UNIT 3

Optimising performance and evaluating contemporary issues within sport

Section A: Applied physiology to optimise performance

CHAPTER 1

Energy systems

–the sources, supply and recovery of energy in the body

LEARNING OBJECTIVES:

By the end of this chapter you should be able to:

- *define energy*
- *identify the sources and locations of energy within the body*
- *explain the role of ATP in providing energy for movement*
- *identify the predominant energy system used related to the type, duration and intensity of exercise for a given activity*
- *compare the effectiveness of the ATP-PC, lactic acid and aerobic systems*
- *identify the chemical/food fuel used, the site of the reaction, the controlling enzymes, the energy yield and any by-products produced for each of the energy pathways*
- *explain the term 'energy continuum' in context of a range of physical activities*
- *explain how the body recovers from exercise with reference to the excess post-exercise oxygen consumption (EPOC)*
- *explain the fast and slow components of the recovery process*
- *define VO_2 max and its role in limiting performance*
- *define and explain the relationship between VO_2 max and OBLA (onset of blood lactate accumulation).*

Introduction

Central to our study of exercise physiology is **energy**. As exercise physiologists we are interested in where we get the energy to exercise from, how we can optimise our energy usage during exercise and how we can recover our energy stores following exercise. In this chapter we will look at how the body converts energy from food into energy for muscular contractions which enable us to run, jump, throw or indeed perform any number of movements used in sporting activity. We will examine the energy requirements of a number of activities ranging from a gymnastic vault to marathon running and determine how the intensity or duration of a particular activity can impact upon how the body supplies energy. Perhaps most importantly we will discover how a knowledge of energy supply can help both coach and athlete maximise performance.

Defining energy

Energy exists in a number of different forms. Electrical, heat and light energy are just some of the forms that we all use on a daily basis. Energy is never lost, it is constantly recycled, often being transferred from one form to another. When boiling a kettle, for example, electrical energy is transformed into heat energy.

KEY TERMS

Energy:
the capacity of the body to perform work

Adenosine triphosphate (ATP):
the energy currency of cells. ATP is the only direct source of energy for all energy requiring processes in the body

EXAM TIP:

Make sure you can give the correct units of measurement of energy. Energy can be measured in calories (kcal) or joules (J); 1 calorie = 4.184 joules

Similarly, energy found in the chemical bonds of food fuels that we eat is transformed into mechanical energy enabling us to move and participate in sporting activity. It is this conversion of chemical energy into mechanical and heat energy that is of particular interest to the sports physiologist and forms the basis of discussion for the rest of this chapter.

Sources of energy in the body

You will recall from your AS studies that for movement to occur chemical energy must be transferred into mechanical energy. Chemical energy in the body is stored in an easy access, energy-rich compound called **adenosine triphosphate** (ATP). ATP exists in all cells and consists of a number of atoms held together by high energy bonds. It is through breaking down these bonds that energy is released for those processes in the body that require energy.

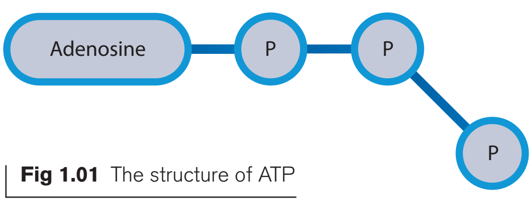

Fig 1.01 The structure of ATP

When energy is required, the enzyme ATPase is released which initiates the breakdown of ATP. It is the outermost bond of ATP that most interests ATPase as it is this bond that stores most energy. Through the breakdown of ATP energy is released leaving Adenosine Diphosphate (ADP) and an inorganic phosphate (Pi), which is illustrated in Fig.1.02.

This reaction can be summarised as follows:

Adenosine triphosphate	⟶	Adenosine diphosphate	+	Inorganic phosphate	+	Energy
ATP	⟶	ADP	+	Pi	+	Energy

Because some of the energy is given off as heat this reaction is termed **exothermic**.

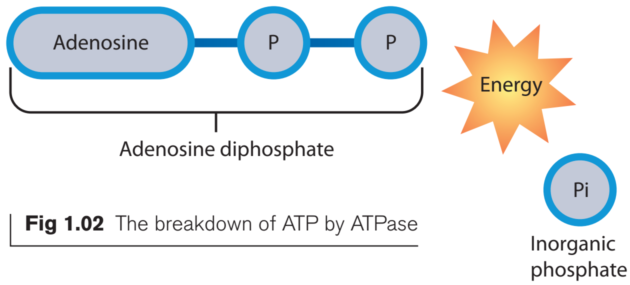

Fig 1.02 The breakdown of ATP by ATPase

REMEMBER!

Through the breakdown of ATP, energy is released to enable the muscles to contract, the heart to beat, and the brain to fire electrical impulses.

There is only a limited supply of ATP within the muscle cell, probably only enough to perform, for example, a maximal weight lift in the weights gym or a sprint start for 2 or 3 seconds. This is because if we were to have an unlimited supply of ATP we would have to carry around a supply equivalent to our own body weight in order to meet the body's daily energy requirements! This is obviously not very practical, so the body has adapted to become a green recycling machine. ATP is constantly recycled to ensure a continuous supply of energy. However recycling or resynthesising of ATP itself requires energy and this energy is acquired from the food that we eat.

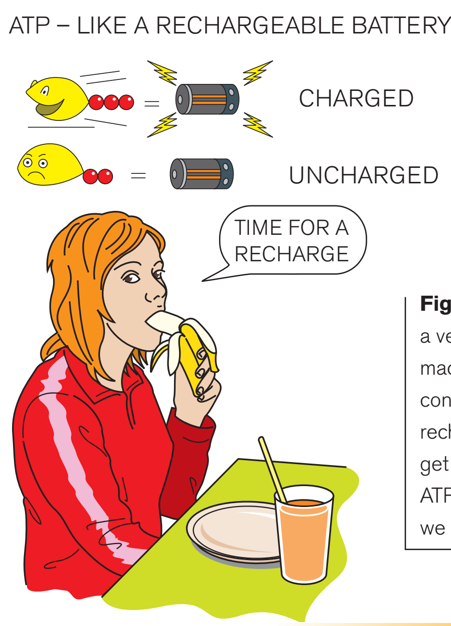

Fig 1.03 The body is a very effective green machine, as ATP needs constant recycling or recharging. We typically get the energy to recycle ATP from the foods that we eat.

KEY TERMS

Exothermic reaction:
a chemical reaction that releases energy

Phosphocreatine:
a high energy compound which exists in the muscle cells alongside ATP and provides the energy for ATP resynthesis when the intensity of exercise is very high

Anaerobic metabolism:
the release of energy through the breakdown of food fuels in the absence of oxygen

Aerobic metabolism:
the release of energy through the breakdown of food fuels in the presence of oxygen

REMEMBER!

There is only sufficient ATP stored within the muscle cell to perform high intensity activity for 2 or 3 seconds.

The fuels for ATP resynthesis are derived from the following sources:

- **Phosphocreatine:** Phosphocreatine (PCr) is used to resynthesise ATP in the first 10 seconds of intense exercise. To help facilitate this immediate resynthesis of ATP, PCr is stored within the muscle cell itself alongside ATP. However, stores of PCr are limited. Good dietary sources of creatine include red meat and fish.
- **Glycogen** (stored carbohydrate)**:** Glycogen is stored in the muscles (350g) and liver (100g). It is first converted to glucose before being broken down to release the energy for ATP resynthesis. During high intensity exercise glycogen can be used without the presence of oxygen (**anaerobic metabolism**). However much more energy can be released from glycogen during **aerobic metabolism** when oxygen is available. Stores of glycogen are maintained through eating complex carbohydrates such as pasta and porridge oats.
- **Triglycerides** (muscular stores of fat)**:** At rest up to two-thirds of our energy requirement is met through the breakdown of **fatty acids**. This is because fat can provide more energy per gram than glycogen (1g of fat provides 9.1kcal of energy compared to 4.1kcal of energy for every 1g of glycogen). In spite of the fact that fat requires about 15% more oxygen than glycogen to metabolise it remains the favoured fuel source at rest and during endurance-based activity.

Fats can only be used as an energy source when there is a plentiful supply of oxygen and must be used in conjunction with glycogen. This is because the transport of fatty acids in the blood is poor (and slow!) due to their low solubility. Consequently fatty acids do not arrive at the muscle cell in sufficient quantities to sustain muscle contraction on their own. Glycogen must therefore provide the supplementary energy.

- **Proteins:** Protein is the least favoured source of energy, only contributing 5–10% of the total energy yield. In the presence of oxygen, protein is used as an energy provider, usually when stores of glycogen are low. Good dietary sources of protein include meat, fish and dairy products. You will recall that protein's primary function is to facilitate the growth and repair of the body's cells, including muscle tissue.

KEY TERMS

Fatty acids:
the component of fat used for energy provision

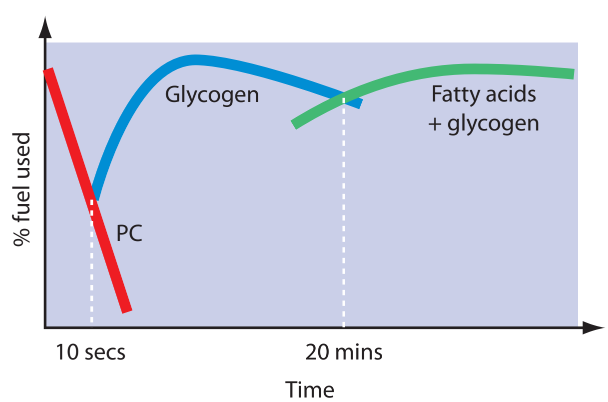

Fig 1.04 Sources of energy for ATP resynthesis against time

REMEMBER!

When exercising at higher intensities, the body will rely more upon glycogen as a source of fuel.

TASK 1.01

Keep a diary of all the food and drink that you consume in one day.

From the packaging calculate how much energy you have consumed in both calories (kcal) and Joules (j).

TIP – You may need to measure out quantities of foodstuffs to give an accurate picture of your energy intake.

The conversion of these fuels into energy which can then be used to resynthesise ATP occurs through one of three pathways or **energy systems**. It is the intensity and duration of the exercise that dictates whether oxygen is present and ultimately which energy system predominates.

The three energy systems are:

1. the aerobic (oxidative) system
2. the lactic acid or lactate anaerobic system
3. the ATP-PC or alactic system.

The more intense the activity (e.g. the harder the athlete is working, signalled perhaps by a higher heart rate) the more the performer will rely on the production of energy from anaerobic pathways such as the ATP-PC system or lactic acid system. As exercise intensity decreases and endurance increases the more the athlete will rely on the aerobic system for providing the energy to resynthesise ATP.

As most of our daily energy requirements are supplied by the aerobic system, it is this system we will visit first.

REMEMBER!

The source of energy for ATP resynthesis is dependent largely upon the intensity and duration of the sporting activity.

The aerobic (oxidative) energy system

During resting conditions or during exercise where the demand for energy is low, oxygen is readily available (hence the name aerobic system) to release stored energy from muscle glycogen, fats and proteins. The aerobic system is the body's preferred energy pathway as it is by far the most efficient in terms of ATP resynthesis. In fact the energy yield from aerobic metabolism is 18 times greater than that gained from anaerobic processes.

During times where there is a plentiful supply of oxygen (i.e. oxygen supply exceeds oxygen demand) glycogen is first converted to glucose-6-phosphate before it is broken down into pyruvate (pyruvic acid). This all takes place in the sarcoplasm of the muscle cell and results from the actions of the enzyme phosphofructokinase (PFK) and is illustrated as the first few stages in Figure 1.07.

Under anaerobic conditions pyruvic acid (pyruvate) is converted into fatigue-inducing lactic acid by the enzyme **lactate dehydrogenase** (LDH). However when oxygen is in rich supply, pyruvic acid is instead converted into **acetyl-coenzyme-A** by combining with the enzyme **pyruvate dehydrogenase**. The site for energy release now moves to specialised parts of the cell known as **mitochondria**. These industrious units are in abundance within the muscle and manufacture energy for ATP resynthesis by facilitating the many chemical reactions required to completely break down our stores of glycogen and fats to ensure a continuous supply of energy. Because of their ability to supply lots of energy mitochondria are particularly found in large numbers in slow twitch muscle fibres.

Fig 1.05 illustrates a mitochondrion. You can see from this diagram that there are two key stages of the aerobic system that take place within the mitochondria: the **Krebs cycle** and the **electron transport system**.

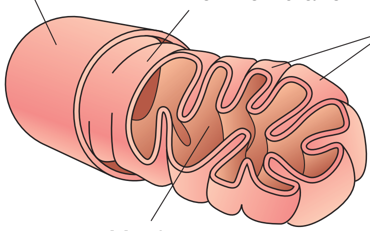

Fig 1.05 A mitochondrion

REMEMBER!

The aerobic system is of particular use to athletes who need to perform relatively low intensity exercise for a long period of time. A triathlete or marathon runner are obvious examples.

Fig 1.06 A race walker will utilise the aerobic system to provide energy for muscular contractions

KEY TERMS

Mitochondrion:
the powerhouse of the cell. Mitochondria are specialised structures within all cells that are the site of ATP production under aerobic conditions

Krebs cycle:
a series of chemical reactions that occur in the matrix of the mitochondria yielding sufficient energy to resynthesise 2 ATP molecules and carbon dioxide. It forms part of the aerobic system

Electron transport system:
a series of reactions in the cristae of the mitochondria where the majority of energy is yielded for ATP resynthesis. 34 moles of ATP can be resynthesised from just 1 mole of glycogen at this stage of the aerobic system

Mole:
an amount of a substance that contains a standardised number of atoms (6.0225×10^{23} known as Avogadro's number)

REMEMBER!

Slow twitch muscle fibres house many more mitochondria than fast twitch fibres and hence are more suited to aerobic activity such as marathon running.

The Krebs cycle

The **Krebs cycle** takes place in the fluid-filled matrix of the mitochondria which has a rich supply of enzymes that are ready to perform the necessary chemical reactions to help release the remaining energy stored within the molecule.

Three significant events occur at this stage.

1. **Oxidation of citric acid.** This involves the removal of hydrogen atoms from the compound which enter the final stage of the aerobic system; the electron transport system.
2. **Production of carbon dioxide.** The removal of hydrogen means that only carbon and oxygen remain. These combine to form carbon dioxide which is carried around to the lungs where it is breathed out.

3. **Resynthesis of ATP.** Sufficient energy is released at this stage to resynthesise 2 **moles** of ATP

The electron transport system

This final stage of glycogen breakdown occurs in the **cristae** of the mitochondria. Hydrogen given off at the Krebs cycle stage is carried to the electron transport system.

There are two important features of this stage of the aerobic pathway:

1. **Water (H_2O)** is formed when the hydrogen ions (H+) and electrons (e-) combine with oxygen through a series of enzyme reactions.
2. **Resynthesis of ATP:** By far the majority of energy is released here for the resynthesis of ATP. In fact 34 moles of ATP can be resynthesised, making this by far the most efficient source of energy in the body.

Other fuels used in aerobic energy production

So far we have only focused our attention on the aerobic breakdown of glycogen. However fat and protein can also be metabolised under aerobic conditions to form CO_2, H_2O and energy for ATP resynthesis. Fats stored in the muscle as triglycerides must first be broken down into glycerol and free fatty acids (FFAs) before they go through the process of **beta(ß)-oxidation** (the fat equivalent of glycolysis). Following beta-oxidation fatty acids can enter the Krebs cycle where they can then follow the same path of metabolism as glycogen. The main difference between fat and glycogen metabolism, however, is that substantially more energy (for ATP resynthesis) can be elicited from one mole of fatty acids than from one mole of glycogen. Consequently, fatty acids become the preferred fuel as the duration of exercise increases. Typically this occurs after 20 minutes of sub-maximal activity. This has important consequences for endurance performers as it enables them to spare their glycogen for later in the event or competition, when intensity of the exercise might increase.

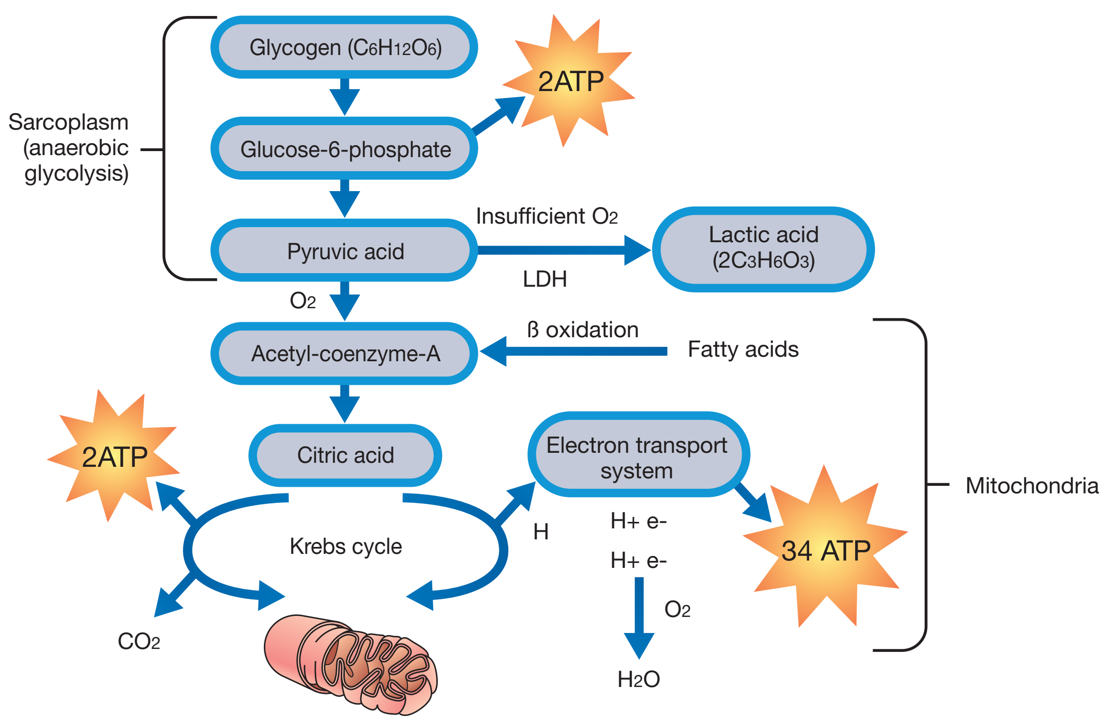

Fig.1.07 ATP resynthesis via the aerobic system

Advantages to the athlete of using the aerobic system

- Significantly more ATP can be resynthesised under aerobic conditions than anaerobic (36 ATP aerobically compared to 2 ATP anaerobically – from one mole of glycogen).
- The body has substantial stores of muscle glycogen and triglycerides to enable exercise to last for several hours.
- Oxidation of glycogen and fatty acids do not produce any fatiguing by-products.

Drawbacks of this system to the athlete

- When we go from a resting state to exercise it takes a while for sufficient oxygen to become available to meet the new demands of the activity and enable the complete breakdown of glycogen and fatty acids. Consequently this system cannot provide energy to resysnthesise ATP in the immediate short term (unless the activity is of particularly low intensity) or during higher intensity activity
- Although fatty acids are the preferred fuel during endurance events such as a marathon, the transport of fatty acids to the muscle is slow and requires about 15% more oxygen than that required to break down the equivalent amount of glycogen.
- Due to the low solubility of fatty acids the endurance athlete will usually use a mixture of both glycogen and fatty acids to provide the energy for ATP resynthesis. When glycogen becomes depleted and the body attempts to metabolise fatty acids as a sole source of fuel, muscle spasms may result. This is commonly known as hitting the wall.

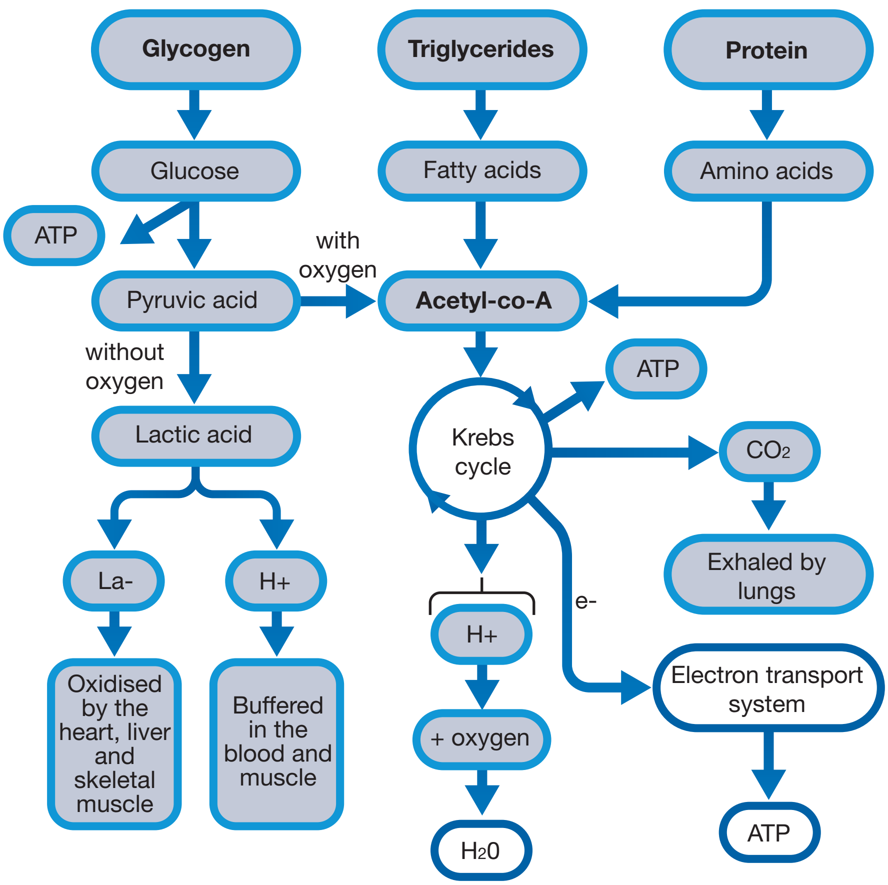

Fig 1.08 A summary of ATP resynthesis from the three main energy providing nutrients

The complete breakdown of one mole of glycogen can be summarised as follows:

$C_6H_{12}O_6 + 6O_2 \longrightarrow 6CO_2 + 6H_2O + ENERGY$
$Energy + 38ADP + 38Pi \longrightarrow 38ATP$

TASK 1.02

During a 10,000m race the aerobic system will be used for the majority of the event to resysnthesise ATP. Complete the table below with the required information.

	Site of reaction	Fuels used	Active enzymes	Molecules of ATP produced
Aerobic system (oxidative)				

The aerobic system and recovery

The **recovery** process is concerned with returning the body to its pre-exercise state so that heart rate, oxygen consumption, blood lactate levels and glycogen stores are at exactly the same levels as they were **before** the exercise commenced!

You will know from your own experience that whatever the exercise you may have performed, whether it be a maximal lift in the weights room or a 5km run, the recovery period involves a period where breathing and heart rates are elevated. This occurs because all recovery is dependent upon the consumption of oxygen, and the elevated respiratory and heart rates ensure that adequate amounts of oxygen are taken into the body and delivered to the muscles to enable a swift recovery. The oxygen delivered to the muscles will help rebuild stores of PC and ATP as well as remove any lactic acid that may have accumulated during the activity.

KEY TERMS

Recovery:
the return of the body to its pre-exercise state

REMEMBER!

As recovery can only occur when there is sufficient oxygen available then it is often associated with the aerobic energy system.

TASK 1.03

An investigation to examine recovery heart rate response to varying intensities of exercise.

Equipment: heart rate monitor, stop watch, gymnastics bench, metronome. (If you do not have access to a heart rate monitor then record your heart rate at the carotid artery for a 10 second count and multiply by 6 to convert to beats per minute.)

1. Record resting heart rate at the beginning of the class.
2. Record heart rate just prior to exercise.
3. Commence exercising by stepping onto and off the bench in time with the metronome that has been set at a low intensity.
4. Record your heart rate after one, two and three minutes of exercise. After the third minute of exercise stop the test. Continue to record your pulse each minute during recovery.

Time	Exercise intensity		
	Low	Medium	High
Resting HR			
HR prior to exercise			
Exercise 1 min			
Exercise 2 min			
Exercise 3 min			
Recovery 1 min			
Recovery 2 min			
Recovery 3 min			
Recovery 4 min			
Recovery 5 min			
Recovery 6 min			
Recovery 7 min			

Table 1.01 Example table: copy out a similar one for this task

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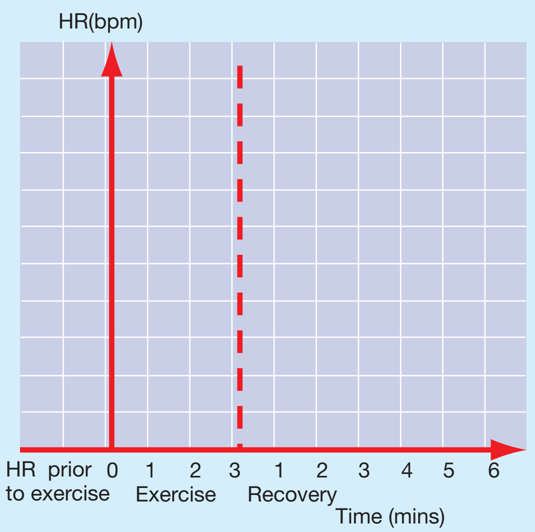
TASK 1.03 CONTINUED

5. Once your heart rate has returned to its resting value (or within a few beats) repeat the test at a medium intensity. Record your results as before.
6. Repeat the exercise for a third time but at very high intensity. Once again record your results.
7. Now use your results to plot a graph for each of the three workloads. Plot each graph using the same axes placing heart rate along the *y* axis and time along the bottom *x* axis. Don't forget to show your resting heart rate values on the graph.
8. For each of your graphs explain the pattern of recovery heart rate.



NB: The length of the recovery period depends upon the intensity and to a lesser degree the duration of the previous exercise.

Fig. 1.09 Example graph: copy out a similar one on graph paper

Excess post-exercise oxygen consumption (EPOC)

Excess post-exercise oxygen consumption represents the extra volume of oxygen consumed following exercise that enables the body to fully recover and return to its pre-exercise state.

At the very beginning of exercise (even at low intensities) or when exercise is of high intensity it is likely that the body will need to work anaerobically for a period of time as there may be insufficient oxygen available to use the aerobic energy system exclusively to provide the energy for muscular work, i.e. a **deficit** occurs in the oxygen supply. The oxygen deficit thus represents the amount of extra oxygen required to enable the entire activity to be completed using the aerobic energy system. Since it takes a while for the aerobic system to 'kick in' and provide the muscles with energy at the beginning of activity, a deficit will always develop.

Researchers have identified two stages of recovery:

- **Stage 1:** The **fast replenishment stage** (formerly referred to as the alactacid debt)
- **Stage 2:** The **slow replenishment stage** (formerly known as the lactacid debt).

REMEMBER!

The term oxygen debt was often used to explain the restoration of ATP and PC and removal of lactic acid during recovery. But this failed to explain the extra oxygen needed during recovery to restore muscle oxymyoglobin and to keep respiratory and heart rates elevated. EPOC is therefore the preferred term now and the oxygen debt viewed as one part of this process.

TASK 1.04

Examine the graphs you drew in Task 1.03.
Can you identify a fast and slow stage of oxygen consumption during the recovery phase? If so shade these stages on the graph and label them 'fast stage' and 'slow stage'.

KEY TERMS

Excess post-exercise oxygen consumption (EPOC):
the volume of oxygen consumed during recovery above that which normally would have been consumed at rest during the same period of time

Oxygen deficit:
the volume of extra oxygen required to complete the entire activity aerobically

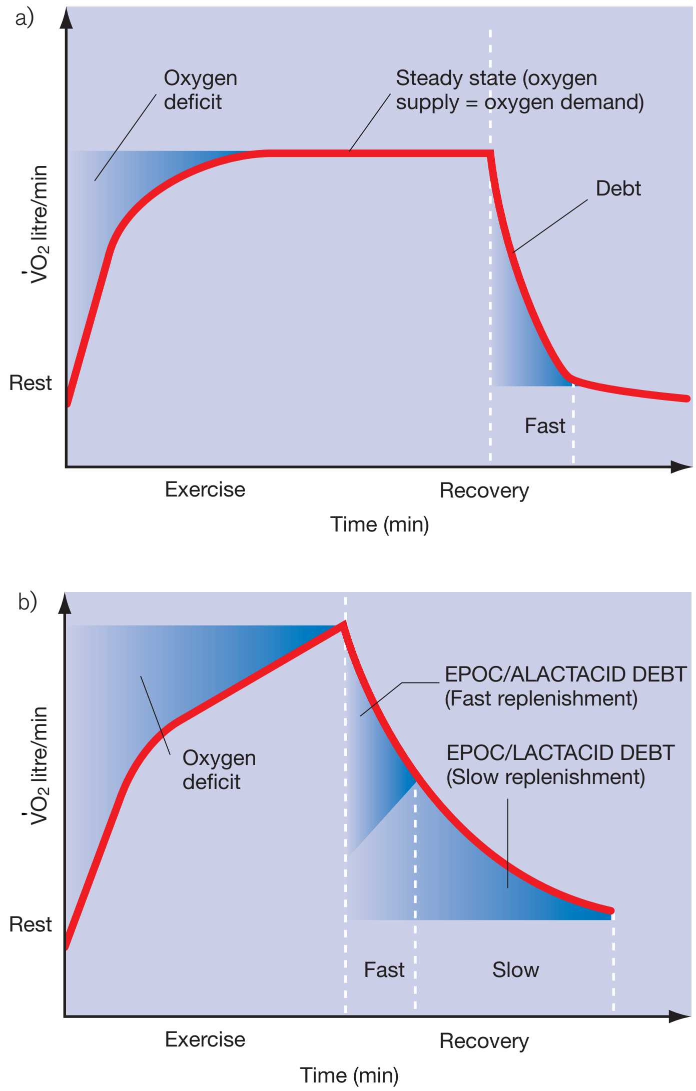


Fig 1.10 Oxygen consumption during and following (a) a sub-maximal task and (b) maximal task

REMEMBER!

1. You will notice from Figure 1.10a that the volume of EPOC is greater than the volume of oxygen deficit. This is because the 'muscles' of recovery such as the heart and respiratory muscles require oxygen to keep breathing and heart rates elevated.

2. You will note from Figure 1.10b that the 2 stages of recovery are clearly visible following maximal or high intensity exercise. However following sub-maximal or low intensity exercise only the fast stage may be evident. This is because the majority of the work has been completed aerobically and little lactic acid has accumulated during the exercise.

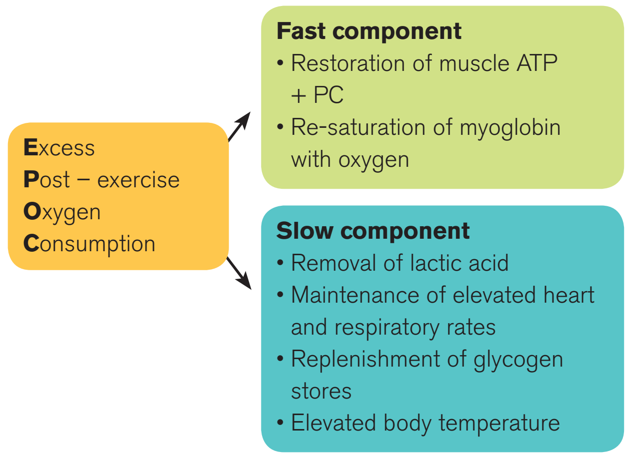


Fig. 1.11 The components of excess post-exercise oxygen consumption (EPOC)

KEY TERMS

Fast replenishment:
the first component of EPOC. Oxygen consumed is used to resaturate myoglobin and resynthesise ATP and PC. It takes approximately 2–3 minutes

Slow replenishment:
the second component of EPOC. Oxygen consumed during this stage is largely used to remove lactic acid which takes about 1 hour. In addition oxygen is also used to maintain cardiac and respiratory rates and normalise body temperature

The fast replenishment stage

This is the first stage of the recovery process and relates to the immediate consumption of oxygen following exercise. Its primary function is to re-saturate myoglobin with oxygen and provide aerobic energy to resynthesise adenosine triphosphate (ATP) and phosphocreatine (PC).The fast stage of recovery is usually completed within 2–3 minutes and utilises up to 4 litres of oxygen.

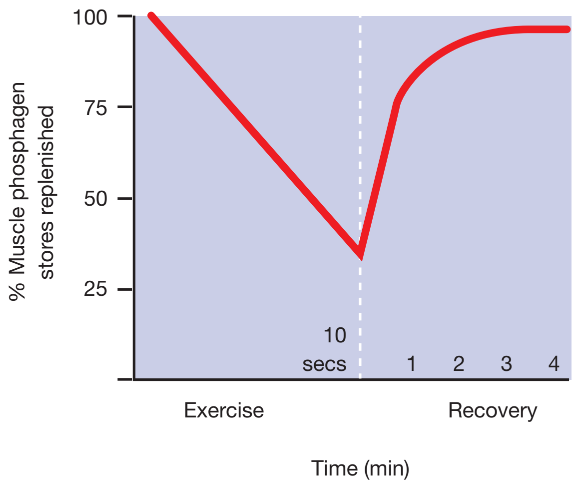


Fig 1.12 The replenishment of muscle phosphagens following maximal exercise

> **REMEMBER!**
>
> 50 per cent of PC stores are restored within the first 30 seconds of recovery!

The slow replenishment stage

The slow replenishment stage of EPOC can take up to 2 hours and utilises between 5 and 10 litres of extra oxygen depending upon the intensity of the preceding exercise.

The oxygen consumed during the slow stage of recovery has several functions:

- **Removal of lactic acid:** Lactic acid accumulated during exercise must be removed if the body is to recover fully. You will recall that most lactic acid is converted back into pyruvate and then into CO_2 and water, the remainder being converted into muscle glycogen, blood glucose and protein. Much of the oxygen consumed during this stage is therefore used to provide the energy to enable this removal of lactic acid to take place. Typically the oxidation and removal of lactic acid takes about an hour, but this can be accelerated by performing a cool down. The cool down or **active recovery** helps keep the metabolic activity of the muscles high and the capillaries dilated so that oxygen can be flushed through the muscle tissue oxidising and removing any lactic acid accumulated.
- **Maintenance of elevated heart and respiratory rates:** Like all muscles, the muscles of the respiratory system and the heart require oxygen to provide energy for them to work continuously. During the recovery period extra energy is required to keep the heart and respiratory rates elevated above resting levels. This is so the lungs can take in plenty of oxygen which can then be pumped around the body by the heart to the working muscles to re-saturate myoglobin, resynthesise muscle phosphagens (ATP and PC) and remove lactic acid.
- **Replenishment of muscle glycogen stores:** During all types of exercise it is likely that some muscle glycogen stores will become depleted. It is in the interests of the performer to replenish these stores as soon after exercise as possible. The replenishment of these muscular stores of glycogen is largely dependent upon two key factors:

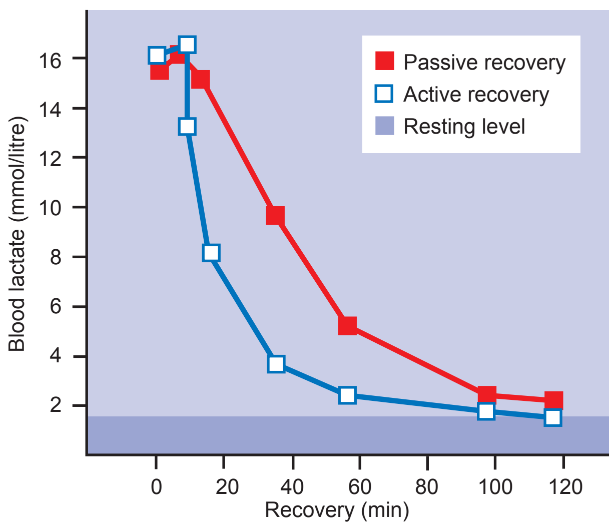
  1. The type of exercise that has been performed
  2. The amount and timing of carbohydrate consumption following exercise.

> **REMEMBER!**
>
> The best time to consume a post-exercise meal is as soon as is practical following the activity. The rate of muscle glycogen replacement is significantly quicker during the first 45–60 minutes. This is known as the **carbohydrate window.**

First of all let us consider the type of exercise performed. Studies have suggested that following **continuous, endurance-based activity** little glycogen is restored in the period immediately following activity. Complete muscle glycogen repletion can take up to 48 hours in this instance. During **high intensity, short duration activity**, however, a significant amount of muscle glycogen can be resynthesised within 30 minutes to one hour immediately following exercise (probably due to conversion of lactic acid back into glycogen via the **cori cycle**) and complete resynthesis requires a 24-hour recovery period.

The second key factor concerns the amount of carbohydrate consumed following exercise. Muscle glycogen repletion occurs more rapidly when a high carbohydrate meal is consumed within the first 45–60 minutes following exercise: this is commonly known as the **carbohydrate window**. A high carbohydrate meal should consist of 200–300g of carbohydrate.

- An **elevated body temperature**: You have probably all experienced the increase in body temperature that accompanies all exercise whether it is a maximal all-out effort on the bench press or a 5Km run. This increase in body temperature generally results from the increased metabolic activity of the body which provides the energy to perform work. However with every 10° increase in body temperature the metabolic activity of the cells doubles. Oxygen is needed to feed this increase even during the recovery period and continues to do so until the body has cooled right back down to normal resting temperatures. The oxygen for this comes through the slow replenishment stage of EPOC.



Note that blood lactate levels return towards normal resting levels much quicker when a period of active recovery has taken place.

Fig 1.13 The effect of cool down or active recovery on recovery time following a bout of high intensity work

REMEMBER!

A 400m runner will consume a large volume of oxygen during the slow replenishment stage as a large amount of lactic acid will have accumulated in their muscles.

KEY TERMS

Active recovery:
a recovery period during which time light exercise is performed

Rest recovery:
a recovery period during which time the performer has rested passively

Cori cycle:
the process where lactic acid is taken to the liver for conversion into glucose and glycogen

REMEMBER!

The exercise intensity during a cool down that best removes lactic acid is between 30–45% VO_2max for untrained subjects and 50–65% VO_2max for trained performers.

TASK 1.05

Figure 1.14 is often used to illustrate EPOC.

1. From the graph state what each of the letters A–E represents.
2. For what is the oxygen consumed during part 'D' used?
3. Which letters can be used to determine EPOC?

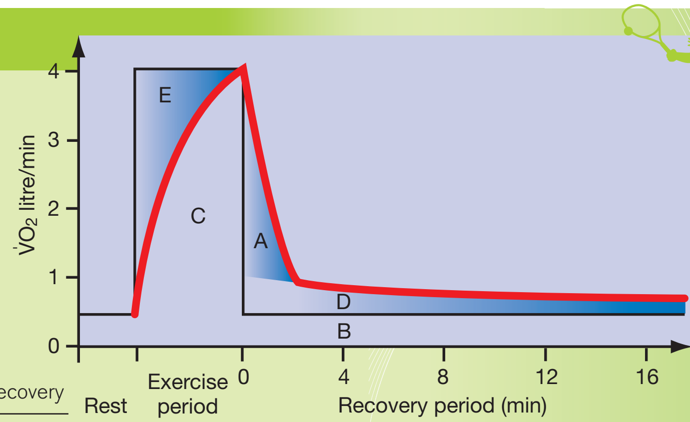


Fig 1.14 Oxygen consumption during exercise and recovery

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TASK 1.06

The data in table 1.03 relates to the rate of lactate removal during recovery from exhaustive exercise following (i) **rest recovery** and (ii) active recovery.

1. Draw a graph of % lactate removed against time using the data in the table. Briefly explain what the graph shows.
2. On your graph mark off the times for each type of recovery when 50 per cent of blood lactate had been removed. What does this suggest?
3. What type of activity would you suggest a performer undertake during a period of active recovery?
4. What intensity of exercise (measured as a percentage of VO_2max) would you suggest the active recovery period is completed for a) an untrained subject b) a trained performer?

% lactate removed	Recovery time (mins) (Rest recovery)	Recovery time (mins) (Active recovery)
20	8	4
40	20	8
60	35	15
80	55	25
100	180	70

TASK 1.07

Copy out the following table and complete the approximate recovery times for each factor

Recovery process	Recovery time
Re-saturation of myoglobin with oxygen	
Resynthesis of muscular stores of ATP and PC	
Repayment of fast component of EPOC	
Removal of lactic acid: • with active recovery • with rest recovery	
Repayment of slow component of EPOC	
Restoration of muscle glycogen stores	

Maximal oxygen consumption (VO_2max)

Lance Armstrong's is **VO_2max** reported as 83.8ml/kg/min, Paula Radcliffe's an amazing 80ml/kg/min and Matt Pinsent has the highest ever recorded in the UK at a staggering 8.5 litres/min! What do these figures represent? Well it's their VO_2max of course! Indeed if you go into the chat rooms of any marathon running web sites conversation soon turns to the size of your VO_2max. For effective endurance performance we need a big and efficient pump to deliver oxygen-rich blood to the muscles and we need mitochondria-rich muscles to use the oxygen and enable high rates of exercise.

VO_2max or maximal oxygen uptake can therefore be defined as:

'…the maximum volume of oxygen that can be utilised or consumed by the working muscles per minute…'

A high VO_2max, or maximal oxygen uptake, is indeed one of the hallmark characteristics of great endurance performance in activities such as swimming, cycling, rowing and running. However, it is elite cross country skiers that are considered the most powerful in oxygen uptake capacity. This is probably because cross country skiing engages just about all of the major muscle groups of the body. This is not, however, the only determining factor of VO_2 max.

The ability of the muscles to consume the greatest amount of oxygen as possible the body is dependent upon two further key factors:

1. An effective oxygen delivery system that brings oxygen from the atmosphere into the working muscles
2. An aerobic-friendly muscle structure which possesses a large volume of myoglobin and a high density of mitochondria which can be used to produce ATP via the aerobic energy system.

Measuring maximal oxygen consumption (VO_2max)

You will recall from your AS studies that there are several tests of maximal oxygen consumption (VO_2max). These tests are listed below:

- The multi-stage fitness test
- Harvard step test
- PWC170 test
- Cooper 12-minute run test.

Whilst the multi-stage fitness test gives a reasonable prediction of VO_2max it cannot give a truly objective measure of the volume of oxygen actually consumed by the working muscles. The only way we can possibly do this is in a sports science laboratory where **direct gas analysis** can take place. In order to determine an athlete's true maximal aerobic capacity, exercise conditions must be created that maximally stress the blood delivery capacity of the heart.

Fig.1.15 Cross-country skiers reportedly have the highest VO_2max of all sports performers

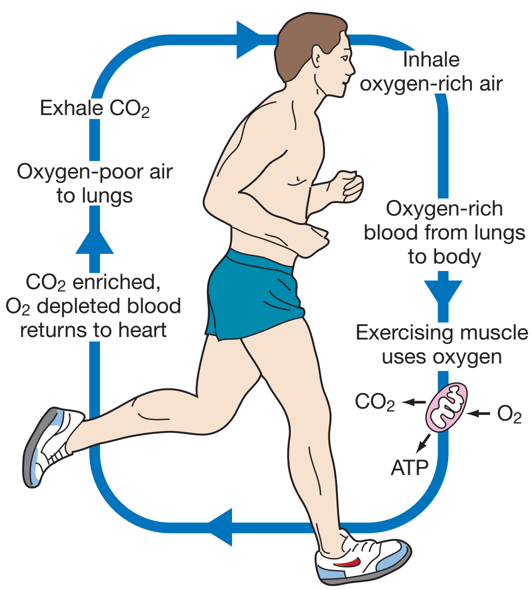

Fig 1.16 Oxygen transport and consumption during exercise

Here is an example of a VO_2 max treadmill test using Johnny, a typical A level student as a subject:

1. Firstly Johnny is weighed. This is so his VO_2 max can be given relative to his body weight. A simple reading of ml/min would ignore the fact that larger people have larger lungs and are capable of taking in more oxygen into their bodies.
2. Following a warm-up, Johnny places a mask over his mouth which is attached to the computer by a hose tubing. Johnny begins the treadmill test at a speed of 10km/h. Whilst running he breathes through a two-way valve system. The computer analyses the relative concentrations of oxygen and carbon dioxide inspired and expired respectively. From this it is possible to calculate the amount of oxygen extracted and consumed by the muscles and the amount of carbon dioxide produced over time. In order to reach an exhaustion point and get a maximum reading the treadmill speed is increased by 1km/h every minute.
3. After 2 minutes the speed of running has increased to 12km/h, the graph below shows an increase in the level of oxygen breathed in and carbon dioxide breathed out. The distance between the two values shows that Johnny is

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working aerobically with a good supply of oxygen to the muscles. He is in steady state where oxygen demand is being met by oxygen supply.

4. After 7 minutes the speed has increased to 17 km/h and Johnny's heart rate has increased significantly to 192 bpm. His breathing rate has become faster as the levels of carbon dioxide increase further. Now the level of oxygen begins to level out. Johnny will have to call on more and more anaerobic energy to meet any further extra energy demands as his body struggles to get oxygen to his muscles.
5. After 10 minutes Johnny is racing along at 20 km/h, his heart is doing overtime at over 200 bpm and his lungs are working at their maximum to get oxygen into the body. This is the point where the VO_2 max is taken. His reading is 57.6 ml/kg/min. After nearly 10.5 minutes Johnny is completely exhausted. He can no longer exercise and the test is stopped.
6. Johnny's reading of 57.6 ml/kg/min is good and shows that he has some capacity to perform endurance based activity.

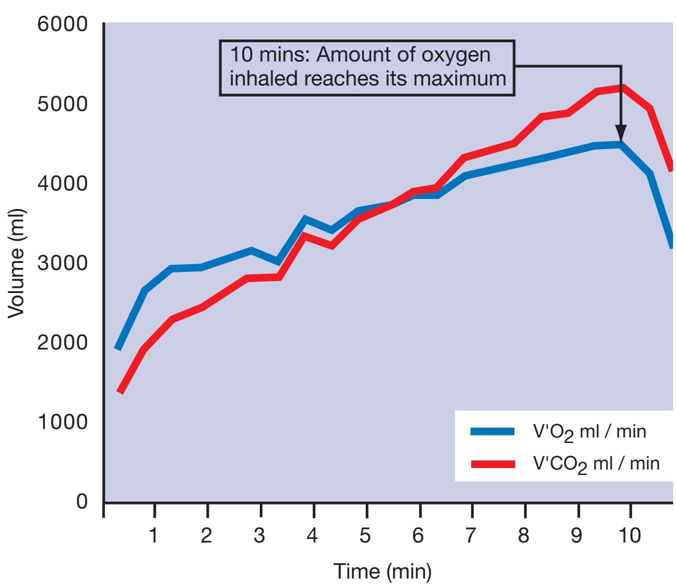

Fig 1.17 VO_2max timeline: Johnny's results

KEY TERMS

Direct gas analysis:
the most valid and reliable method of measuring VO_2max. During the test, subjects are measured at progressively increasing intensities on a treadmill, cycle ergometer or rowing machine. Concentrations of oxygen and carbon dioxide inspired and expired are monitored

Maximal oxygen consumption (VO_2max):
the maximum volume of oxygen that can be utilised or consumed by the working muscles per minute. It is usually measured in ml/kg/min

REMEMBER!

VO_2max is expressed as a rate, either millilitres per kg of bodyweight per minute for weight bearing activities such as running or litres per minute for partial weight bearing activities such as rowing or cycling.

TASK 1.08

Use the following data to plot a bar graph illustrating the expected VO_2max scores for the activities shown.

Activity	Male (ml/kg/min)	Female (ml/kg/min)
Triathlete	80	72
Marathon runner	78	68
Distance swimmer	72	64
Middle distance runner (800–1500)	72	63
Games player	66	56
Gymnast	56	47
Weightlifter	52	43

KEY TERMS

Absolute VO_2max:
a VO_2max value given in litres/min

Relative VO_2max:
a VO_2max value that takes account of bodyweight and measured in millilitres of oxygen per kg of bodyweight per minute (ml/kg/min)

REMEMBER!

1. The average VO_2max score for an average 'A' level student should be around 45–55 ml/kg/min for males and 35–44ml/kg/min for females.

2. Surprisingly, endurance training such as following a continuous training regime can only improve VO_2max by between 10 and 20%.

3. When we consider **absolute VO_2max** the typical untrained male has a value of 3.5 litres/min whilst that of a female is approximately 2 litres/min – a 43% difference! When we consider bodyweight to give a **relative** value this difference is reduced to 15–20%.

4. As a rule of thumb when VO_2max is measured in relative terms (taking bodyweight into consideration) female athletes have a score of approximately 10ml lower than comparable males of the same activity group

Factors affecting maximal oxygen consumption (VO_2max)

Fig 1.18 summarises the main factors that affect an individual's maximal oxygen consumption.

Physiology
The physiological make up of the body will almost certainly affect VO_2 max. Below are just a few physiological factors that contribute to a higher VO_2max score:
* a high percentage of slow twitch (type 1) muscle fibres
* high capillary density
* high mitochondrial density and myoglobin content
* high blood volume and haemoglobin content.

Lifestyle
Smoking, leading a sedentary lifestyle and having a poor diet can greatly reduce VO_2max values.

Age
Typically VO_2max will decrease with age. After the age of 25 years, VO_2max is thought to decrease by about 1 per cent per year. Regular physical activity can slow down the rate of this decline.

Genetics
Studies on identical and fraternal twins have suggested that genetics accounts for 25 to 50 per cent of VO_2max scores.
It appears that Olympic champions are born with a unique potential that is transformed into athletic performance through years of hard training.

Body composition
Research shows that VO_2max scores decrease as the percentage of body fat increases. This is because fat is non-functional weight that must be carried around. Typically males should aim for a body fat per cent of between 14–17 per cent whilst females should aim for a value between 24–29 per cent.

Gender
When we consider absolute VO_2max, the typical untrained male has a value of 3.5 litres/min whilst that of a female is approximately 2l/min – a 43 per cent difference! When we consider bodyweight to give a relative value this difference is reduced to 15 to 20 per cent.

Training
VO_2max can only be improved by 10 to 20 per cent following training. This is somewhat surprising given the vast improvement in the delivery and transport of oxygen resulting from long-term endurance training. The best methods of training to improve VO_2max include continuous training, Fartlek and aerobic interval training.

Fig 1.18 Factors affecting maximal oxygen consumption (VO_2max)

TASK 1.09

If your absolute VO_2max was measured at 4.0 litres/min and you weighed 75kg, calculate your relative VO_2max.

TASK 1.10

Design a training programme aimed at improving the VO_2max of a performer. Make sure you prescribe appropriate methods of training and clearly state the expected intensity of training.

EXAM TIP:

Make sure you are able to describe a test of VO_2max. You must be able to critically evaluate the test commenting on its validity and reliability.

The respiratory exchange ratio (RER)

The **respiratory exchange ratio** is the ratio of the volume of carbon dioxide expired per minute to the volume of oxygen consumed per minute and is used by the coach and athlete as a measure of the intensity at which the athlete is training.

The respiratory ratio can be assessed as follows:

$$\text{Respiratory exchange ratio} = \frac{\text{Carbon dioxide expired per minute } (VCO_2)}{\text{Oxygen consumed per minute } (VO_2)}$$

However, the amount of energy released through the consumption of every litre of oxygen is dependent upon the type of food fuel that is metabolised.

You will recall from page 9 that the following formula can be used to summarise the aerobic breakdown of glucose (our usable form of carbohydrate):

$$C_6H_{12}O_6 \text{ (glucose)} + 6O_2 \longrightarrow 6CO_2 + 6H_2O + \text{energy}$$

From this equation we can see that to break down one mole of glucose, 6 moles of oxygen are required which elicits energy plus 6 moles of carbon dioxide and 6 moles of water. Notice that all the oxygen inspired here is used to form carbon dioxide.

$$RER = \frac{VCO_2}{VO_2} = \frac{6CO_2}{6O_2} = 1.0$$

However, when fat is oxidised the oxygen inspired does not only combine with carbon to form carbon dioxide but some is also required to combine with hydrogen to produce water:

$$C_{16}H_{32}O_2 \text{ (fat)} + 23O_2 \longrightarrow 16CO_2 + 16H_2O$$

So this formula tells us that in order to break down one mole of fat 23 moles of oxygen is required: 16 moles of which combine with carbon to form carbon dioxide, the remaining 7 moles combine with hydrogen to form water.

$$RER = \frac{VCO_2}{VO_2} = \frac{16\ CO_2}{23\ O_2} = 0.17$$

So the metabolism of fat only elicits 70% of the energy per litre of oxygen consumed than when compared to carbohydrate. So although fat contains twice the chemical energy of carbohydrate per gram, it requires more oxygen to release the energy stored within it.

KEY TERMS

Respiratory exchange ratio:
a method of determining which metabolic fuel is predominantly in use during exercise. It is calculated by analysing oxygen consumption and carbon dioxide production

EXAM TIP:

It is usual to refer to VCO_2/VO_2 at cellular level as the respiratory quotient (RQ) and at lung level as the respiratory exchange ratio (RER).

The respiratory exchange ratio is important for the coach and athlete when planning training, as it can be used to assess the intensity at which a performer is working. If the RER is closer to 1 this suggests that the athlete is working hard and training at a higher intensity as more carbohydrate is being used as a metabolic fuel. Conversely, if the RER is closer to 0.7 then the body is relying more heavily on fat as a metabolic fuel and the intensity of the training will be comparatively lighter.

REMEMBER!

The respiratory exchange ratio can only be assessed under laboratory conditions where the consumption of oxygen and the production of carbon dioxide can be analysed through direct gas analysis.

The anaerobic energy systems

The ATP-PC (alactic) system

We have established that muscular stores of ATP will have depleted after about 3 seconds of maximal activity. For high intensity activity to continue the immediate recycling of ATP is necessary. However the rapid increase in activity results in insufficient oxygen being available (an oxygen deficit) to sustain this ATP resysnthesis. The body therefore relies upon a second energy-rich compound found alongside ATP in the muscle cells. This compound is **phosphocreatine (PCr)**.

Like ATP the breakdown of phosphocreatine takes place in the **sarcoplasm** of a muscle cell and is facilitated by the enzyme **creatine kinase**. The release of creatine kinase is stimulated by the increase in ADP and inorganic phosphates (both products of ATP breakdown)

PCr ⟶ Creatine + Pi + energy

Unlike ATP, the energy released from the breakdown of phosphocreatine is not used for muscle contraction but is instead used to recycle ATP, so that it can once again be broken down to maintain a constant energy supply.

Energy (from PCr breakdown) + ADP + Pi ⟶ ATP

As energy is required for this reaction to take place it is known as an **endothermic reaction**.

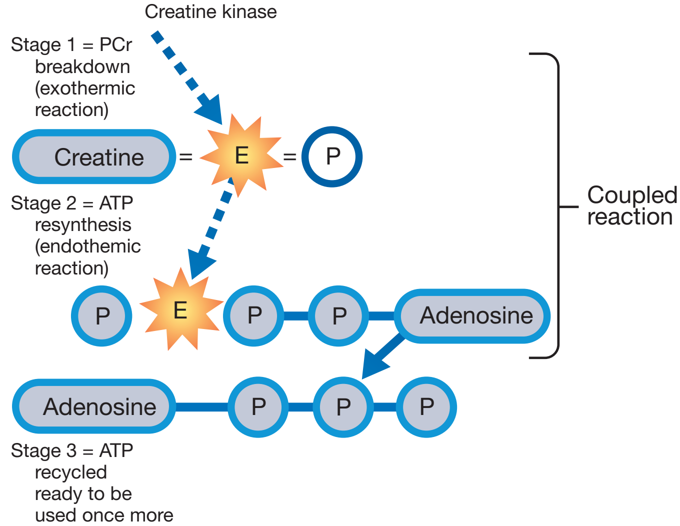

Fig 1.19 The ATP-PC system as a coupled reaction

The coupled reaction

Because PCr exists alongside ATP in the sarcoplasm of the muscle cell, as rapidly as energy is released from ATP during exercise it is restored through the breakdown of PCr. This linked reaction more or less occurs simultaneously and It takes one molecule of PCr to recycle one molecule of ATP.

Advantages of this system to the athlete

- The most important feature of this system is that ATP can be resynthesised very rapidly (almost immediately) by PCr.
- PCr stores are recovered very quickly, within 2–3 minutes of exercise stopping. This means that high intensity exercise can once again be undertaken.
- It is an anaerobic process and so does not need to wait for the 3 minutes or so for sufficient oxygen to be present.
- There are no fatiguing by-products which could delay recovery.
- Some athletes may seek to extend the time that they can use this system through **creatine supplementation**.

REMEMBER!

1. The ATP-PC system is of particular use to athletes who compete at high intensity for about 10 seconds such as a 100m sprinter or a gymnast performing a vault
2. **Creatine supplementation:** Some athletes seek to extend the threshold of the ATP-PC system by ingesting creatine monohydrate. Side effects such as abdominal cramps, bloating and dehydration have been recorded.

Drawbacks of this system to the athlete

- The main drawback is that there is only a limited supply of PCr stored in the muscle cell, sufficient only to resynthesise ATP for approximately 10 second or so. Fatigue occurs when concentrations of PCr fall significantly and can no longer sustain ATP resynthesis.
- Resynthesis of PCr can only take place when there is sufficient oxygen available – this is usually during resting conditions once exercise has ceased.
- Only 1 mole of ATP can be recycled through 1 mole of PCr.

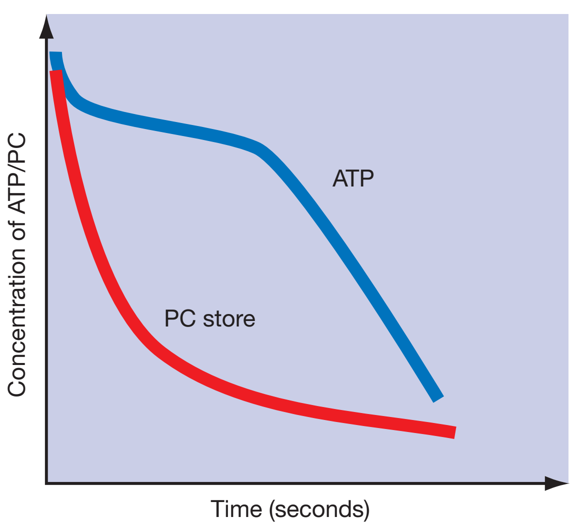

Fig.1.20 Muscle phosphagen depletion during a 100m sprint

Note that ATP levels remain high at the start of the race due to the action of PCr providing energy to maintain levels. However, after pproximately ten seconds, stores of phosphocreatine have become depleted and ATP levels fall rapidly.

REMEMBER!

Don't forget that for very high intense activities lasting less than 3 seconds, such as a maximum weight lift, energy will be provided solely through the breakdown of ATP.

KEY TERMS

Sarcoplasm:
fluid that surrounds the nucleus of a muscle cell, that is the site for both anaerobic energy pathways

Creatine kinase:
the enzyme used to release energy from phosphocreatine

Endothermic reaction:
a chemical reaction that consumes energy

Coupled reaction:
a reaction where the product of one reaction is used in a linked (second) reaction. the ATP-PC system is an example of a coupled reaction

The lactic acid (lactate anaerobic) system

Most activities last longer than the 10 second threshold of the ATP-PC system. If strenuous exercise is required to continue, ATP must be resynthesised from another fuel source. In fact, the body switches to **glycogen** (our stored form of carbohydrate) to fuel the working muscles once phosphocreatine stores have been depleted. The glycogen which is stored in the liver and muscles must first be converted into glucose-6-phosphate before it is broken down to **pyruvate** by the enzyme **phosphofructokinase (PFK)** in a process known as **glycolysis**. It is during glycolysis (which takes place in the sarcoplasm of the muscle cell) that energy is released to facilitate ATP resynthesis. In fact a net gain of 2 moles of ATP are gained for every mole of glycogen broken down. In the absence of oxygen, pyruvate is converted into lactate (lactic acid) by the enzyme **lactate dehydrogenase (LDH)**.

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TASK 1.11

During a 100m sprint ATP will initially split to enable the athlete to drive away from the starting blocks. PCr is then broken down to maintain a constant supply of energy for the remainder of the race. Complete the table below with the required information.

	Site of reaction	Fuel used	Active enzyme	Molecules of ATP produced
ATP splitting				
ATP-PC system				

$$C_6H_{12}O_6 \longrightarrow 2(C_3H_6O_3) + \text{ENERGY}$$

(glucose) (lactic acid)

$$\text{ENERGY} + 2\text{ADP} + 2\text{Pi} \quad 2\text{ATP}$$

- During aerobic activities such as a 10,000m run the lactic acid system can be called upon to produce an extra burst of energy during the race or indeed at the end of the race during a sprint finish.

Advantages of this system to the athlete

- Because there are few chemical reactions, ATP can be resynthesised relatively quickly for activities or bouts of exercise that last between 10 seconds and 3 minutes.
- It is an anaerobic process and so does not need to wait for the 3 minutes or so for sufficient oxygen to be present.
- Any lactic acid that has accumulated can be converted back into liver glycogen or indeed be used as a metabolic fuel by reconversion into pyruvate and entry into the aerobic system.

Drawbacks of this system to the athlete

- The most obvious drawback of this system is the accumulation of lactic acid which can make glycolytic enzymes acidic. This causes them to lose their catalytic ability, inhibiting energy production through glycolysis. The intensity of the exercise must be reduced or in the worst case scenario stopped so that the body can remove the lactic acid that has accumulated.
- Only a small amount of energy (approximately 5%) locked inside our glycogen molecule can be released in the absence of oxygen. The remaining 95% can only be released in the presence of oxygen.

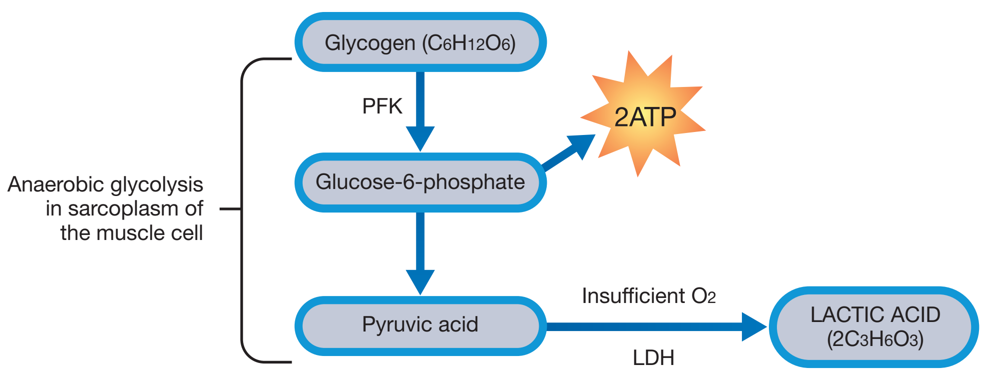

Fig.1.21 A summary of the lactic acid system

TASK 1.12

During a 400m hurdles race the ATP-PCr system will be used during the first 10 seconds or so and then the lactic acid system will provide the energy for ATP resysnthesis for the remainder of the race. Complete the table below with the required information.

	Site of reaction	Fuel used	Active enzyme	Molecules of ATP produced
Lactate anaerobic system				

KEY TERMS

Threshold:
the point where one energy system is exhausted and another takes over as the predominant system, e.g. the LA-O_2 threshold represents the point where sufficient oxygen becomes available to enable the aerobic system to take over as the major energy provider

Glycogen:
the form of carbohydrate stored in the muscles and liver

Glycolysis:
the breakdown of glucose to pyruvic acid

REMEMBER!

The lactic acid system is of particular use to athletes who need to perform high intensity exercise for a period of 1–2 minutes. A 400m runner is an obvious example, as is a squash player during a lengthy rally.

Onset of blood lactate accumulation (OBLA)

A large VO_2max sets the ceiling for endurance performance and is an indication of the size of our aerobic performance engine. However it is the onset of blood lactate accumulation **(OBLA)** that determines the actual percentage of that engine power that can be utilised.

The onset of blood lactate accumulation describes the point at which lactic acid starts to accumulate in the muscles. During normal resting conditions the amount of lactic acid circulating in the blood is between 1 to 2 **millimoles**/litre. This rises dramatically during intense exercise. Quite simply, the more intense the exercise the greater the extent of lactic acid production. The OBLA is said to occur when concentrations of lactic acid in the blood reach 4millimoles/litre.

Just like VO_2max, OBLA occurs at different intensities of exercise for different people and **it is expressed as a percentage of your VO_2max**. For the average untrained individual OBLA occurs at around 55–60% of their VO_2max whilst trained endurance performers can delay OBLA until they have utilised 85–90% of their VO_2max.

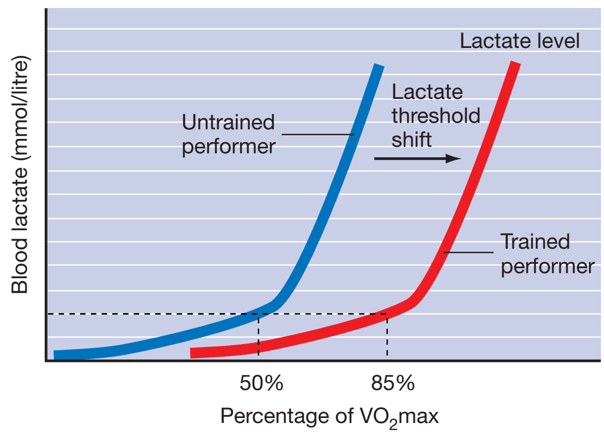

Fig 1.22 A comparison of the point of OBLA between trained and untrained athletes when measured as a percentage of their VO_2max

REMEMBER!

You may have heard of the lactate **threshold** and anaerobic threshold. Together with OBLA these describe the same phenomenon.

KEY TERMS

Onset of blood lactate accumulation (OBLA):
the point at which lactic acid begins to accumulate in the blood. Usually taken when concentrations of lactic acid reach 4mmole/litre of blood

Millimole (mmole):
a unit used to measure the amount of a chemical substance. It is equal to 1/1000 of a mole

APPLY IT!

Lance Armstrong can tap into an exceptionally high percentage of his VO_2max. His OBLA reportedly occurs at 88.6% of his VO_2max.

Lactate sampling and measuring OBLA

OBLA can only truly be measured in a sports science laboratory. The test should be conducted using a mode of exercise most suited to the performer, usually a treadmill, bicycle ergometer, rowing ergometer or swimming bench. Typically the test is conducted in 4–6 stages. During the first stage the exercise intensity is set at about 50% of VO_2max and increases in intensity at the start of each of the subsequent stages. Each stage generally lasts about 5 minutes. At the end of each stage heart rate recorded, oxygen consumption measured and blood samples are taken by a small prick on the finger or earlobe and the concentration of blood lactate is analysed. The point at which blood lactate levels rise to 4mmol/litre of blood usually signals OBLA. The exercise intensity, oxygen consumption and heart rate at this point is now recorded and used to monitor progress and assess exercise intensity during training.

OBLA and training

Improvements in endurance capacity can be observed where lower lactate levels are recorded for any given exercise intensity. This shows that the body has adapted to cope with higher levels of blood lactate and increased the rate of its removal through effective **buffering**. You will recall that untrained individuals usually reach OBLA at about 55–60% of VO_2max. With training this figure can increase to 70% or even higher. Elite endurance athletes such as Lance Armstrong have values approaching 90%. Whist OBLA is a much greater product of training than VO_2max it is still influenced by genetics.

A word on lactic acid

You will recall that lactic acid is produced when there is insufficient oxygen available to sustain a given exercise intensity. The pyruvic acid produced during glycolysis is converted to lactic acid by the enzyme lactate dehydrogenase. Once formed lactic acid quickly dissociates into lactate and hydrogen ions (H+). It is the presence of hydrogen ions that make the muscle acidic and ultimately causes muscle fatigue. The acidic environment slows down enzyme activity and ceases the breakdown of further glycogen. High levels of acidity can also irritate nerve endings which can cause some degree of pain – the 'heavy legs' often associated with lactic acid can thus be blamed on the hydrogen ions.

However lactic acid is not always the bad guy it is made out to be. The heart, the liver, the kidneys and inactive muscles are all locations where lactic acid can be taken up from the blood and either converted back into pyruvate and metabolised in the mitochondria producing energy or converted back to glycogen and glucose in the liver. The table below summarises what happens to the lactic acid once it has been removed from the muscle.

Lactic acid from blood	
Conversion into CO_2 and H_2O	Up to 65%
Conversion into glycogen	Up to 20%
Conversion into protein	Up to 10%
Conversion into glucose	Up to 5%
Conversion into sweat and urine	Up to 5%

Table 1.02 The fate of lactic acid

TASK 1.13

Using the information from table 1.04 plot a graph of blood lactate accumulation (mmol/litre on *y* axis) against running speed (ms^{-1} on *x* axis).

1. On your graph show the point of OBLA. Give a brief explanation as to why you have chosen this point on the graph.
2. At what running speed did OBLA occur?

Blood lactate (mmol/litre)	2.9	3.7	5.7	9.1
Running speed ms^{-1}	3.5	4.00	4.5	4.9

Factors influencing the rate of lactic acid accumulation

- **Exercise intensity:** the higher the exercise intensity the greater the ATP demand which can only be sustained using glycogen as a fuel. As fast twitch fibres possess greater stores of glycogen (and therefore lactate dehydrogenase) pyruvate is soon converted to lactic acid.
- **The respiratory exchange ratio (RER):**

$$\frac{VCO_2 \text{ expired/min}}{VO_2 \text{ uptake/min}}$$

The closer the value is to 1.0 the more likely the body is using glycogen as a fuel and the greater the chance of lactic acid accumultation. If the value is nearer 0.7 then fatty acids is the likely fuel. This is also known as the respiratory quotient.

- **Muscle fibre type:** Slow twitch fibres produce less lactate at a given workload than fast twitch fibres. As slow twitch muscle fibres possess greater amounts of mitochondria, pyruvate will tend to converted into Acetyl Co A and move into the mitochondria with little lactate production.
- **Rate of blood lactate removal:** If the rate of lactate removal equals the rate of production then blood lactate concentrations should remain constant. When the rate of lactate production exceeds the rate of removal then blood lactate will accumulate as we reach OBLA.
- **The trained status of the working muscles:** If muscles are trained then they benefit from the associated **adaptive responses**. These include improved capacity for aerobic respiration due to higher mitochondrial and capillary density, improved use of fatty acids as a fuel (which do not produce lactic acid!) and increased stores of myoglobin.

TASK 1.14

The graph below provides data gained from an OBLA test on a middle distance runner.

1. Use the graph to calculate OBLA of the runner given she has a VO_2max of 61ml/kg/min.
2. If her HRmax is 182bpm at what percentage of HRmax does OBLA occur?

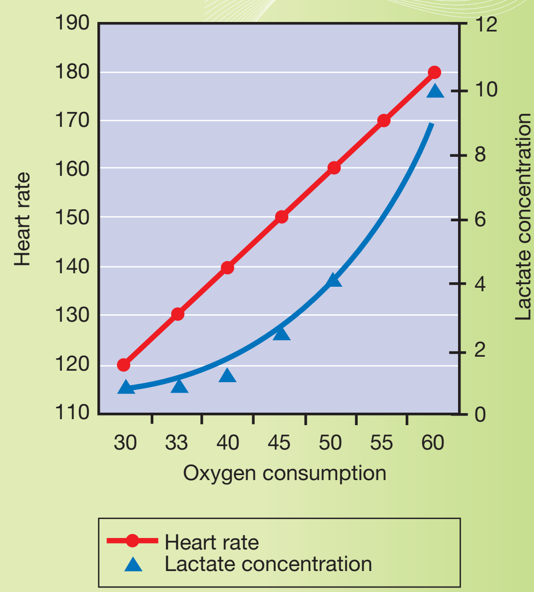

Fig 1.23 The relationship of oxygen consumption to heart rate and lactate concentration of a middle-distance runner during a maximal test to exhaustion

APPLY IT!

A cyclist during a time trial can use data from the OBLA test to determine her racing heart rate by calculating the percentage of HRmax that leads to OBLA. If she had a HRmax of 182bpm and OBLA occurred at a HR of 158bpm this equates to about 87 per cent of HRmax. Her racing heart rate should be somewhere just below this point.

KEY TERMS

Buffering:
a process which helps in the removal of lactic acid and maintains blood and muscle pH (acidity)

Adaptive responses:
the anatomical and physiological changes that occur to the body as a consequence of training

EXAM TIPS:

1. Although lactic acid and lactate are often used interchangeably, they are not in fact the same thing.
2. The following equation can be used to calculate the percentage of VO_2max used by a performer:

$$\frac{VO_2 \text{ (amount of } O_2 \text{ used)}}{VO_2\text{max (max potential)}}$$

ATHLETE PROFILE

Becky Wing is currently studying AS PE at Sixth Form College in Farnborough, Hampshire. At the age of 16, Becky is already an Olympian. She was a member of the Great Britain Gymnastics team in the Beijing Olympics finishing in 9th place in the team event. She is currently preparing for the 2012 London Olympics.

Becky has access to three personal coaches at her Heathrow Gymnastics Club and two National gymnastic coaches. She trains between 4 to 6 hours, 6 days per week. Each session will consist of a half-hour warm up and up to 1 hour of conditioning work. The conditioning work mainly focuses on the development of explosive strength and muscular endurance, the two key components of fitness required by gymnasts. Her explosive strength training which consists of plyometrics type activity will help develop and improve the efficiency of her ATP-PC system whilst the muscular endurance training will seek to enhance the removal of lactic acid extending the time that she can use the lactate anaerobic system before fatigue sets in. This will of course be essential during a floor routine which consists of approximately 90 seconds of very high intensity activity.

ExamCafé

Relax, refresh, result!

Refresh your memory

Revision checklist

Make sure you know the following:

- Energy is the capacity to perform work.
- Energy is measured in calories (kcal) or joules (J). 1 calorie = 4.184 joules.
- The food fuels: fats, carbohydrates and proteins are the major energy sources in the body.
- Food fuels however are only a secondary source of energy – the energy stored within them must first be converted and stored as adenosine triphosphate (ATP) before it can be accessed.
- ATP is the energy currency of all cells and is the only direct source of energy in the body.
- When energy is required ATP is broken down by the enzyme ATPase to release energy plus ADP (adenosine diphosphate) and an inorganic phosphate (Pi)
  ATP $\longrightarrow$ ADP + Pi + Energy.
- This reaction is exothermic which means that energy is released in the form of heat.
- There is only sufficient ATP stored within the muscles to perform high intensity exercise for 2 or 3 seconds.
- Once ATP has been broken down to release energy it must be constantly recycled.
- There are three energy systems that provide the energy for ATP resynthesis.
- The source of energy for ATP resynthesis is dependent upon primarily the intensity and then the duration of the activity.
- During low intensity exercise of longer duration the aerobic (oxidative) energy system is used for ATP resynthesis.
- During medium–high intensity exercise the lactic acid system is used for ATP resynthesis.
- During short periods of maximum exercise intensity the ATP-PC (alactic) energy system is used for ATP resynthesis.

Aerobic energy systems

- The aerobic system uses a combination of fats and carbohydrates to provide the energy for ATP resynthesis.
- The aerobic system is the most efficient energy system yielding 18 times more energy than anaerobic processes.
- The site for aerobic respiration are the mitochondria which are the powerhouses of the muscle cells.
- The Krebs cycle takes place in the matrix of the mitochondria and produces carbon dioxide and sufficient energy to recycle 2 moles of ATP.
- The electron transport system is the final stage of the aerobic system which produces water and enough energy to resynthesise 34 moles of ATP.
- Enzymes used in the aerobic system include phosphofructokinase (PFK), glycogen phophorylase (GP) and lipase.
- As the duration of the exercise period increases fatty acids become the preferred fuel as more energy can be elicited from one mole of fatty acids than from one mole of glycogen.
- The complete breakdown of one mole of glycogen can be summarised as follows:

$$C_6H_{12}O_6 + 6O_2 \longrightarrow 6CO_2 + 6H_2O + \text{Energy}$$

$$\text{Energy} + 38ADP + 38Pi \longrightarrow 38ATP$$

- Recovery is concerned with returning the body to its pre-exercise state.
- Recovery can only occur via the aerobic system and only then when there is sufficient oxygen available.
- The oxygen deficit is the volume of oxygen required to complete an activity entirely aerobically.
- Excess post-exercise oxygen consumption (EPOC) is the volume of oxygen consumed during recovery above that which normally would have been consumed at rest during the same period of time.
- There are two stages to EPOC: the fast and slow stages.
- The fast stage of EPOC occurs rapidly, taking just 2–3 minutes. The oxygen consumed during this stage is used to replenish ATP and PC stores and to re-saturate myoglobin.
- The slow stage of EPOC takes up to 1 hour. The oxygen consumed during this stage is used to remove lactic acid and provide the energy to maintain elevated heart and respiratory rates.
- A low VO_2max score can limit performance in endurance activities.
- Factors that can limit VO_2max include: genetics, physiological make-up, lifestyle choices, age, sex, and the volume of training undertaken.

Anaerobic energy systems

- The ATP-PC system is the first of the anaerobic energy systems and used in those activities that are of the highest intensity but short in duration, lasting between 3 and 10 seconds – such as a 100m sprint.
- The fuel for resynthesis in the ATP-PC system is phosphocreatine, a high energy compound found in all muscle cells.
- Enzymes used in the ATP-PC system include creatine kinase which breaks down PC.
- The ATP-PC system involves a coupled reaction which occurs when the product of one reaction is used in a second reaction.
- The ATP-PC system can be summarised as follows:

  $PC \longrightarrow Pi + C + \text{Energy}; \text{Energy} + ADP + Pi \longrightarrow ATP$

- The main drawback of the ATP-PC system is that there is only a limited supply of PC in the muscle cell which is exhausted after approximately 10 seconds.
- The lactate anaerobic or lactic acid system is predominant in activities of moderate to high intensity that are of 1–3 minutes' duration – such as a 400m run.
- The lactate anaerobic system involves the process of glycolysis, which relates to the breakdown of glycogen and glucose.
- Under the lactate anaerobic system, energy resulting from the breakdown of glycogen into pyruvate is sufficient to recycle 2 moles of ATP.
- Enzymes involved in glycolysis include phosphofructokinase (PFK) and glycogen phosphorylase (GP).
- In the absence of oxygen pyruvate is converted into lactic acid by the enzyme lactate dehydrogenase.
- Any lactic acid produced during exercise can be converted back into liver glycogen or used as a metabolic fuel by reconversion into pyruvate and entry into the aerobic system.
- The lactate anaerobic system can be summarised as follows:

  $C_6H_{12}O_6 \longrightarrow 2C_3H_6O_3 + \text{Energy}; \text{Energy} + 2ADP + 2Pi \longrightarrow 2ATP$

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- Drawbacks of the lactate anaerobic system include the fatiguing effect of lactic acid on the muscles, and the fact that only a tiny amount (5%) of the energy stored within the glucose molecule can be accessed to provide energy for ATP resynthesis.
- The onset of blood lactate accumulation (OBLA) is the point at which lactic acid begins to accumulate in the blood.
- OBLA is usually said to have occurred when concentrations of lactic acid reach 4mmol/litre of blood.
- OBLA can be expressed as a percentage of VO_2max. Trained performers can achieve a higher percentage of their VO_2max than the untrained. Training therefore delays OBLA.
- The rate of lactate accumulation is dependent upon exercise intensity, muscle fibre type, the trained status of the working muscles and the rate of blood lactate removal.
- Buffering is a process which helps in the removal of lactic acid and maintains blood and muscle pH at acceptable levels.
- The removal of lactic acid occurs in a number of different ways: up to 65% is converted into carbon dioxide and water; up to 20% is converted back into muscle and liver glycogen; up to 10% is converted into protein, up to 5% is converted into blood glucose; up to 5% is removed as sweat and urine.

Revise as you go

1. Write out an equation which summarises each of the three energy systems.
2. Explain the specialist role of the mitochondria in the production of energy.
3. Draw a diagrammatic representation of each of the three energy systems.
4. Compare the three energy pathways with regard to their relative efficiency.
5. Explain the energy continuum in relation to a games player of your choice. Use specific examples from the game when each energy system is likely to be in use.
6. Explain what happens when a marathon runner 'hits the wall'.
7. What nutritional advice would you give a marathon runner preparing for a major competition in the coming week?
8. Construct a food fuel graph which illustrates the predominant food fuel against time during a triathlon.
9. Why might performers take creatine supplements? What type of performer is likely to benefit from creatine supplementation?
10. Outline some methods of training you would use to develop and improve your ATP-PC system. For one of these methods give an example of a training session.
11. Define VO_2max.
12. Suggest typical VO_2max values for the following:
    a) a healthy male 'A' level PE student
    b) a centre in netball
    c) an Olympic rower.
13. The multi-stage fitness test or 'bleep test is often used to determine the VO_2max of an athlete. Briefly outline this test and give reasons why this may not be the most accurate test to use.
14. Identify and explain the procedures of a more valid test that may be used.
15. Outline the factors that could limit VO_2max.
16. Suggest a method to improve VO_2max.
17. Explain why the VO_2max of women is typically 15–20 per cent lower than that of men from the same activity group.
18. Define the following terms:
    - recovery
    - oxygen deficit
    - EPOC
19. How long does it take the fast component of EPOC to recover?
20. How is lactic acid removed from the muscle following a 400m run? What organs and tissues are involved in the removal of lactate?
21. Explain the terms 'active recovery' and 'rest recovery'. How do these different types of recovery influence the speed of lactate removal?

22. Explain the replenishment of muscle glycogen stores with reference to:
    - the type of exercise performed
    - the post-event meal.
23. Outline the recovery patterns for the following performers:
    - a gymnast performing a vault
    - an 'iron-man' triathlete
    - a 200m butterfly swimmer.
24. Swimmers are often required to compete in several events during a swimming gala. What advice would you give a swimmer concerning recovery between events?
25. Briefly explain why EPOC is often larger than the oxygen deficit.
26. How can knowledge of the recovery process be of use to the coach and athlete when designing training programmes?
27. Explain what you understand by the term 'OBLA'.
28. OBLA and lactate threshold are often used interchangeably. How is the lactate threshold related to VO_2max?
29. At what point does OBLA typically occur? What might cause an athlete to reach OBLA?
30. Andrew Johns represents Great Britain in Triathlon. Explain how knowledge of blood lactate levels during a triathlon might assist his performance.
31. Briefly outline the factors that affect the rate of lactate accumulation.
32. Explain what you understand by the term 'buffering'. How does the body buffer lactic acid?
33. What happens to lactic acid once it has been produced in the body?