CHAPTER 2 - PULMONARY FUNCTION, TRANSPORT OF BLOOD GASES, CARDIAC & VASCULAR FUNCTION

Text between pages 27 and 51, answers to questions on pages 48 to 51 of the textbook.

1) a) A hockey player has a match in one hour’s time. Describe how inspiration occurs during this resting period.

Answer
- External intercostal muscles and diaphragm contract.
- Internal intercostal muscles relax.
- The action of these contracting muscles is to increase the volume of the thoracic cavity.
- As pleural and pulmonary pressures are reduced (air pressure within the lungs is reduced as their volume expands).
- Air in the lungs is at lower pressure than the air in the atmosphere outside.
- Since air moves from areas of high pressure to areas of low pressure.
- Air rushes into the lungs.

b) During the hockey match, the player must increase the volume of gas exchanged in the lungs and muscles. Explain the changes in the mechanics of breathing (inspiration and expiration) which facilitate this increase.

Answer
During inspiration:
- Additional respiratory muscles contract.
- Namely sternocleidomastoid, scalenes and pectoralis minor.
- Effect is that the diaphragm contracts and flattens (moves downward away from the lungs) with more force.
- Increased lifting of sternum.
- Which gives increased thoracic cavity volume.
- Decreased pleural and pulmonary pressures (within the lungs).
- Lower pulmonary air pressure.
- So the pressure of air outside is still bigger than inside.
- More air rushes into the lungs.

During expiration:
- Active respiratory muscles contract.
- Namely internal intercostal and rectus abdominus.
- The diaphragm relaxes and domes upward thereby compressing the lungs.
- The ribs and sternum are pulled in and down with more force.
- This decreases the size of the thoracic cavity volume.
- Gives increased pleural and pulmonary pressures (the pressure of the air inside the lungs is increased).
- So the air inside the lungs is at a higher pressure than the atmospheric air outside.
- More air is forced out of the lungs.
2) a) The diagram in figure 2.30 represents the lung volume changes based on a number of spirometer readings during various breathing actions. With reference to the trace, briefly explain resting tidal volume (TV), expiratory reserve volume (ERV), vital capacity (VC), and residual volume (RV).

**Answer**

**Definitions:**
- **Resting tidal volume** is that volume of air that is breathed in or out during one breath at rest.
- **Expiratory reserve volume** is that volume of air that can be forcibly expired over and above resting tidal volume.
- **Vital capacity** is the maximal volume of air that can be forcibly expired after maximal inspiration in one breath.
- **Residual volume** is that volume of air remaining in the lungs after maximal expiration.

b) Using the information in the spirometer trace, state what happens to the following volumes during the exercise period: residual volume (RV), inspiratory volume (IRV), and expiratory volume (ERV).

**Answer**
- Residual volume remains the same.
- IRV decreases.
- ERV decreases.

c) Why does tidal volume change by only a small amount during the exercise period?

**Answer**
- Major respiratory regulator is carbon dioxide.
- Which controls rate of breathing (f).
- And depth (TV) of breathing.
- Effect of exercise is to increase pCO₂.
- And stimulate a bigger increase in breathing rate when compared with tidal volume.
- So that the increased levels of CO₂ are removed quickly from the body.

d) Identify two effects of regular aerobic training on lung volumes and capacities.

**Two effects from the following:**

**Answer**
- Improved strength of respiratory muscles.
- Increase in TV, VC at expense of RV.
- At submaximal workloads slight decrease in frequency of breaths.
- During maximal workloads big increase in frequency of breaths, hence big increase in minute ventilation.
- Hence increased gaseous exchange and VO₂max.
- At submaximal workloads VO₂max will be less because of greater efficiency of O₂ uptake.
2) e) A student measured the volume of air that he or she ventilated at rest and during submaximal exercise. The results are shown in table 2.7 below.

Table 2.7 – ventilation at rest and during submaximal exercise

<table>
<thead>
<tr>
<th>activity level</th>
<th>inhalation volume (TV)</th>
<th>breathing rate (f)</th>
<th>minute ventilation volume (VE)</th>
</tr>
</thead>
<tbody>
<tr>
<td>at rest</td>
<td>500 ml</td>
<td>one every 6 seconds</td>
<td>A</td>
</tr>
<tr>
<td>submaximal exercise</td>
<td>800 ml</td>
<td>one every 2 seconds</td>
<td>B</td>
</tr>
</tbody>
</table>

Define what is meant by the term ‘minute ventilation volume’ and calculate the values for A and B, clearly showing the method used.

**Answer**

- Minute ventilation volume is the volume of air inspired or expired in one minute - notated as VE.
- It is a combination of tidal or inhalation volume (TV) and breathing rate (f).

\[
VE = TV \times f
\]

- At rest:
  \[
  VE = 500 \times 10 = 5,000 \text{ ml min}^{-1} = 5 \text{ dm}^3 \text{ min}^{-1} = 5 \text{ litres min}^{-1}.
  \]
- During submaximal exercise:
  \[
  VE = 800 \times 30 = 24,000 \text{ ml min}^{-1} = 24 \text{ dm}^3 \text{ min}^{-1} = 24 \text{ litres min}^{-1}.
  \]

3) a) Describe how pulmonary ventilation is regulated during quiet breathing.

**Answer**

- Pulmonary ventilation is regulated by the respiratory control centre (RCC), located within the medulla oblongata of the brain.
- The RCC consists of two parts: the inspiratory and expiratory centres.
- The inspiratory centre is responsible for the basic rhythm of ventilation.
  - At rest impulses are sent via the phrenic and intercostal nerves to the external intercostal muscles and diaphragm.
  - Causing these muscles to contract to bring about inspiration.
  - When stimulation ceases these muscles relax causing expiration.
- The expiratory centre is inactive during quiet breathing.
- The apneustic centre controls the intensity of breathing. It does this by prolonging the firing of the inspiratory neurones, thereby increasing lung volumes.
- The pneumotaxic centre does the opposite of the apneustic centre, resulting in the fine-tuning of the breathing rate.

b) Identify the three chemical stimuli that control the rate and depth of breathing. How do these chemical stimuli control respiration during exercise?

**Answer**

- Partial pressure of carbon dioxide \((pCO_2)\) is the major regulator of respiration.
- Partial pressure of oxygen \((pO_2)\).
- Acidity \((pH)\).

How do these chemical stimuli control respiration during exercise?

- Effect of exercise is to increase the production of \(CO_2\) and \(H^+\), and decrease \(O_2\) and pH.
- An increase in pCO\(_2\) or a decrease in pH stimulates the peripheral and central chemoreceptors.
- Which send nerve impulses into the inspiratory control centre in the medulla.
- Then out via the phrenic and intercostal nerves to the respiratory muscles.
- Which contract more forcefully (increased lung volumes) and more frequently (increased \(f\) – frequency of breathing).
- The response is to decrease pCO\(_2\) levels and increase pH and pO\(_2\).
4) The breathing characteristics of individuals vary during physical activity. Table 2.8 shows the proportion of oxygen and carbon dioxide breathed during exercise compared with resting values.

Table 2.8 – proportion of \( O_2 \) and \( CO_2 \) breathed during exercise, compared to at rest

<table>
<thead>
<tr>
<th></th>
<th>inhaled air</th>
<th>exhaled air at rest</th>
<th>exhaled air during exercise</th>
</tr>
</thead>
<tbody>
<tr>
<td>%( O_2 )</td>
<td>21</td>
<td>17</td>
<td>15</td>
</tr>
<tr>
<td>%( CO_2 )</td>
<td>0.049</td>
<td>3</td>
<td>6</td>
</tr>
</tbody>
</table>

a) Use the information in table 2.8 to describe the effects of exercise on gaseous exchange in the lungs. Explain why these changes occur. 4 marks

**Answer**

**The effects of exercise on gaseous exchange:**
- Exhaled oxygen decreases from 17% to 15%.
- Exhaled carbon dioxide increases from 3% to 6%.

**Explain why these changes occur:**
- This is because increased amounts of oxygen are required by skeletal muscle during aerobic tissue respiration.
- With a corresponding amount of carbon dioxide being produced as a waste product.

b) How does the blood transport oxygen? 2 marks

**Answer**

- \( Hb + 4O_2 \rightarrow Hb(O_2)_4 \)
- Or transported as oxyhaemoglobin.
- 3% of oxygen is dissolved in blood plasma.

c) Explain how oxygen is exchanged between the blood and active muscle tissues. 3 marks

**Answer**

- Gas molecules, such as oxygen, **diffuse** from high to low pressure - called a **diffusion gradient**.
- Arriving oxygen partial pressure (\( pO_2 \)) in arterial blood is greater than oxygen partial pressure in tissue.
- Myoglobin in the tissue cells has a greater affinity for \( O_2 \) than haemoglobin in the arriving blood.
- Therefore \( O_2 \) detaches itself from the haemoglobin in the blood and is released into active muscle cells.
- Myoglobin transports \( O_2 \) to the **mitochondria** for aerobic energy production.

d) Identify the three ways \( CO_2 \) is transported by the blood. How does increased \( CO_2 \) production stimulate further release of \( O_2 \) for tissue cell respiration? 5 marks

**Answer**

- **Carbonic acid (dissociated into \( H^+ \) and \( HCO_3^- \) ions)** (73%).
- **Carbaminohaemoglobin** (23%).
- **Dissolved in plasma** (7%).

**Method 1:**
- \( CO_2 \) combines with \( H_2O \) to form \( H_2CO_3 \).
- This acid is unstable and so releases \( H^+ \) to form a bicarbonate ion (\( HCO_3^- \)).
- The freed \( H^+ \) reacts with \( HbO_2 \) to form haemoglobin acid.
- Which triggers off the release of more oxygen for tissue cell respiration.
- \( H^+ + HbO_2 \rightarrow HHb + O_2 \)

**Method 2:**
- \( CO_2 \) combines with haemoglobin to form carbaminohaemoglobin.
- Which triggers off the release of more oxygen for tissue cell respiration.
- \( CO_2 + HbO_2 \rightarrow HbCO_2 + O_2 \)
5) The binding of oxygen to haemoglobin depends on $pO_2$ in the blood and the affinity of haemoglobin with oxygen. The curves in figure 2.31 show how different concentrations of carbon dioxide affect the saturation of haemoglobin at varying partial pressures of oxygen.

a) Explain what is meant by partial pressure of oxygen ($pO_2$). 1 mark

Answer
- The pressure that oxygen ($pO_2$) exerts within a mixture of gases.

b) What are the values of percentage saturation of haemoglobin on the three curves when the partial pressure of oxygen is 5.0 kPa? 3 marks

Answer
- Curve A - haemoglobin is fully saturated with oxygen – 100%.
- Curve B - haemoglobin is 68% saturated with oxygen.
- Curve C – haemoglobin is 55% saturated with oxygen.

c) What are the implications of the carbon dioxide values for curves B and C for an athlete? 2 marks

Answer
- The greater $pCO_2$ the less % of HbO$_2$ saturation.
- This is because as more energy is released by respiring muscle cells.
- More $CO_2$ is produced as a waste product.
- Diffusing across into the blood capillaries.
- Therefore the more $CO_2$ in the blood and surrounding the red blood cells (and hence the haemoglobin in the red blood cells), the less oxygen can be carried by the haemoglobin.
- This means that the difference (in the case of curve B at 5.0 kPa – this is $100-68 = 32\%$ of the oxygen carried).
- Detaches itself from the haemoglobin and diffuses into the muscle cells where it is available for respiration.
- When more $CO_2$ is present (during violent exercise) as in the case of curve C at $pCO_2 = 9.3$ kPa, at the same $pO_2$ (5.0 kPa) haemoglobin releases $100-55 = 45\%$ of the oxygen carried.
- So the more exercise, the more oxygen released and made available for more exercise.

d) Why is the partial pressure of oxygen ($pO_2$) important to the process of gaseous exchange? 3 marks

Answer
- The increased loading of $CO_2$ causes more unloading of $O_2$ from haemoglobin.
- And so more $O_2$ is released for tissue cell respiration to sustain the physical activity undertaken.

Importance of $pO_2$ in gaseous exchange in the alveoli:
- The $pO_2$ in the lung alveoli must be higher than the $pO_2$ in the pulmonary blood.
- In order for oxygen to diffuse into the bloodstream.

Importance of $pO_2$ in gaseous exchange at tissue cell sites:
- Similarly, the arterial $pO_2$ must be greater at the tissue site than in the tissue cells.
- In order for oxygen to diffuse into tissue cells.
6) Figure 2.32 shows a diagrammatic picture of the cardiac impulse. Using the information in this diagram, describe the flow of blood during the specific stages of the cardiac cycle, in relation to the cardiac impulse. In your answer explain how the heart valves help control the direction of blood flow. 8 marks

**Answer**

**Atrial and ventricular diastole:**
- During atrial and ventricular diastole there is no electrical impulse from the SA node.
- And so relaxed heart muscle chambers (atria and ventricles) fill with blood.
- From the venae cavae (on the right hand side of the heart).
- And the pulmonary veins (on the left hand side of the heart).
- As the *cuspid* valves open and the *semi-lunar* valves close.

Diastole is followed by systole consisting of two distinct phases:

**Atrial systole:**
- The SA node creates an electrical impulse.
- This causes a wave-like contraction over the atria myocardium.
- Forcing the remaining blood from the atrial chambers.
- Past the *cuspid* valves.
- Into the ventricles.

**Ventricular systole:**
- The impulse reaches the AV node.
- The *cuspid* valves close during ventricular systole.
- The impulse travels down the **bundle of His** to the **Purkinje fibres**.
- Across ventricular myocardium.
- Which then contracts as the *semi-lunar* valves open.
- Blood is forced out of the ventricles.
- Into the aorta (left hand side).
- And the pulmonary arteries (right hand side).
- *Myocardial contractions, during systole, are said to be myogenic or under involuntary nervous control.*

7) \( Q = SV \times HR \). Explain the meaning of this equation and give typical resting values that you would expect in an endurance-based athlete. 6 marks

**Answer**

- \( Q \) represents cardiac output – is defined as the volume of blood pumped by the left ventricle in one minute.
- And is a combination of \( SV \) – stroke volume is defined as the volume of blood pumped by the left ventricle of the heart per beat.
- \( x \) \( HR \) – heart rate is defined as the number of beats of the heart per minute (bpm).
- Typical resting values for an endurance-based athlete:
  \[
  Q = SV \times HR = 5.6 \text{ litres min}^{-1} = 110\text{ml} \times 51 \text{ (or same values in dm}^3 \text{ min}^{-1}).
  \]

8) A fit 18 year old female student performs a 400m time trial in one minute.

a) Sketch and label a graph to show a typical heart rate response from a point 5 minutes before the start of the run, during the time trial, and over the 20 minute recovery period. 4 marks

**Answer**

See graph in figure 2.33.

- a Anticipatory rise just before start of exercise.
- b Initial rapid increase in HR.
- c To reach \( HR_{max} \) at end of time trial.
- d Recovery initially rapid.
- e Tapering off slowly towards resting values.
8) b) Explain why heart rate takes some time to return to its resting value following the exercise period. 2 marks

Answer
- **There is a raised** $\text{O}_2$ **demand of active muscle tissue.**
- **There are raised** levels of $\text{CO}_2$.
- **And a build up of lactic acid** during high intensity work which takes time to clear.
- **Body organs** such as the heart, need additional $\text{O}_2$ above resting $\text{O}_2$ consumption.
- **This reflects the size of EPOC or oxygen debt.**
- **Hence HR values stay elevated above resting values until the oxygen debt is purged.**


c) Identify a hormone that is responsible for heart rate increases prior to and during an exercise period. 1 mark

Answer
- **Adrenaline** or noradrenaline.

d) Heart rate is regulated by neural, hormonal and intrinsic factors. How does the nervous system detect and respond to changes in heart rate during an exercise period? 4 marks

Answer
- **The cardiac control centre** (CCC) **responds to neural information.**
- **This is supplied by proprioceptors** and other reflexes.
- **Such as the baroreceptor** reflex, sensitive to changes in blood pressure.
- **And the chemoreceptor** reflex, sensitive to changes in $\text{CO}_2$ and pH levels.
- **For example, a decrease in pH** and an increase in $\text{CO}_2$ **levels increase the action of the sympathetic nervous system (SNS), via the accelerator nerve.**
- **To increase stimulation of the SA node.**
- **Thereby increasing heart rate.**

9) Running a marathon in hot conditions sets up a competition between the active muscles and the skin for limited blood supply. How does the human body respond to meet the needs of supplying oxygen to exercising muscle and how can the athlete control this response? 3 marks

Answer
- **Sympathetic nervous system stimulates increase in heart rate.**
- **To compensate for reduced blood volume (due to sweating).**
- **And decreased stroke volume as blood pools in the periphery.**
- **Known as the cardiovascular drift.**
- **Need to take regular drinks during run to keep the body rehydrated.**

10) Jodie Swallow is a top class female British Triathlete, and has a resting heart rate of 36 bpm. Give reasons why such an athlete might have a low resting heart rate. 4 marks

Answer
- **Due to bradycardia or slow heart beat.**
- **Effects of an aerobic endurance-based triathlete training programme is to produce cardiac hypertrophy** i.e. heart becomes bigger and stronger (mainly left ventricle).
- **Producing an increase in stroke volume (SV).**
- **And decrease in resting heart rate (HR_{rest}).**
- **A reduced resting heart rate allows for an increase in diastolic filling time.**
- **The net effect is that the heart does not have to pump as frequently for the same given resting oxygen consumption.**
11) Table 2.9 shows the rate of blood flow (in cm³ per minute) to different parts of the body in a trained male athlete, at rest and while exercising at maximum effort on a cycle ergometer. Study the data carefully before answering the following questions.

Table 2.9 – estimated blood flow at rest and during maximum effort

<table>
<thead>
<tr>
<th>organ or system</th>
<th>estimated blood flow in cm³ min⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>at rest</td>
</tr>
<tr>
<td>skeletal muscle</td>
<td>1000</td>
</tr>
<tr>
<td>coronary vessels</td>
<td>250</td>
</tr>
<tr>
<td>skin</td>
<td>500</td>
</tr>
<tr>
<td>kidneys</td>
<td>1000</td>
</tr>
<tr>
<td>liver &amp; gut</td>
<td>1250</td>
</tr>
<tr>
<td>other organs</td>
<td>1000</td>
</tr>
</tbody>
</table>

a) The rate of blood flow to the ‘entire body’ increases significantly during exercise. Explain briefly how the heart achieves this. 2 marks

Answer
• Increased heart rate.
• Increased stroke volume.
• Therefore increased cardiac output.

b) What percentage of the total blood flow is directed to the skeletal muscle at rest and during maximum effort? Show your calculations. 3 marks

Answer
The percentage of total blood flow directed to skeletal muscle at rest is:

\[
\frac{1000 \times 100}{5000} = 20\%.
\]

The percentage of total blood flow directed to skeletal muscle during maximal effort is:

\[
\frac{26400 \times 100}{30000} = 88\%.
\]

c) How is blood flow to various regions of the body controlled? 4 marks

Answer
• Achieved through vasomotor control.
• Which creates the vascular shunt.
• This is vasodilation, which is the expansion of arteries and arterioles, and relaxation of pre-capillary sphincters to increase blood flow to active muscle tissue.
• This is in response to a cessation of neural signals to the smooth muscle walls of these blood vessels.
• Also vasoconstriction, which is the restriction of arteries and arterioles, and contraction of pre-capillary sphincters to decrease blood flow to non-active tissue.
• This is a response to increased neural signals from baroreceptors which detect changes in cardiac output.
• These neural signals go to the smooth muscle walls of these particular blood vessels.
12) a) What is meant by the concept ‘venous return mechanism’?  

Answer  
Venous return is the transport of blood from the capillaries, through venules, veins and venae cavae to the right atrium of the heart.

b) Describe how it is aided during physical activity when a person is exercising in an upright position.  

Answer  
Venous return is aided by exercise due to increased actions of skeletal muscle and respiratory and cardiac pumps and limited action of venoconstriction of veins.

• Increased activity in skeletal muscle results from contracting and relaxing squeezing sections of veins.
• Therefore causing increased blood flow back towards the heart.
• Blood cannot flow the opposite way because of pocket valves placed every so often in each vein.

c) Explain the importance of the skeletal muscle pump mechanism during an active cool-down.  

Answer  
Skeletal muscles continue to contract to squeeze vein walls, forcing blood back towards the heart.

• Thereby preventing blood pooling and an associated sudden drop in blood pressure.
• And removing of waste products such as carbon dioxide and lactic acid.

d) What effect does enhanced venous return have upon cardiac output and stroke volume?  

Answer  
Stroke volume is dependent on the amount of venous return.

• Up to 70% of the total volume of blood is contained in the veins at rest.
• Increased venous return will cause myocardial tissue to be stretched even further.
• And so contract more forcibly.
• To increase stroke volume (Starling’s Law of the heart).
• Cardiac output is a combination of SV and HR.
• Therefore an increased stroke volume will create an increased cardiac output.

13) a) How is oxygen transported by the blood?  

Answer  
O₂ transport:

• Via attachment with haemoglobin Hb + 4O₂ → Hb(O₂)₄.
• Transported as oxyhaemoglobin (97%).
• Dissolved in plasma (3%).

b) Identify the main method whereby carbon dioxide is transported in venous blood.  

Answer  
CO₂ main transporter:

• Carbonic acid – 70% (which dissociates into H⁺ and HCO₃⁻).

c) Explain how increased levels of carbon dioxide levels affect performance during physical activity.  

Answer  
Chemoreceptors are sensitive to changes in carbon dioxide levels.

• When carbon dioxide levels increase the cardiac control centre (CCC in medulla oblongata) is alerted.
• CCC sends neural impulses to pacemaker.
• To increase heart rate, stroke volume and hence cardiac output.
• And increase rate and depth of breathing (f and TV) and hence minute ventilation (VE).
• And stimulating redistribution of blood – blood shunting mechanism.
• To transport more oxygenated blood to active tissues.
• At tissue cell site increased carbon dioxide production causes more unloading of oxygen from haemoglobin (Böhr effect).
14) A simple calculation of blood pressure can be written as:
Blood Pressure = Cardiac Output \times \text{Resistance to blood flow}

a) Identify one factor that affects resistance to the flow of blood within systemic blood vessels. 1 mark

Answer

One from the following list:

- **Friction** between moving blood and the walls of blood vessels.
- **Length** of blood vessels.
- **Diameter** or lumen width of blood vessels.
- **Viscosity** of blood.

b) Blood pressure is quoted as two numbers. An example would be resting values of 120/80 mmHg. Explain what each of these numbers refer to. 2 marks

Answer

- The first number (120 mmHg) refers to **systolic** blood pressure or blood pressure when heart (ventricles) is (are) contracting.
- The second number (80 mmHg) refers to **diastolic** blood pressure or blood pressure when heart (ventricles) is (are) relaxing.

c) How would these blood pressure values change during a game of football and a rugby scrum lasting 6 seconds? Give a reason for each of your answers. 3 marks

Answer

- During dynamic exercise such as a football game, an active player’s systolic blood pressure would rise.
- As a result of increased cardiac output.
- And diastolic blood pressure would remain at the same resting value.
- A 6 second isometric maximal exertion rugby scrum raises both systolic and diastolic blood pressures to force blood into the capillary bed.

A reason for each of your answers:

- Because this isometric position reduces the actions of the skeletal muscle and respiratory pumps.
- Which in turn reduces venous return, cardiac output, blood pressure and capillary blood flow.
- Therefore both systolic and diastolic pressures increase to force more blood through the capillaries of working muscles.

15) Table 2.10 identifies differences in total blood volume, plasma volume, and blood cell volume between untrained and highly trained endurance males (same age, height and body mass). Comment on the data that is presented in table 2.10 and suggest how the trained athlete would benefit from these increased volumes. 4 marks

Table 2.10 – blood volumes in trained and untrained males

<table>
<thead>
<tr>
<th>subjects</th>
<th>total blood volume (dm^3)</th>
<th>plasma volume (dm^3)</th>
<th>blood cell volume (dm^3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>trained male</td>
<td>7</td>
<td>4.2</td>
<td>2.8</td>
</tr>
<tr>
<td>untrained male</td>
<td>5.6</td>
<td>3.2</td>
<td>2.4</td>
</tr>
</tbody>
</table>

Answer

- One of the effects of endurance training is to increase blood volume, resulting primarily from an increase in plasma volume, but there is also a small increase in red blood cells as observed in the figures in table 2.10.

Benefits:

- A bigger plasma volume reduces blood viscosity and improves circulation and oxygen availability.
- A bigger red blood cell count, with **increased levels** of haemoglobin, is available in blood for increased oxygen transport and hence an increase in $V_{O_{2max}}$. 