Focus Area 1: In Movement

1.1 Application of energy sources affecting physical performance

- The contribution of energy systems in specific activities
- The interplay of energy systems
- Energy contributions and fatigue

The Contribution of Energy Systems in Specific Activities

ATP – The Immediate Energy Source

The human body requires a constant supply of energy to fuel all of our daily bodily functions, including physical activity. As physical activity increases, there is also an increased demand for energy due to increased muscular contractions. Ultimately, it is our capacity to transfer energy at a high rate to the contractile elements of the muscular system that determines our capacity for exercise.

An 'energy rich' molecule called adenosine triphosphate (ATP) is the universal and immediate usable form of chemical energy for all 'biological' work performed by any cell within the body. ATP is considered the energy 'currency' of the human body.

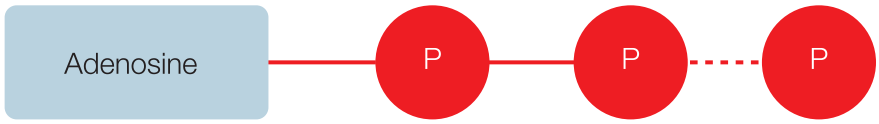

Figure 1.1.1: ATP consists of one adenosine molecule and three phosphate molecules.

The ATP molecule is very complex, but essentially its structure consists of a 'high energy' bond that glues the end two phosphate (P) molecules together. This connection contains a great deal of potential chemical energy, so when the phosphate bond is chemically broken, energy is released to allow the body's cells to perform work.

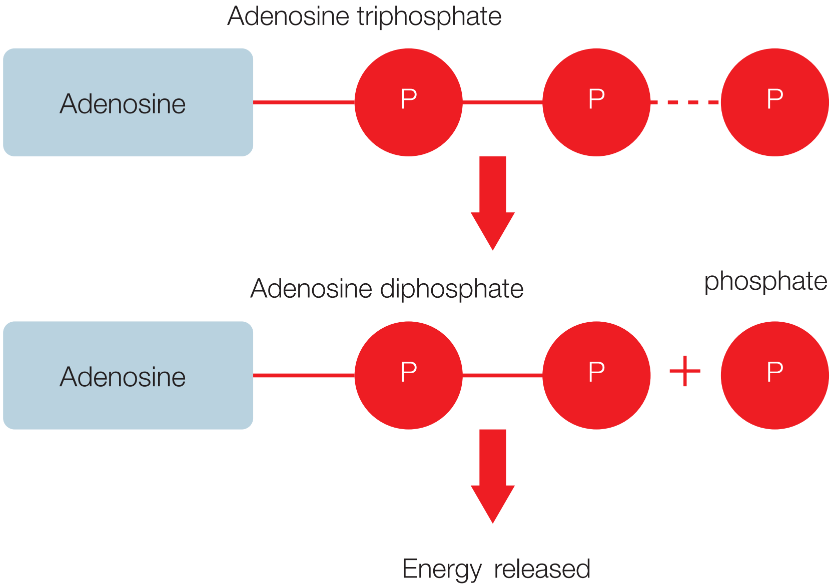

Figure 1.1.2: Energy stored inside the ATP molecule is released when the last phosphate (P) high energy-bond is broken forming the molecule ADP.

The chemical equation of this process can be represented as follows:

$$ATP \rightarrow ADP + P + ENERGY$$

Because ATP is stored directly in nearly every cell of the human body, the energy provided by the breakdown of ATP is used for all ‘biological’ functions including mechanical work (muscle fibres), nerve conduction (nerve cells) and secretion (endocrine cells) etc.

Although the ATP molecule is stored ‘onsite’ in all skeletal muscles ready to supply energy for muscular contractions, its stores are extremely limited. The muscles only have enough ATP to fuel approximately 2 seconds of maximal activity before ATP is fully exhausted.

Because the stored ATP is in such small supply and easily exhausted, the body needs to continually rebuild the ATP molecule to maintain a constant energy supply. The molecules required to rebuild ATP are found in the products of its initial breakdown – **adenosine diphosphate (ADP) + phosphate (P)**, but the rebuilding process also requires energy.

$$ADP + P + ENERGY \rightarrow ATP$$

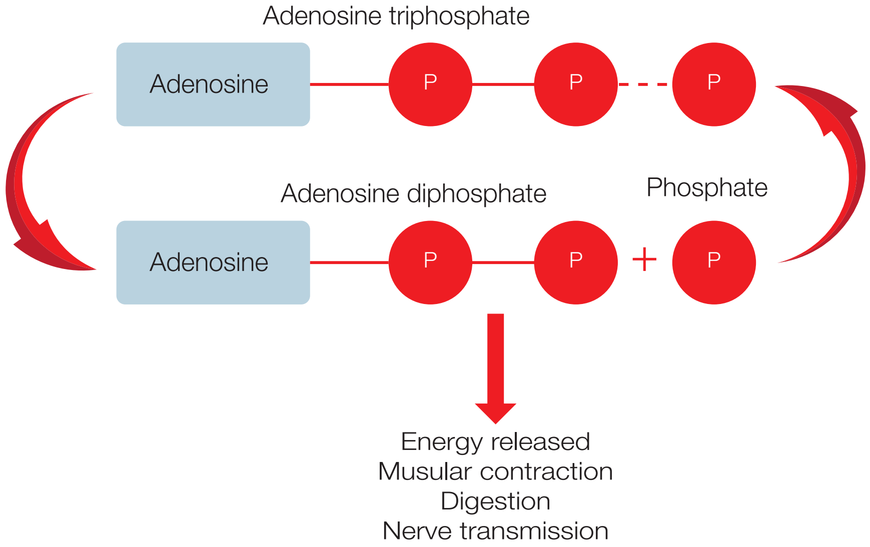

Figure 1.1.3: Energy is required to rebuild the ATP molecule using the adenosine diphosphate (ADP) and phosphate (P) molecules.

The energy required to rebuild the ATP molecule comes from three different chemical reactions within the body, referred to as our **energy systems**. Two of the energy systems rely on the food we eat to provide the energy to rebuild ATP, whilst the other uses a stored chemical compound called creatine phosphate.

The three energy systems are:

- ATP-CP system
- Lactic acid system
- Aerobic system

Each energy system has its own advantages and disadvantages when rebuilding ATP. No matter the activity we are performing, it is likely that all three energy systems will contribute to the rebuilding of ATP. The dominant energy system used to rebuild ATP will depend to a large degree upon the **intensity** and **duration** of the activity being performed.

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Energy System: ATP-CP

During very high intensity activity, energy is needed by the muscles as quickly as possible to rebuild the ATP molecule, and this comes from another 'high energy' bond compound known as **Creatine Phosphate (CP)**. Like ATP, when the creatine (C) and phosphate (P) bond is chemically broken, energy is instantly released to rebuild the ATP molecule.

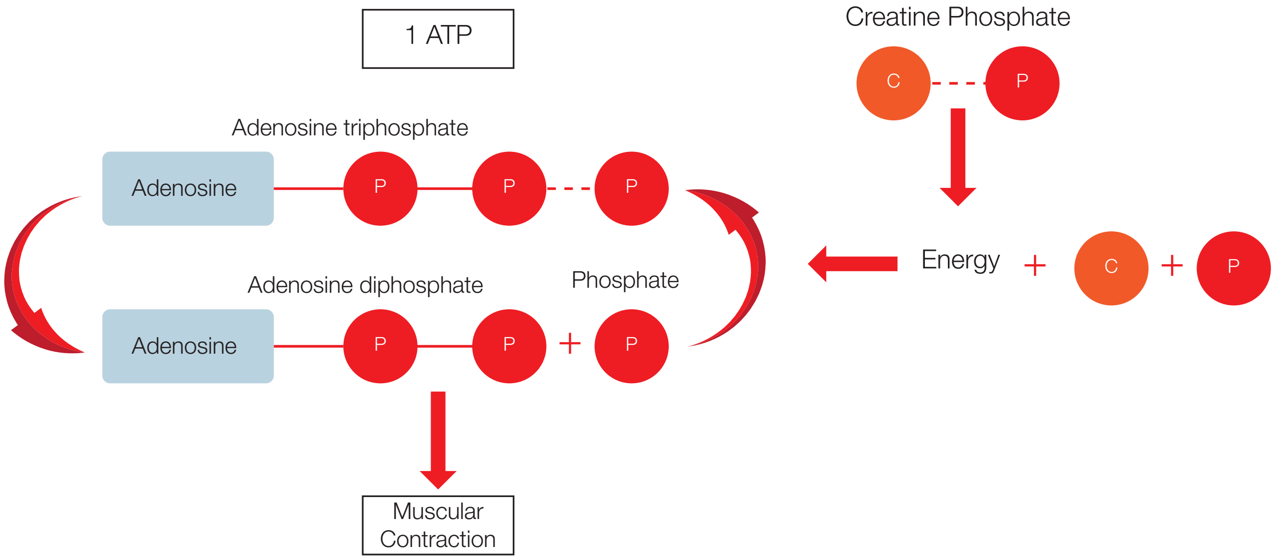

Figure 1.1.4: Energy released from the breakdown of Creatine Phosphate (CP) is used to rebuild ATP.

The ATP-CP system supplies immediate energy for any sprint or maximal intensity, short duration work <10 seconds.

Alternative names for the ATP-CP energy system:

- ATP-PC system
- Alactacid system
- Phosphate system.

Muscle stores of CP are very limited, so less than 10 seconds is the average time for which this system can be the dominant energy system to rebuild the ATP molecule.

Figure 1.1.5 and 1.1.6: Maximal (100%) effort for a short duration (<10 seconds) see the ATP-CP energy system dominant.

Once depleted, the ATP-CP energy system can quickly recovery with 50% CP restored after 30 seconds and 100% CP restored after approximately 3 minutes following a passive recovery.

Table 1.1.1: Summary of the ATP-CP Energy System

ATP–CP Energy System	
Positives	**Negatives**
CP stored in muscles 'ready to go' instantly	Very limited CP stores in muscle – fully depleted <10 seconds maximal effort
Used for maximal intensity (100% effort)	
Anaerobic (does not require O_2 to be delivered to muscles) = instant energy	
No fatiguing by-products, so termed 'alactacid' = no lactic acid produced	
Quick to rebuild CP: • 50% CP rebuilt in 30 seconds • 100% CP rebuilt in 3 minutes	

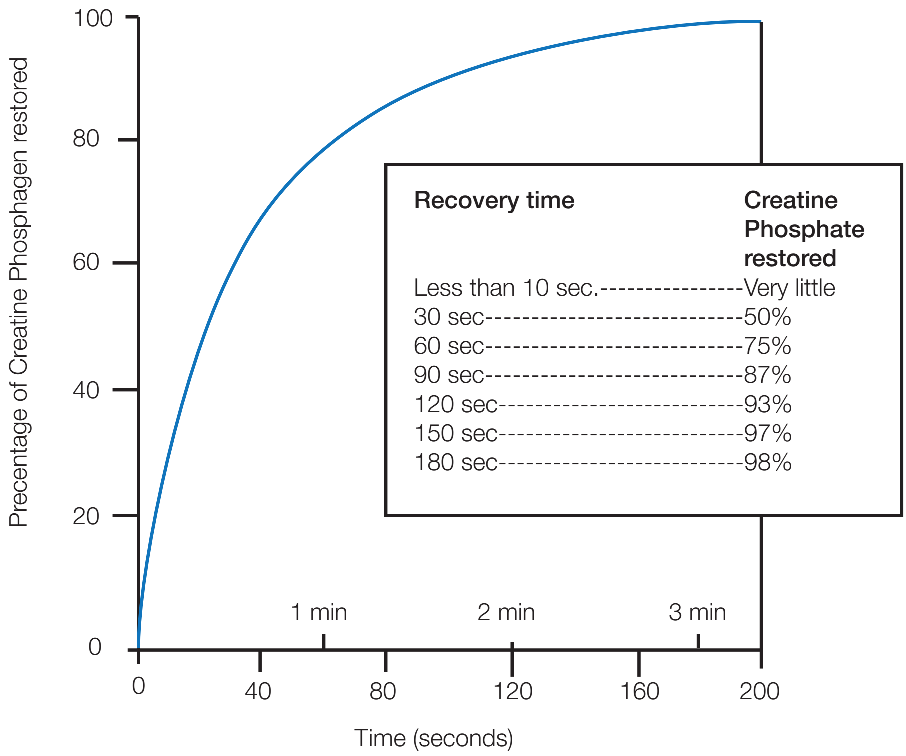

Figure 1.1.7: The rate of Creatine Phosphate (CP) restored over time, following exhaustive exercise.

Focus Questions

1. Describe the intensity and duration of exercise where the ATP-CP system would be the dominant source of energy to rebuild ATP.

2. Explain the term Alactacid:

3. Identify and explain two specific athletic events (track or field) and two (specific game related) activities within a team-sport that would rely predominantly on the ATP-CP system for energy to rebuild ATP:

   (a) Track or Field:

   (b) Team sport (specific game related):

4. With reference to the Figure 1.1.7 showing the rate of Creatine Phosphate (CP) restored over time, answer the following:

   Why is it possible for an athlete to sprint maximally (100%) for 50m in 6 seconds; rest for 3 minutes, sprint another 50m in 6 seconds and repeat this cycle several times without a drop in speed?

   Explain your answer using information from the graph:

Energy System: Lactic Acid

The lactic acid energy system is important to supply quick energy to rebuild ATP during high intensity efforts (85%+) ranging from 10 seconds to approximately 1 minute of high intensity exercise.

Alternative names for the Lactic Acid energy system:

- Anaerobic Glycolysis
- Lactacid energy system.

Definitions

Anaerobic – a process that does not require oxygen

Glycolysis – breakdown of carbohydrate (glycogen)

Lactacid – lactic acid is produced

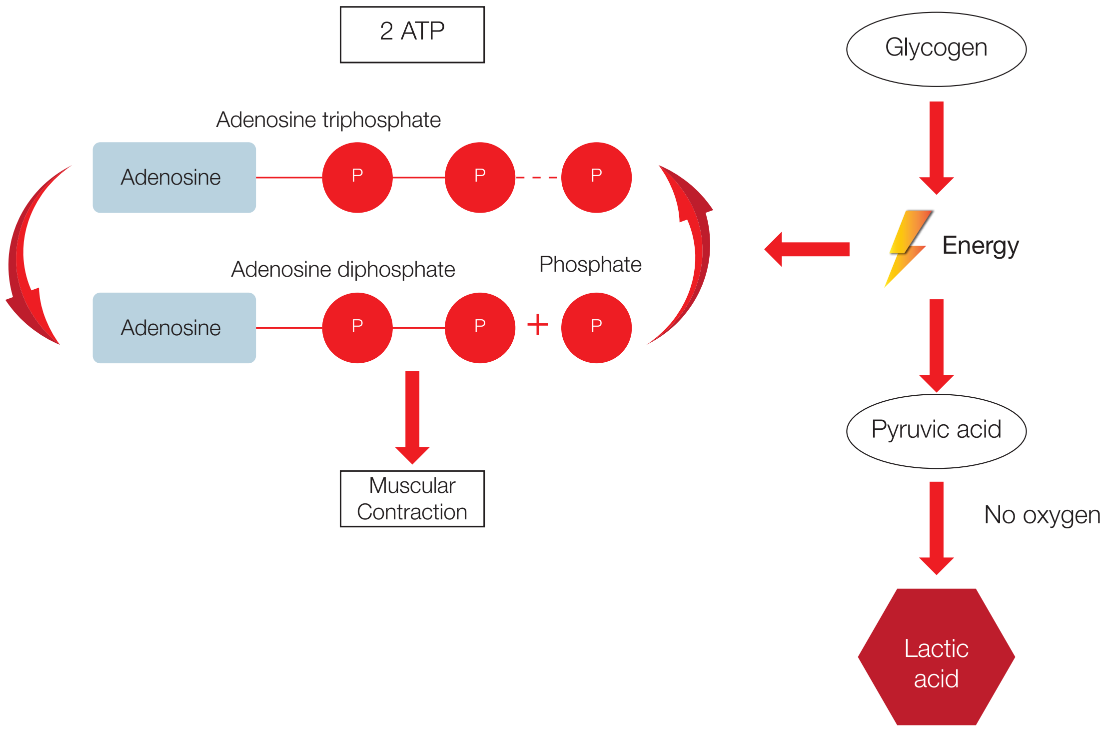

Figure 1.1.8: Anaerobic glycolysis energy pathway

The lactic acid system partially breaks down some of the energy stored within a glycogen molecule to rebuild ATP. This process occurs in the cytoplasm of the muscle cell and involves a series of chemical reactions that break down glucose into pyruvic acid, producing enough energy to rebuild 2 ATP molecules.

When exercise intensity is high, the body is unable to deliver sufficient oxygen to the exercising muscles. This means glycogen is only partially broken down to a substance called pyruvic acid, which (in the absence of oxygen) converts to a byproduct called lactic acid. The lactic acid produced in the muscles during high intensity exercise quickly moves out of the muscle into the bloodstream as lactate and hydrogen ions (H^+). The accumulation of lactate and the corresponding increase in hydrogen ions (H^+) in the blood are considered contributing factors to muscular fatigue because they lower the muscle pH levels (increasing acidity) and interfere with the skeletal muscle's ability to contract. When an athlete is rapidly accumulating lactate during exercise, they are said to be exercising at a level above their **lactate threshold** or **Onset of Blood Lactate Accumulation (OBLA)** – refer to Table 1.1.6 and Figure 1.1.17.

The lactic acid energy system is dominant when supplying energy to rebuild ATP in short term (10 seconds to 1 minute), high intensity activities >85% (HR_{max}). This is when an athlete is exercising above their **lactate threshold** or **OBLA** where the rapid accumulation of blood lactate (>4mmol/L) and hydrogen (H^+) ions will cause muscular fatigue.

Figure 1.1.9 and Figure 1.1.10: High intensity (85% HR_{max}) effort and short duration (10 seconds to 1 minute) exercise rely predominantly on the lactic acid energy system

These track athletes (Figure 1.1.9) are running at a high intensity for approximately 45 seconds in a 400m race. This is a classic example of high intensity exercise (>85% HR_{max}) for a short duration (< 1 minute) using the lactic acid energy system as the dominant energy system to rebuild ATP.

The accumulation of lactate and H^+ towards the end of the race can cause high levels of fatigue.

The soccer player is jumping maximally for a contested ball. In isolation, this may appear that the ATP-CP system will be dominant to rebuild ATP because it is a maximal (100%) effort of very short duration (<10 seconds).

However, in team sports, an elite player will often make many high intensity, repeated efforts without a full recovery to replenish muscle CP stores. Therefore, with CP muscle stores depleted, the lactic acid system will become the dominant supplier of energy during repeated high intensity efforts as a game progresses, explaining the high levels of lactate accumulation and fatigue associated with elite team sport competition.

Since lactic acid is produced from the incomplete breakdown of a carbohydrate, it can actually be removed from the blood following exercise by being rebuilt into a carbohydrate (either glucose or glycogen) where it can be stored again in the liver or muscles (18%) or used as a fuel source in the skeletal muscles (72%). Some lactate is converted to protein in the liver (8%) and some is excreted from the body as sweat or urine (2%).

Research shows that the speed of removal of blood lactate following exhaustive exercise depends on the type of recovery undertaken, with an active cool-down accelerating its removal from the blood, but not necessarily in muscle tissue. Performing aerobic activity in recovery accelerates blood lactate removal with the optimal level of recovery exercises ranging from between 30-45% VO_2max (bicycle) and 55-60% VO_2max (running).

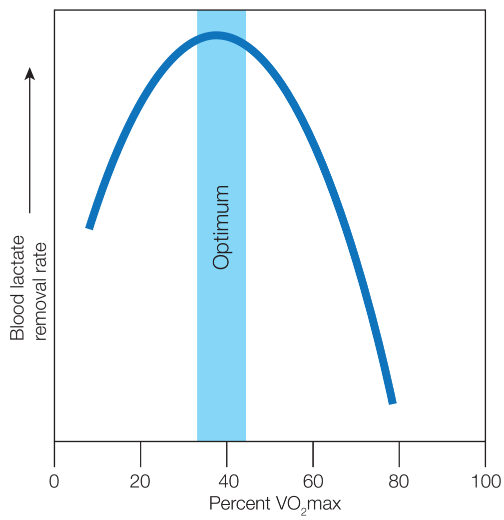

Figure 1.1.11: The relationship between exercise intensity and blood lactate removal rate following exhaustive exercise whilst cycling.

Table 1.1.2: Summary of the Lactic Acid Energy System

Lactic Acid Energy System	
Positives	**Negatives**
Anaerobic (does not require O_2 to be delivered to the muscles) = quicker release of energy	The accumulation of lactate and hydrogen ions cause fatigue: • 'lactacid' = lactic acid produced
High intensity (85% +) energy supply	Slow recovery–lactate and H^+ removal: • 50% removal in 15 minutes • 100% removal in 90 minutes *Note: Active recovery increases removal rate*
Longer duration high intensity energy supply when ATP-CP is depleted: • 10 seconds to 1 minute	Only one fuel: Glycogen

Focus Questions

5. Explain the following terms:

   (a) Pyruvic acid

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   (b) Lactacid

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6. Describe the intensity and duration of exercise where the lactic acid system would be dominant.

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7. Identify and explain two specific athletic events (track or field) and two (specific game related) activities within a team-sport that would rely predominantly on the lactic acid system for energy to rebuild ATP:

   (a) Track or field

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   (b) Team sport (specific game related)

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Focus Questions

8. On a marked athletics track, complete a timed 400m maximal intensity (100%) run. Record your time and answer the following questions:

   Time:.......................sec.

   Describe and explain how you felt at:

   (a) The 100m mark?

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   (b) The end of the run?

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Energy System: Aerobic

When exercise intensity is low (submaximal), the body will have time to deliver the required amounts of O_2 to active skeletal muscles, allowing for the complete breakdown of carbohydrates to provide energy to rebuild ATP.

The aerobic energy system is dominant when providing energy to rebuild ATP during low intensity, prolonged activities. The aerobic system is typically associated with endurance athletes such as triathletes, Tour de France cyclists or AFL midfielders who can cover up to 15km per game etc.

Figure 1.1.12a, b & c: The aerobic energy system is dominant during submaximal intensity (<85% HR_{max}) and long duration (> 1 minute) exercise.

Figure 1.1.13: The aerobic energy system is used to recover from high intensity efforts in team sports.

It should also be noted that the aerobic energy system is vital for power athletes who need to recover from high intensity exercise, when the anaerobic energy systems have been dominant.

The aerobic energy system can help fatigued athlete's to recover by supplying energy to rebuild the CP molecule (100% in 3 minutes) and also remove accumulated lactate and H^+ (100% removal in 90 minutes) following high intensity sprints.

The aerobic energy system is more accurately referred to as the **aerobic glycolysis** system:

- Aerobic: a process that requires oxygen
- Glycolysis: breakdown of carbohydrate (glycogen).

The oxidation of one molecule of glycogen (aerobic glycolysis) begins in exactly the same manner as the lactic acid system, with a series of chemical reactions that break down glycogen into pyruvic acid, producing enough energy to resynthesise 2 ATP molecules. However, if the body is able to deliver sufficient oxygen to the muscles, the pyruvic acid moves into the **mitochondria** of the muscle cells. The mitochondria are specialised cells that permit the breakdown of macronutrient fuels (e.g. glycogen, fatty acids) through interaction with oxygen to produce large amounts of energy.

When pyruvic acid enters the mitochondria, it is completely broken down by a series of complex chemical reactions (known as the Kreb Cycle and the Electron Transport System) into the non-fatigue causing by-products of carbon dioxide (CO_2) and water (H_2O). This process releases enough energy to rebuild a further 36 ATP molecules (providing a total of 38 ATP for the complete process).

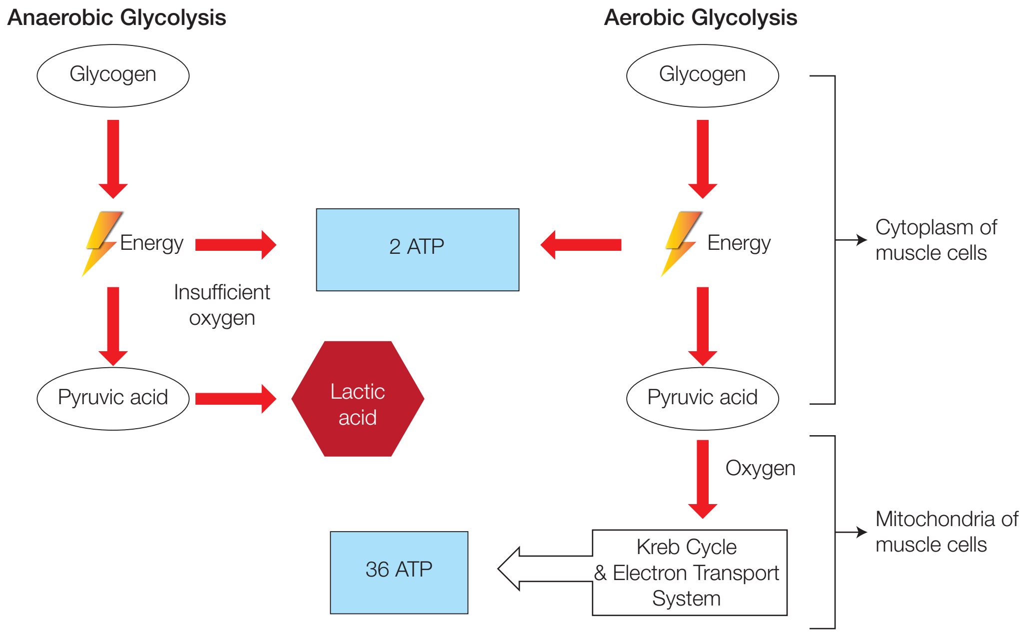

Figure 1.1.14: Oxygen energy pathway (with comparison of aerobic glycolysis and anaerobic glycolysis).

Figure 1.1.14 highlights the similarities in both anaerobic glycolysis (lactic acid system) and aerobic glycolysis (aerobic system) while in the cytoplasm of the muscle cell. However, If exercise is submaximal and sufficient oxygen is delivered to the muscles, pyruvic acid then moves into the mitochondria of the cell, where aerobic glycolysis takes place.

The aerobic energy system is also capable of breaking down fats as a fuel source to provide energy for the rebuilding of the ATP molecule, called **aerobic lipolysis** (refer to Focus Area 3.1). When the oxygen delivery systems of the body (circulatory & respiratory) are not under stress, fats can contribute up to ⅔ of energy requirements during rest and low intensity aerobic exercise such as walking (refer to Figure 3.1.10). However, during moderate to high intensity exercise, the body is simply unable to provide enough oxygen to enable the more complex chemical reactions involved to 'split' the larger fat molecules. Therefore, the contribution of fats during high intensity exercise is limited.

Alternative names for the Aerobic energy system:

- Oxidative system
- Aerobic glycolysis
- Aerobic lipolysis.

At the onset of exercise, there is always an increase in the oxygen consumption of an athlete as they try to deliver extra oxygen to the working muscles. However, it will generally take up to a minute or so for the body to deliver the necessary volume of oxygen to enable the aerobic energy system to become the dominant supplier of energy. This should not be too surprising, because the cardiovascular and respiratory systems will need a bit of time to meet the new oxygen demands. For example, there may be an increase in the ventilation rate (from 12 breaths per minute up to 25 breaths per minute) and an increase in heart rate (from 60 bpm up to 130 bpm) in order to meet the greater volume of oxygen required.

From the onset of submaximal exercise, it may take 1-2 minutes before the athlete can reach a **'steady state'** where their oxygen consumption is matching their oxygen requirements for a given workload and the aerobic energy system is dominant. A steady state is represented by a flat oxygen consumption line on an oxygen consumption graph.

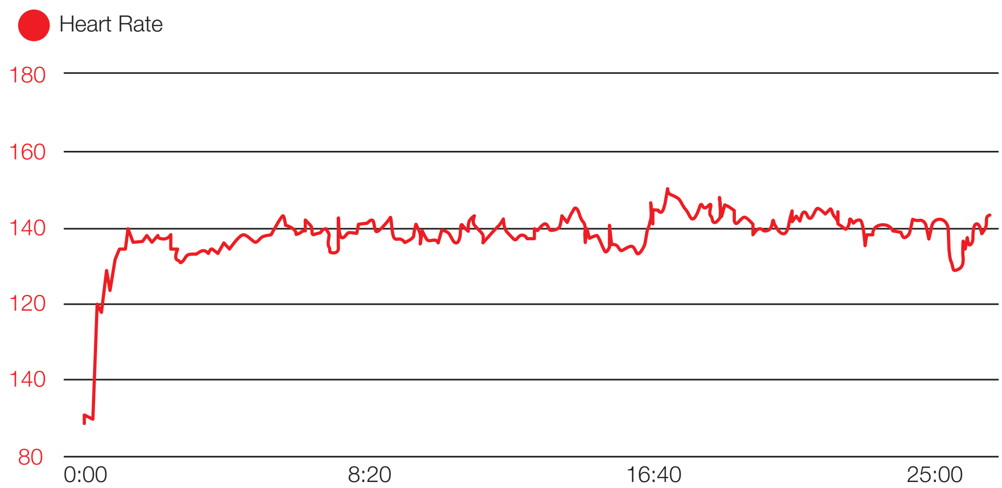

Figure 1.1.15: Heart rate (HR) recorded using a GPS / HR watch during an 'Easy Run' session

The heart rate recording above shows that it took approximately 1-2 minutes for heart rate to rise from 85 bpm to 140 bpm where a steady state (O_2 supply = O_2 demand) was reached and the aerobic energy system is dominant.

It also shows that in reality, a steady state heart rate is not flat! The recording shows heart rate fluctuations within a 135 bpm–142 bpm zone but this is still an 'easy' aerobic training zone.

Until a steady state heart rate is reached, a person's anaerobic energy systems (the lactic acid or perhaps even the ATP-CP system) will need to play a greater role in supplying the energy to rebuild ATP until the athlete's heart rate and ventilation rate increases sufficiently to meet the new oxygen requirements – this is referred to as an O_2 deficit – refer to Focus Area 1.1.18.

Although the aerobic energy system produces no fatiguing by-products when rebuilding ATP, after continuous exercise of 1-2 hours or more, there is likely to be a depletion of the primary fuel stores (muscle and liver glycogen) and an athlete may experience a sudden onset of fatigue known as **'hitting the wall'**. It may take 24-48 hours for the body to replenish muscle glycogen stores even with a high carbohydrate diet – refer to Focus Area 3.1: Nutrition and performance.

Table 1.1.3: Summary of the Aerobic Energy System.

Aerobic Energy System	
Positives	**Negatives**
Long duration energy supply	Aerobic (requires O_2 to be delivered to the muscles) = slow energy
No accumulation of fatigue causing by-products	Only dominant during low intensity (< 85%) exercise
Capable of breaking down all macronutrients: carbohydrates (glycogen & glucose) and fats (also protein in extreme circumstance i.e. starvation)	Slow to increase O_2 supply at the beginning of exercise, causes an O_2 deficit
Provides energy to recover from high intensity exercise	

Focus Questions

9. Explain the terms:

   (a) Submaximal exercise

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   (b) Steady state

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   ....

10. Describe the intensity and duration of exercise where the oxygen system would be the dominant source of energy to rebuild ATP:

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11. Identify and explain two specific athletic events (track or field) and two (specific game related) activities within a team-sport that would rely predominantly on the Aerobic system for energy to rebuild ATP:

    (a) Track or field

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    ....

    (b) Team sport (specific game related)

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12. Identify and explain three differences between aerobic and anaerobic glycolysis:

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Energy System – Overview

The table below shows an overview of the energy systems available to rebuild the ATP required for muscular contraction.

Table 1.1.4: Energy system overview.

	Anaerobic		**Aerobic**	
	ATP-CP	**Lactic Acid**	**Aerobic Glycolysis**	**Aerobic Lipolysis**
Other names	ATP-PC, Phosphate, Alactacid	Anaerobic Glycolysis, Lactacid	Aerobic / Oxygen	
Duration of dominant contribution	<10 seconds • 100m Sprint • Javelin/ Slam Dunk	10 seconds – 60 seconds • 400m • REPEAT max efforts (depleted CP)	60 seconds – 1 ½ hrs+ • 1500m Runner • 10,000m Runner • Jogging	60 seconds – 1 ½ hrs+ • Walking • Marathon (42.2km) • Ultra endurance
Intensity of effort	Maximal Intensity		Sub-maximal Intensity	
	Maximal (95-100%)	High (85-95% HR_{max}) Above OBLA / Lactate Threshold	Moderate (75-85% HR_{max})	Low (50%–75% HR_{max})
Speed of ATP resynthesis	Instant	Fast	Medium	Slow
Fuel	Creatine Phosphate	Glycogen (glucose)	Glycogen (glucose)	Triglycerides – fatty acids
By-product	N/A	Lactate, Hydrogen ions	CO_2 and H_2O	CO_2 and H_2O
Fatigue factor	Limited supply of CP	Lactate / H^+ (low pH = muscle acidity)	Depletion of Glycogen – Hitting the Wall	Fats require lots of O_2 to break down – very slow
Recovery	Time to rebuild CP • 50% = 30 seconds • 100% = 3 minutes	Time to remove Lactate / H^+ • 50% = 15 min • 100% = 90 min Recovery time quicker with an active warm down	Time to replenish muscle glycogen stores: • 1–24 hours, using nutritional strategies	N/A

Maximum Oxygen Consumption (VO_2 Max)

The volume of oxygen consumed by the body for energy production is called the VO_2 and it is measured in litres of oxygen consumed per minute (L/min). If an athlete were to slowly increase exercise intensity, there would be a corresponding increase in oxygen consumption until they reached maximum oxygen consumption (VO_2 max) – the region where oxygen uptake peaks despite further increases in exercise intensity (refer Figure 1.1.16).

Because larger people tend to consume more oxygen than smaller people (purely because of their larger size), VO_2 max is usually expressed as a relative VO_2 max in millilitres of oxygen consumed per kilogram of body weight per minute (ml/kg/min). This allows for the comparison of different-sized individuals. For example, in Figure 1.1.16, the athlete's peak VO_2 max value was 3.6 litres per minute. If the athlete undergoing this test had a mass of 68kg, then their relative oxygen consumption would be calculated as follows:

3.6L/min × 1000 = 3600ml

3600/68kg = 52.9ml/kg/min

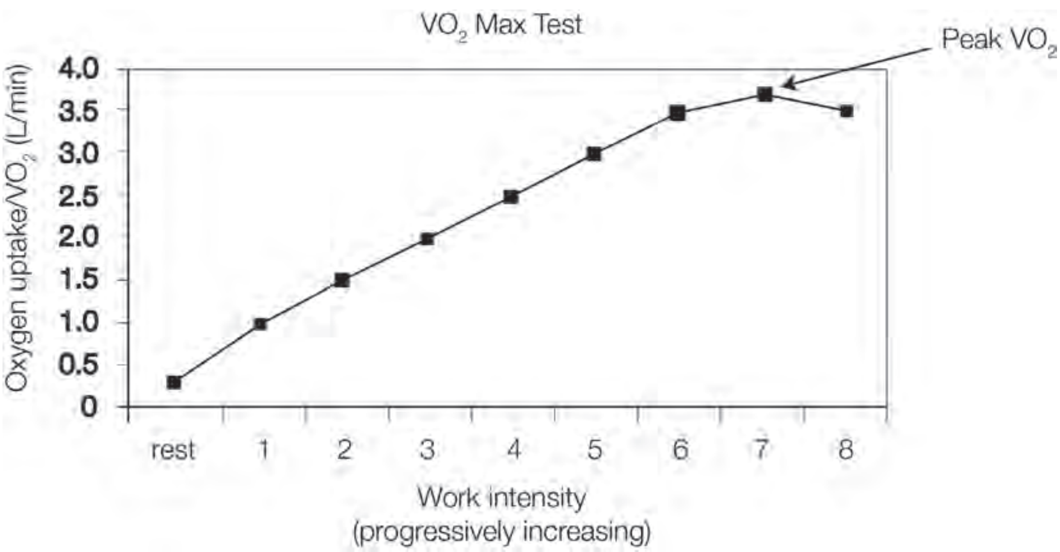

Figure 1.1.16: Maximum Oxygen Consumption (VO_2 max)

Table 1.1.5: Typical VO_2 max values of tested athletes at the AIS. Source: Adapted from Pyke (2001), p. 81.

Sport		Approximate mean of VO_2 max (L/min)	Approximate mean of VO_2 max (ml/kg/min)	Typical range VO_2 max (ml/kg/min)
Running	Male	4.9	75	65-80
	Female	3.5	65	55-70
Rowing	Male – heavy	5.5	60	55-70
	Male – light	4.8	65	55-70
	Female – heavy	3.9	52	45-60
	Female – light	3.4	52	45-60
Cycling – track	Male	5.8	80	65-85
	Female	3.5	63	55-70
Kayaking	Male	4.8	60	55-65
	Female	3.1	50	45-55
Soccer	Male	4.6	60	55-65
	Female	3.1	50	45-55