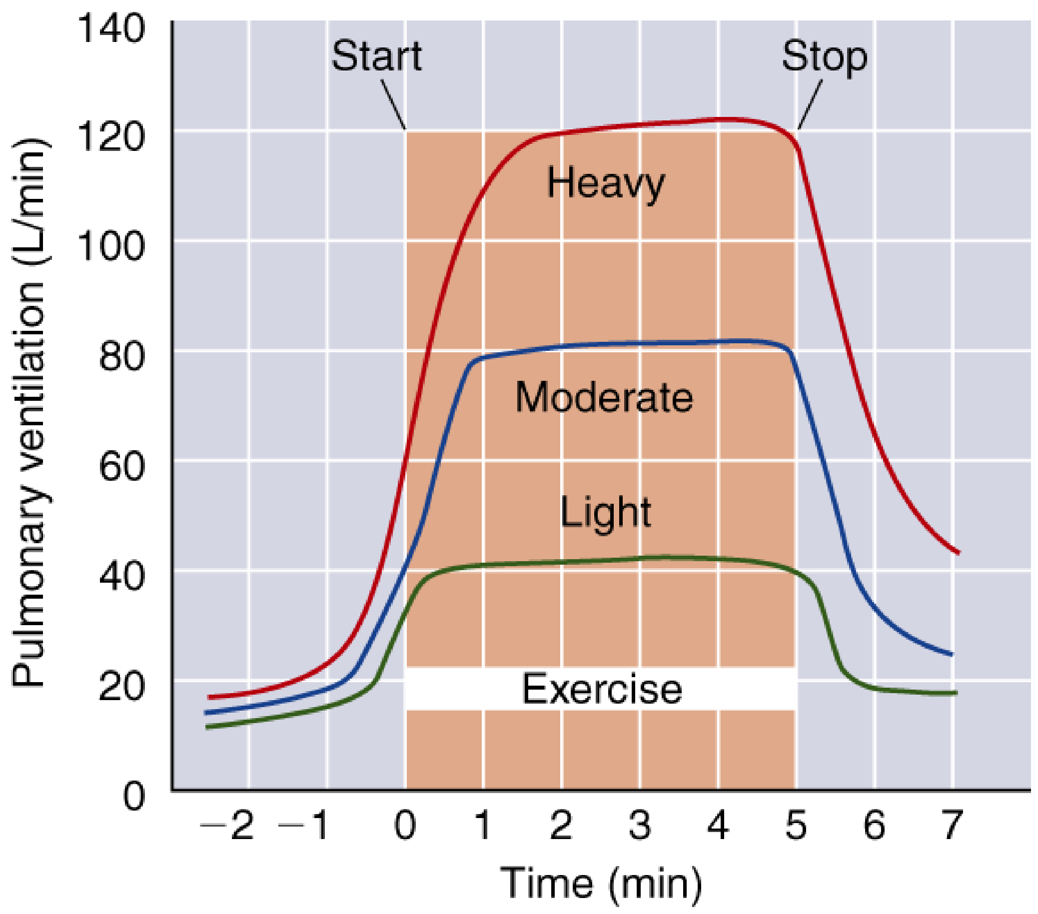
V_E rest = 8 l (e.g.: 0.5l x $15s^{-1}$ = 7.5l/min)

V_E (light exercise) = 40 l

V_E (moderate exercise) = 80 l

V_E (heavy exercise) = 120l (180l in endurance) (e.g.: 2.5l x $50s^{-1}$ = 125l/min)

Ventilatory Response to Exercise



Breathing Terminology

Dyspnea = shortness of breath

Hypervetilation = increase in ventilation that exceeds the metabolic need for oxygen. Voluntary hyperventilation, as is often done before underwater swimming, reduces the ventilatory drive by increasing blood pH

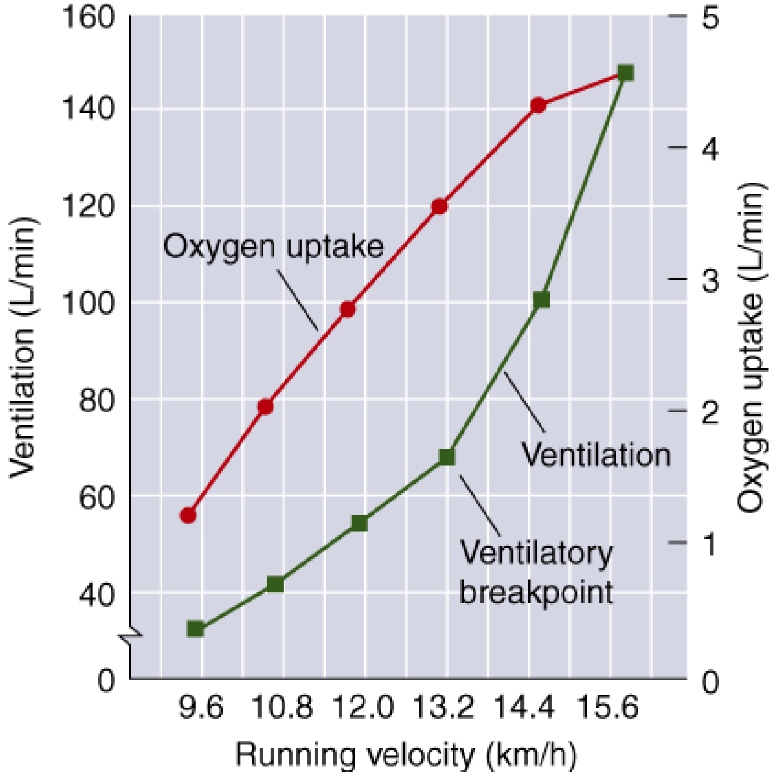
D) Ventilatory Equivalent for Oxygen

- The ratio between volume of oxygen expired per minute and consumed per minute or V_e and VO_2 in a given time frame
- Indicates breathing economy
- At rest — V_E/VO_2 = 23 to 28 L of air breathed per L VO_2 per minute
- At max exercise—V_E/VO_2 = 30 L of air per L VO_2 per minute
- **Generally V_E/VO_2 remains relatively constant over a wide range of exercise levels**

E) Ventilatory Breakpoint

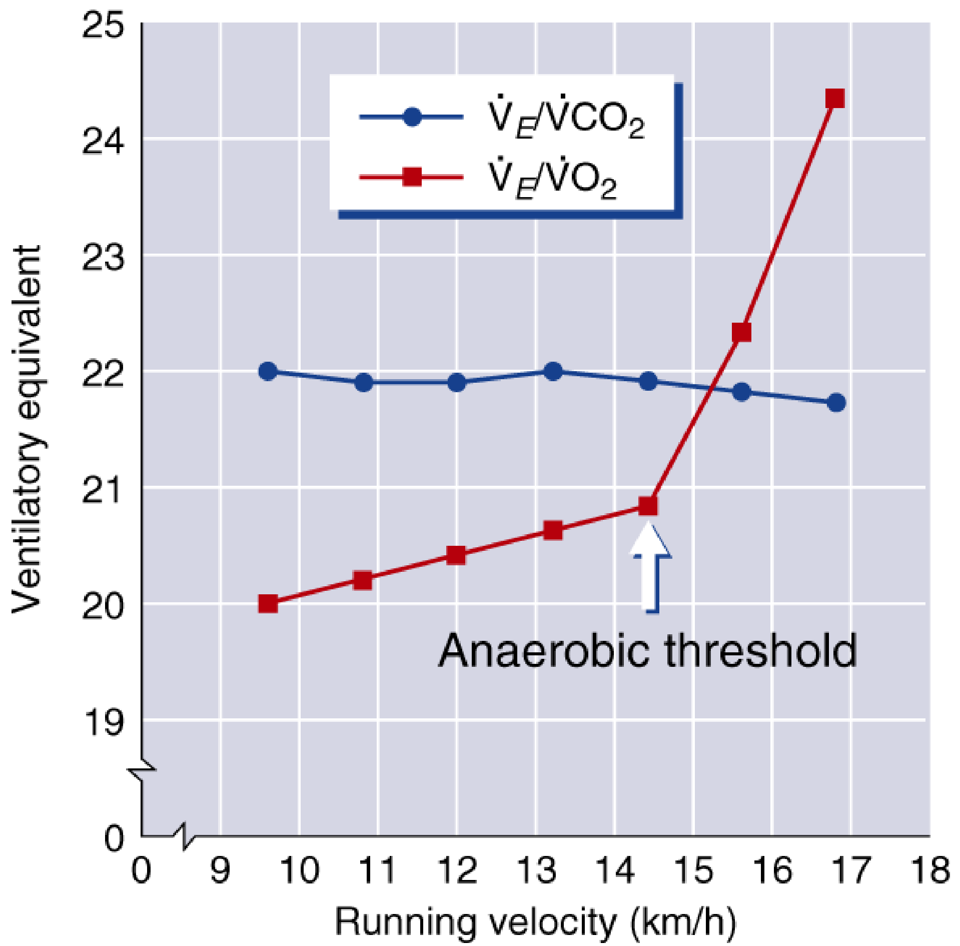
- The point during intense exercise at which ventilation increases disproportionately to the oxygen consumption
- When work rate exceeds 55% to 70% VO_2max, oxygen delivery can no longer match the energy requirements so energy must be derived from **anaerobic glycolysis**
- Anaerobic glycolysis **increases lactate levels**, which **increase CO_2 levels** (buffering)
  – detected by chemoreceptors
  – triggering a respiratory response and **increased ventilation**

Running speed (km/h)	$\dot{V}_E/\dot{V}O_2$
9.6	21.5
10.8	20.0
12.0	20.4
13.2	20.3
14.4	24.9
15.6	33.3

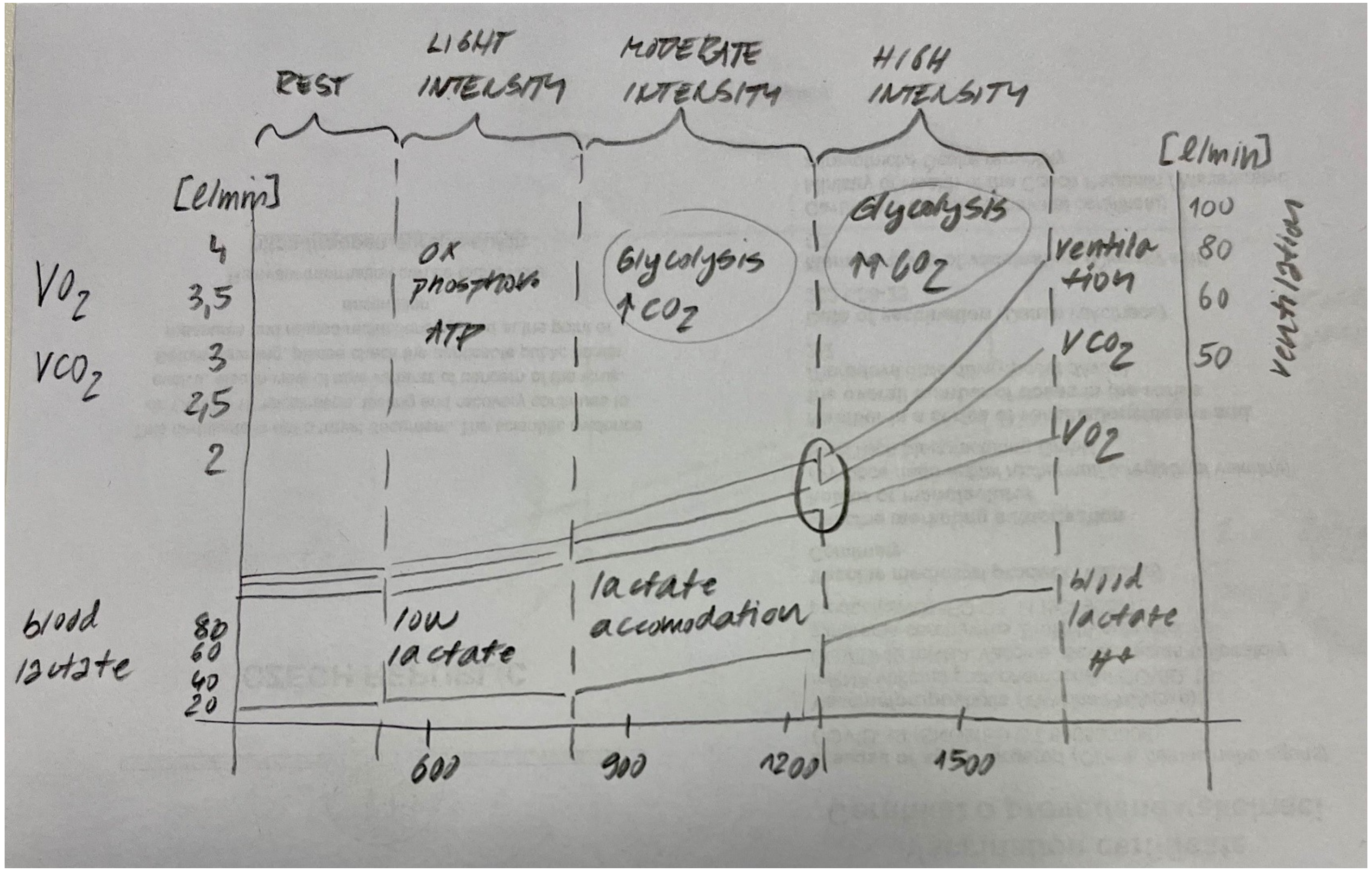


F) Anaerobic Threshold

- The point during intense exercise at which **metabolism** becomes **increasingly more anaerobic**
- Glycolysis as the main source of ATP
- Reflects the lactate threshold under most conditions, though the relationship is not always exact
- An increase in $\mathbf{V_E/VO_2}$ without an concomitant increase in the ventilatory equivalent for carbon dioxide (V_E/VCO_2)



F) Anaerobic Threshold



- Different exercise intensities
- Different source of ATP
    - oxidative phosphorylation; glycolysis
- Reducing the CO2 levels
- Lactate levels (low; accommodation; high)
- Ventilation increase

Ventilatory Breakpoint, Anaerobic Threshold

- During mild, steady-state exercise, ventilation parallels oxygen uptake
- The ventilatory breakpoint is the point at which **ventilation increases disproportionately to the increase in oxygen consumption**
- The anaerobic threshold is identified as the point at which **V_E/VO_2 shows a sudden increase**, while **V_E/VCO_2 stays stable**. It generally reflects lactate threshold

VO_2 Adaptations to Training

Oxygen consumption (VO_2) is

- unaltered or slightly increased at rest
- unaltered or slighted decreased at submaximal rates of work
- increased at maximal exertion (VO_2max—increases range from 0% to 93%)

Factors Affecting VO_2max

Level of conditioning — the greater the level of conditioning the lower the response to training

Heredity — accounts for slightly less than 50% of the variation as well as an individual’s response to training

Age — decreases with age are associated with decreases in activity levels as well as decreases in physiological function

Sex — lower in women than men (20% to 25% lower in untrained women; 10% lower in highly trained women)

Specificity of training — the closer training is to the sport to be performed, the greater the improvement and performance in that sport

Responses to Exercise – Overview

Responses – short term change in physiological function

Sympathetic nervous system responses:

1. Increase in breathing rate (respiratory rate **RR**) – after exercise remains elevated up to 2 hours post exercise (depending on cardiovascular fitness)
2. Increase in Tidal Volume (**TV**; amount of air inhaled per one breath) up to vital capacity
3. Results in increased Minute Ventilation ($\mathbf{V_E}$)

Adaptations to Training – Overview

Adaptations – long term changes in anatomical structure

1. Increased **Vital Capacity** of lungs (minimal and limited due to genetic factors)
2. Stronger **Respiratory Muscles** – diaphragm, intercostal muscles (internal and external) – greater pressure gradient makes the air to flow faster;
3. Faster **O_2 and CO_2 diffusion** – increased capillarization of alveoli (angiogenesis)

Thank You!

Questions?