“She talks so that you can barely hear her. She talks on the exhale, because she cannot talk on the inhale which means that her sentences are interrupted 15 times each minute, for the breathing machine to make her breathe, which makes conversations with her quite leisurely, long pauses in the sentences, and everyone learns to be patient ...” Lorenzo Milam, writing about his sister, 1984
Why does air move into and out of the lungs?
The pressure changes within the thorax during respiration and affects gas movement

- Muscles (internal and external intercostals) are under involuntary control with voluntary over-ride). They contract and expand rib cage

- Movement of air into and out of the lungs is called pulmonary ventilation

- Air moves down a pressure gradient, from high pressure to low pressure

- **Inspiration** (external intercostals contract)
  - Pressure in alveoli < atmospheric pressure so air moves into lungs

- **Expiration** (internal intercostals contract)
  - Pressure in alveoli > atmospheric pressure so air moves out of lungs
The pressure changes within the thorax during respiration and the effect on gas movement (cont)

- Enlargement of the thorax → inflow of air
- Contraction of diaphragm
- Contraction of intercostal muscles → cranial & outward movement of ribs

Requires energy

Can be passive i.e. not require energy
Inspiration - breathing in
EXPIRATION – breathing out

- ↓ size of thorax & lungs → air moves out
- Contracted external intercostal muscles relax
  - Ribs & diaphragm return elastically to rest position
  - Chest volume ↓ → pressure ↑ → air forced out of lungs
- Passive process
  - If ↑ effort needed → internal intercostal and abdominal muscles contract
Main points to remember from this slide:
Pleural sac pressure is about -4mm Hg
Inspiration is an active process, requires energy.
Quiet expiration is by elastic recoil plus active contraction of intercostals if greater force required.
(a) Water-filled balloon

(b) Lollipop

Fig. 11-14, p.477
How does a “collapsed lung” happen?
Outline the physiology of respiration including gas exchange, ventilation, $O_2$ and $CO_2$ transport in the blood.

Some laws of physics are unavoidable …
Outline the physiology of respiration including gas exchange, ventilation, O2 and CO2 transport in the blood

PHYSICS of the RESPIRATORY SYSTEM

1. Rate of diffusion increases with increased surface area and thinner membranes (Ficks Law of Diffusion)

2. Partial pressure of a gas depends on its concentration in moles as a proportion of the total gases. Sum of all the partial pressures = total pressure of gas mixture (Daltons Law of Partial Pressures)

3. In a liquid, the equilibrium concentration of gas is proportional to its partial pressure (Henry’s Law)
In a liquid, the equilibrium concentration of a gas is proportional to its partial pressure (Henry’s Law). The more gas above the liquid $\Rightarrow$ more gas dissolves in the liquid.

Starting condition: no $O_2$ in solution

At equilibrium

\[ P_{O_2} = 100 \text{ mm Hg} \]
\[ [O_2] = 5.2 \text{ mmol/l} \]

\[ P_{O_2} = 0 \text{ mm Hg} \]
\[ [O_2] = 0.15 \text{ mmol/l} \]
4. For a given quantity of any gas in an airtight container, the pressure is inversely related to the volume of the container (Boyle’s Law)

- So if you:
  - Decrease the volume you will increase the pressure
  - Increase the volume, you will decrease the pressure
For a given quantity of a gas in an airtight container, the pressure is inversely related to the volume of the container (Boyle’s Law).

So if you decrease the volume you will increase the pressure; and increase the volume, you will decrease the pressure.
Outline the physiology of respiration including **gas exchange**, ventilation, $O_2$ and $CO_2$ transport in the blood (cont)

**Summary:**

- Partial pressure shown as symbol $P$:
  - E.g. $PO_2$, $P_{V}O_2$, $P_{A}O_2$

- Gas moves from high pressure to low pressure

- Concentration of a gas in a mixture gas is proportional to its partial pressure. Concentration of a gas dissolved in a liquid is proportional to its partial pressure.
  - $CO_2$ is highly soluble, $O_2$ less soluble, $N_2$ very low solubility

- $PO_2$ in atmosphere is important $\rightarrow \downarrow$ with altitude. Impact on training and acclimatisation
Summary continued

$O_2$ & $CO_2$ diffuse due to their different partial pressures:

- $PO_2$ in alveolus > $PO_2$ in venous blood $\therefore$ $O_2$ diffuses from alveolar air into alveolar venous capillary
- $PCO_2$ in blood > $PCO_2$ in alveolus $\therefore$ $CO_2$ moves out from capillary blood into alveolar air
Transport of oxygenated and deoxygenated blood around the body. You just need to know the flow routes and which is oxygenated and which is de-oxygenated, not the numbers in the surrounding graphs.
Movement of air in & out of lungs:

- Little or no gas exchange in large diameter airways (trachea, bronchi, bronchioles): “anatomic dead space”

Alveolar ventilation:

- “Used” and “fresh” air mixes in alveoli
- So air in alveoli contains less $O_2$ & more $CO_2$ compared to atmospheric air (Not an efficient system. Bird does it better)

The efficiency of ventilation:

- Smooth muscle contraction can narrow airway diameters and increase resistance to gas movement. So autonomic nervous system can increase overall resistance of airways
- Can get ventilation perfusion mismatch eg in a horse lying down under anaesthesia. Part of lung that has most blood supply is different to part of lung that has best air supply
Outline the physiology of respiration including gas exchange, ventilation, **O₂** and **CO₂** transport in the blood.

The air - blood barrier in the lung
Outline the physiology of respiration including gas exchange, ventilation, O₂ and CO₂ transport in the blood.

- In blood in alveolar capillaries:
  - Most O₂ is bound to haemoglobin (Hb)
  - A small amount of O₂ is dissolved in solution

- 1 molecule of Hb can carry 4 molecules O₂

- Saturation of Hb molecules with O₂ depends on partial pressure of O₂ (O₂ molecules dissolved in blood). More oxygen in contact with Hb, greater the saturation of Hb
Reminder - transport of oxygenated and deoxygenated blood around the body
Through lungs, then to rest of body …
From lungs

Alveolus in lungs

$P_O_2 = 100 \text{ mm Hg}$

$P_O_2 = 40 \text{ mm Hg}$

Pulmonary capillaries

To body

Systemic capillaries

$P_O_2 = 100 \text{ mm Hg}$

$P_O_2 = 40 \text{ mm Hg}$

$P_O_2 \leq 40 \text{ mm Hg}$

From lungs to body:
- Oxygen enters the blood in the lungs at $P_O_2 = 100 \text{ mm Hg}$.
- Oxygen flows through the pulmonary capillaries at $P_O_2 = 40 \text{ mm Hg}$.

To body:
- Oxygen is transferred from the blood to the tissue cells at $P_O_2 \leq 40 \text{ mm Hg}$.
Outline the physiology of respiration including gas exchange, ventilation, O2 and CO2 transport in the blood.

**OXYGEN-HAEMOGLOBIN CURVES**

With increasing oxygen the % saturation of Hb increases until it reaches a plateau maximum. The Hb is 100% saturated and cannot carry any more O2.

If the animal is anaemic, the plateau of 100% saturation of its Hb is reached sooner at lower total O2 carried.
At higher temperature, Hb can carry less \( \text{O}_2 \) so fish in warm water need more Hb in their blood than cold water fishes.
The physiology of respiration including gas exchange, ventilation, O\textsubscript{2} and CO\textsubscript{2} transport in the blood (cont)

- CO\textsubscript{2} is much more soluble in water than O\textsubscript{2}
- So transport of CO\textsubscript{2} in blood is easier:
  - 5-6% CO\textsubscript{2} dissolved
  - 5-8% bound to Hb
  - 86-90% dissolved as bicarbonate ions (HCO\textsubscript{3}\textsuperscript{-})
- Bicarbonate ions form in RBC with help of enzyme carbonic anhydrase
- Reminder: ↑ blood CO\textsubscript{2} ⇔ ↑ H\textsuperscript{+} & HCO\textsubscript{3}\textsuperscript{-} ⇔ ↓ blood pH
Outline the physiology of respiration including gas exchange, ventilation, \( \text{O}_2 \) and \( \text{CO}_2 \) transport in the blood (cont)

\( \text{CO}_2 \) produced in the tissues travels in the blood from the tissue cells to the alveoli of the lungs
Different lung volumes, capacities and their significance

- Minute ventilation ($V_E$) = Tidal volume (VT) $\times$ Respiration Rate
  - VT = volume of air in each breath, which ventilates the alveoli & airways

- 1 respiratory cycle = 1 inspiration + 1 expiration

- Continuous cycles = Respiration Rate (RR)
  - Measured as breaths per min (or other unit of time)

- There is a range of normal values, depending on fitness level and $O_2$ demand at the time
Lung Volumes and Capacities for a Healthy 70-km Male

**Lung Volumes**

- $V_T$: Tidal volume = 500 mL
- IRV: Inspiratory reserve volume = 3000 mL
- ERV: Expiratory reserve volume = 1000 mL
- RV*: Residual volume* = 1200 mL

**Lung Capacities**

- IC: Inspiratory capacity = $V_T$ + IRV = 3500 mL
- VC: Vital capacity = $V_T$ + IRV + ERV = 4500 mL
- FRC: Functional residual capacity = ERV + RV = 2200 mL
- TLC: Total lung capacity = $V_T$ + ERV + IRV + RV = 5700 mL

*Cannot be measured by spirometry
How is respiration controlled?

- Respiratory control centre is in the medulla oblongata and pons of brain stem

- Chemoreceptors detect chemical signals:
  - Amount of CO$_2$ in blood (& conversion to H$^+$) via pH

- Reflex signals can over-ride
  - Changes in environment eg dive response
Respiratory control centers in the brainstem:

- **Pons respiratory centers**
  - Pneumotaxic center
  - Apneustic center
  - Pre-Bötzinger complex
- **Medullary respiratory center**
  - Dorsal respiratory group
  - Ventral respiratory group

Medulla
Conscious control

\[ \uparrow \text{CO}_2 \quad \downarrow \text{pH} \quad \downarrow \text{O}_2 \]

Higher brain centers

Medullary chemoreceptors

Carotid and aortic body chemoreceptors

Limbic system

Pons

Afferent sensory neurons

Central Pattern Generator (Medulla oblongata—Pre-\text{I}+ \text{pre-Bötzinger complex})

Somatic motor neurons

Intercostal muscles and diaphragm

\[ \uparrow \text{Rate and depth of ventilation} \]

Negative feedback

Heart

Sensory nerve fiber

Carotid sinus

Carotid body

Carotid artery

Aortic arch

Aortic bodies
Arterial $P_{O_2} < 60$ mm Hg

Relieves

Emergency life-saving mechanism

Peripheral chemoreceptors

Medullary respiratory center

↑ Ventilation

↑ Arterial $P_{O_2}$

No effect on

Central chemoreceptors
↑ Arterial $P_{CO_2}$

(when arterial $P_{CO_2}$ > 70–80 mm Hg)

↑ Brain-ECF $P_{CO_2}$

$\text{CO}_2 + \text{H}_2\text{O} \xrightarrow{\text{ca}} \text{H}^+ + \text{HCO}_3^-$

↑ Brain-ECF $\text{H}^+$

Peripheral chemoreceptors → Medullary respiratory center → ↑ Ventilation → ↓ Arterial $P_{CO_2}$

Relieves
An alternative diagram:

Control centers in the brain regulate breathing.
Some pathological conditions of the respiratory system – What can go wrong?

- Hypoxia and hyperoxia = lower / higher $O_2$ than normal in blood
- Hypercapnia and hypocapnia = higher / lower $CO_2$ than normal in blood
  - **Hypercapnia** = $\uparrow CO_2$ in the blood. Can be due to hypoventilation for any reason e.g. rebreathing exhaled $CO_2$, reduced consciousness or lung disease. Associated with $\downarrow pH$ (as CO2 is an acidic gas) and an increase in respiration (breathing) rate.
- Emphysema = the air sacs of the lungs are damaged and enlarged, causing breathlessness and possibly hypercapnia.
- Pneumonia = lung inflammation due to bacterial or viral infection. The air sacs fill with pus and may become solid
- Anoxia = no oxygen, as in tissues
- Bronchitis = infection / inflammation of bronchi
- Apnea = breath-holding
- Hyperventilation and hypoventilation …
Hyperventilation and hypoventilation ...

(a) Hypoventilation

- Arterial blood: \( \uparrow P_{CO_2}, \uparrow [H^+], \downarrow P_{O_2} \)
- Chemoreceptors: Detect and respond
- Respiratory control center
- \( \downarrow \) Ventilation

(b) Hyperventilation

- Arterial blood: \( \downarrow P_{CO_2}, \downarrow [H^+], \uparrow P_{O_2} \)
- Chemoreceptors: Detect and respond
- Respiratory control center
- \( \downarrow \) Ventilation
What is a hiccup?

- Also called “singultus”
- Irritation of the diaphragm – eg by an air bubble in the cranial part of the stomach, causes an involuntary (reflex) contraction of the diaphragm.
- Once triggered, the reflex causes a strong contraction of the diaphragm followed about 0.25 seconds later by closure of the vocal cords, which results in the classic "hic" sound.
- How to fix – hold your breath (↑CO₂ in blood inhibits reflex), drink water (displaces air bubble), hang upside down (moves air bubble more caudo-laterally).
- Foetus even does it *in utero* (associated with myelination of phrenic nerve)
Relate basic mammalian respiration to adaptations in different animals (fish, birds, reptiles)
http://www.biozoomer.com/2013/01/respiratory-organs-of-fish-frog.html
http://milksnakeresource.weebly.com/respiratory-system.html
Fish

Water flows in through mouth

Fish gill

Water flows over gills, then out.

http://www.biozoomer.com/2013/01/respiratory-organs-of-fish-frog.html
Relate basic mammalian respiration to adaptations in different animals (fish, birds, reptiles)

- Unidirectional air movement during inspiration and expiration
- Air sacs (no diaphragm)
- **Gas exchange in parabronchi of lungs** (no alveoli)
- More efficient:
  - Needed for higher metabolic rate
  - ↑ oxygen saturation of Hb at low atmospheric concentrations of oxygen (altitude)
Birds

http://www.peteducation.com/article.cfm?c=15+1829&aid=2721
Deep-diving mammals

- Seals, whales, dolphins are capable of long underwater dives
- Weddell seal → 5% O₂ in lungs, 70% in blood
- Huge spleen stores huge volumes of blood
- Large concentrations of myoglobin in muscles
- Heart rate and O₂ consumption rate decrease
- Blood is redirected from muscles to brain spinal cord and eyes

- “Bohr Shift” helps too – additional oxygen can be released from Hb at lower pH i.e. when higher levels of CO₂ (Moves Hb-O₂ saturation curve to the right)
Pinnipeds (seals) and cetaceans (whales)

- During diving, animals show voluntary apnoea ranging from a few minutes to more than an hour.
- Conducting airway walls are strengthened (thicker cartilage rings) in order to handle gases at higher pressure.
  - Oxyhaemoglobin provides $O_2$ reserve.
  - Again Bohr Shift releases extra oxygen as $\uparrow CO_2$ drives $\downarrow pH$.
Respiratory adaptations of other animals – Players of the didgeridoo: “Circular breathing”

http://www.slideshare.net/seasprite/presentation-10-respiration-and-gas-exchange-presentation?next_slideshow=1

http://www.slideshare.net/neutromec/ppt-respiratory-system-physiology

www.forthecontemporaryflutist.com
Learning Objectives

- Outline the functions of the respiratory tract.
- Describe the gross anatomy of the respiratory system.
- Outline the passage of air from the atmosphere to the alveoli.
- Relate respiratory tract anatomy to function.
- Outline the physiology of respiration including gas exchange, ventilation, O₂ and CO₂ transport in the blood.
- Describe the pressure changes within the thorax during respiration and explain their effect on gas movement.
- Describe different lung volumes and capacities and explain their significance.
- Describe how respiration is controlled.
- Outline some pathological conditions of the respiratory system
- Relate basic mammalian respiration to adaptations in different animals (fish, birds, reptiles)