CHAPTER 16:
Energy

LEARNING OBJECTIVES

By the end of this chapter you should have knowledge and understanding of:

• how to define energy, work and power
• the role of ATP; the breakdown and re-synthesis of ATP; coupled reactions and exothermic and endothermic reactions
• the three energy systems: ATP/PC; alactic; the lactic acid and aerobic system
• the contribution of each energy system in relation to the duration/intensity of exercise
• the predominant energy system used related to type of exercise
• the inter-changing between thresholds during an activity, for example the onset of blood lactate accumulation (OBLA), and the effect of level of fitness, availability of oxygen and food fuels, and enzyme control on energy system used
• how the body returns to its pre-exercise state: the oxygen debt/excess post-exercise oxygen consumption (EPOC); the alactacid and lactacid debt components; replenishment of myoglobin stores and fuel stores and the removal of carbon dioxide
• the implications of the recovery process for planning physical activity sessions.

Energy concepts

Before looking at energy definitions, it is useful to understand where energy begins and ends. There are many forms of energy but you are required to understand just three forms. These are better learned if you follow the original source of all energy: light from the sun. Plants convert light energy into stored chemical energy, which humans then obtain by their consumption of those plants or of the animals that eat plants. People store this energy as carbohydrates, fats or proteins – chemical compounds composed of carbon, hydrogen and oxygen bonds storing energy. We do not directly use energy from these chemical stores for muscular work but further store this chemical energy in the form of a high energy compound called adenosine triphosphate (ATP) within our muscles. Energy stored within the compound ATP is termed potential energy and it is readily available as an energy source for the muscles to contract. The energy used to make the muscles contract is termed kinetic energy. Fig 16.1 shows the conversion of energy from light to chemical to potential and finally to kinetic energy in the form of muscular contractions.

KEY TERMS

Chemical energy

Energy stored within the bonds of chemical compounds (within molecules).

Adenosine triphosphate (ATP)

Chemical energy stored as a high energy compound in the body. It is the only immediately usable source of energy in the human body.

Potential energy

‘Stored’ energy which is ready to be used when required.

Kinetic energy

Energy in the form of muscle contraction/joint movement.
Energy is the ability to perform work or put mass into motion. When applied more directly, energy refers to the ability of the muscles to contract (kinetic energy) and apply force that may limit or increase performance in physical activity.

Energy is usually measured in joules (J), which is the unit to describe the force 1 Newton (equivalent to 1 kilogram) acting through a distance of 1 metre. Energy is also measured in calories, where 1 calorie is equal to 4.18 joules.

Work is done when a force is applied to a body to move it over a certain distance. It is expressed as follows:

\[
\text{Work} = \text{force (N)} \times \text{distance moved (m)}
\]

The units of measurement for work are joules (J).

**Key Term**

**Force**

A pull or push that alters, or tends to alter, the state of motion of a body. It is measured in Newtons (N).

**Apply It!**

Remember that 1 Joule = 1 Newton (1 Newton acting through a distance of 1 metre). Hence, to move a 100-metre sprinter weighing 75 kg a distance of 1 metre requires a force of 750 N, and therefore to move the sprinter 2 metres requires a force of 1500 N.

**Task 1**

Calculate the work to move a sprinter weighing 85 kg a distance of 4 metres.
Power
Power is the rate at which work can be done, i.e. work divided by time. Hence power is force multiplied by distance divided by the time taken.

\[
\text{Power} = \frac{\text{work}}{\text{time}} = \frac{\text{force (N) x distance (m)}}{\text{time (seconds)}}
\]

The units of measurement for power are watts (W).

In simple terms, force multiplied by distance represents pure strength, but when divided by time it represents speed.

Adenosine triphosphate (ATP)
As you saw on page 365, energy from ATP that is stored within muscles provides the kinetic energy for muscles to apply force to participate in physical activity. Fig 16.2 shows that the compound ATP is made up of one complex element, adenosine, and three simple phosphate (P) elements held together by high energy bonds. When the enzyme ATPase breaks the bond between the last two phosphates, this releases the store of potential energy for muscular contractions. This is termed...
an exothermic reaction as it releases energy and in doing so it leaves behind a compound termed adenosine diphosphate (ADP). Although this is more complex, it is easier to think of ADP as having lost its high energy bond between the last two phosphates.

ATP RESYNTHESIS
Since ATP is the only usable source of energy for work, it is clear that the body needs to rebuild ATP as quickly as it uses it. This is achieved by a process called ATP resynthesis, by which the breakdown of ATP into ADP becomes a reversible reaction.

Fig 16.2 highlights that the major role of ATP is to act as a potential energy store to supply the energy for muscle contractions (kinetic energy). But why is it so important? ATP is the only usable source of energy that the body/muscles can utilise for work. Hence no ATP means no energy for work and thus muscle fatigue.

ATP is a simple compound which can be quickly broken down and is stored exactly where it is needed within the muscles. However, there is a major problem in that the body only has limited stores of ATP – enough to supply energy for approximately 2–3 seconds of muscular work. So, how can athletes exercise for long periods if the only usable source of energy runs out after 2–3 seconds?

There is, however, one major problem: where does the energy to resynthesise ADP back into ATP come from? The body has three energy systems: ATP/PC, lactic acid and aerobic, which have the same function. Via coupled reactions, these supply energy to re-synthesise ADP back into ATP. As you will see, these three energy systems do not work in isolation but work together to provide a constant supply of energy to resynthesise ATP. You will also see that the relative contribution of energy supplied from each energy system is primarily dependent upon the duration and intensity of exercise.
The ATP/PC (Alactic) system

The ATP/PC energy system provides energy, via coupled reactions, to resynthesise ADP back into ATP. PC (phospho-creatine) is another high-energy phosphate compound which stores potential energy. When ATP levels fall and ADP levels increase, this stimulates the release of the enzyme creatine kinase, which breaks down the PC bond releasing energy (exothermic reaction). This energy cannot be used for muscular work but is coupled to the resynthesis of ADP back into ATP. Fig 16.3 below shows this coupled reaction, where the energy released from PC is used to resynthesise ADP back into ATP in an endothermic reaction.

Although the ATP/PC system can work aerobically, it does not require oxygen so is termed anaerobic and takes place in the sarcoplasm of muscle cells. As a simple compound located exactly where it is required, PC is quickly broken down. However, with limited stores and with just one PC resynthesising only one ATP, it can only supply energy to resynthesise ATP for 3 to 10 seconds during an all-out maximal sprint.

Fig 16.4 is a graphical representation of how PC is broken down in order to maintain the body’s supply of ATP during a sprint. There are no fatiguing by-products, creatine and Pi remain in the muscle cell until, during recovery, they are resynthesised back into PC via energy from the aerobic system.

**Exam tip**

When answering energy system questions, always ask ‘where has the energy come from?’ If it is not ATP then it cannot be used for muscular work; it is more likely to be energy that has been released to resynthesise ADP back into ATP as part of a coupled reaction.

**Fig 16.4 Breakdown of PC coupled to ATP resynthesis during sprinting (Source: J. Wilmore and D. Costill, Physiology of Sport and Exercise, 2nd edition, 1998)**

**Apply it!**

The ATP/PC system is the predominant energy system used when requiring high intensity, very short duration moments or events, for example the 100-metre sprint, long/triple jump and team games requiring explosive jumping to head, catch or dive for a ball.
The energy from the breakdown of PC is not used for muscular work but to resynthesise ADP back into ATP in a coupled reaction.

**TRAINING ADAPTATIONS**

Anaerobic training, which overloads the ATP/PC system, increases the body’s muscle stores of ATP and PC. This delays the threshold between the ATP/PC and the lactic acid system and thus increases the potential duration of high intensity exercise for up to 1–2 seconds.

**Lactic acid system**

The lactic acid (LA) energy system breaks down the fuel glucose to provide energy, via coupled reactions, to resynthesise ADP back into ATP. Glucose (C₆H₁₂O₆) is supplied directly from the digestion of carbohydrates or from glycogen – the stored form of carbohydrate located in the muscles and liver and readily available as an energy fuel. The decrease in PC stores activates the enzyme glycogen phosphorylase to break down glycogen into glucose, which is then further broken down in a series of reactions called glycolysis. Like the ATP/PC system, the LA system takes place in the muscle cell sarcoplasm and does not require oxygen so is termed anaerobic glycolysis.

**EXAM TIP**

Don’t be misled by questions which ask you to explain when and why the energy systems are used. Simply answer which of the advantages/disadvantages are applied to when or why as highlighted in Tasks 3, 4 and 5.

**Table 2 Advantages and disadvantages of the ATP/PC system**

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Does not require oxygen</td>
<td>• Only small amounts of ATP and PC stored in muscle cells</td>
</tr>
<tr>
<td>• PC stored in muscle cell as readily available energy source</td>
<td>• 1 PC resynthesises 1 ATP</td>
</tr>
<tr>
<td>• Simple/small compound so very quick reaction/resynthesis of ATP</td>
<td>• Only provides energy to resynthesise ATP for up to about 8–10 seconds</td>
</tr>
<tr>
<td>• Automatically stimulated by a decrease in ATP and increase in ADP</td>
<td></td>
</tr>
<tr>
<td>• Provides energy for explosive high-intensity exercise/movements</td>
<td></td>
</tr>
<tr>
<td>• No fatiguing by-products</td>
<td></td>
</tr>
<tr>
<td>• PC can itself be quickly resynthesised so recovery time quick</td>
<td></td>
</tr>
</tbody>
</table>
During glycolysis, the enzyme phosphofructokinase (PFK) initiates the partial breakdown of glucose into pyruvic acid (pyruvate $\text{C}_3\text{H}_4\text{O}_3$), but in the absence of sufficient oxygen, pyruvic acid is further broken down into lactic acid by the enzyme lactate dehydrogenase (LDH). Fig 16.5 summarises how the breakdown of one mole of glucose is coupled to the resynthesis of two moles of ATP.

Although more complex and therefore slower than the reactions of the ATP/PC system, the LA system is still a relatively quick process as it is not dependent upon oxygen. Furthermore, glycogen is readily available as an energy fuel in the muscles. The LA system provides energy to resynthesise ATP during the first 2–3 minutes of high-intensity short-duration anaerobic activity. If exercise is flat out to exhaustion, the LA system may only last for up to 30 seconds, but if the intensity is lowered then duration may prolong for up to a few minutes of anaerobic activity.

The main limitation of the LA system is due to the onset of blood lactate accumulation (OBLA). As lactic acid ($\text{C}_3\text{H}_6\text{O}_3$) accumulates it decreases the pH (higher acidity) within the muscle cells, which inhibits the enzymes involved in glycolysis and thus prevents the breakdown of glucose and induces muscle fatigue.

**KEY TERM**

**Lactate/lactic acid**

Anaerobic glycolysis produces lactic acid ($\text{C}_3\text{H}_6\text{O}_3$), but it is quickly converted into a substrate salt called lactate which is easier to disperse via the bloodstream. Although different compounds, the terms ‘lactate’ and ‘lactic acid’ are often used interchangeably.

**REMEMBER**

The energy released from glycogen/glucose via anaerobic glycolysis is not used for muscular work but to resynthesise ADP back into ATP in a coupled reaction.

**APPLY IT!**

The LA system is the predominant energy system for the 400-metre sprint and for midfield team games players when they have a high number of repeated high-intensity sprints without any time to recover.
**TRAINING ADAPTATIONS**

Repeated bouts of anaerobic training which overload the LA system increase the body’s tolerance to lactic acid and its buffering capacity against high levels of lactic acid. Similarly, they increase the body’s stores of glycogen. This has the effect of delaying the OBLA and prolonging the lactic acid system threshold by delaying fatigue. This allows athletes to work at higher intensities for longer periods, which is invaluable in events such as the 400-metre sprint/hurdles and 50–100m events in swimming. It also allows team games players to carry out a higher percentage of repeated sprints before muscle fatigue occurs.

**REMEMBER**

Don’t be misled by questions which ask you to explain when and why the energy systems are used. Simply answer which of the advantages/disadvantages are applied to when or why as highlighted in Tasks 3, 4 and 5.

**TASK 4**

For each of the advantages and disadvantages listed in Table 3, identify whether they can explain when or why the LA system will be used.

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### APPLY IT!

The ATP/PC and LA systems are the predominant energy systems used during the first few minutes of high-intensity low-duration exercise. However, they are unable to provide all the energy required beyond this time and they are both reliant on the aerobic energy system to help them recover during and after exercise.

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### The aerobic energy system

The aerobic or ‘oxidative’ system breaks down glycogen, glucose and fats to provide energy, via coupled reactions, which is used to resynthesise ADP back into ATP. Unlike the LA system, the aerobic system uses oxygen to completely break down one mole of glucose into H₂O and CO₂ in three complex stages:

- **Stage 1: Aerobic glycolysis**
- **Stage 2: Kreb’s cycle**
- **Stage 3: Electron transport chain (ETC)**

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### STAGE 1: AEROBIC GLYCOLYSIS

Aerobic glycolysis is the same process as anaerobic glycolysis except that the presence of oxygen inhibits the accumulation of lactic acid by diverting pyruvic acid further into the aerobic system. Pyruvic acid combines with coenzyme A to form Acetyl CoA. This is a complex series of reactions which is easier learned diagrammatically in stages using Fig 16.6 and translating (+) into ‘combines with’ and (=) into ‘to form’.

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### Table 3 Advantages and disadvantages of the LA system

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
</table>
| - Large glycogen store in muscle/liver is readily available as a potential energy source  
- Resynthesises two molecules of ATP – more than the PC system  
- Requires fewer reactions than the aerobic system so provides a quicker supply of energy  
- Glycogen phosphorylase and PFK enzyme activation due to a decrease in PC  
- Provides energy for high-intensity exercise lasting between 10 and 180 seconds  
- Can work aerobically and anaerobically | - Not as quick as ATP/PC system  
- Produces lactic acid, which is a fatiguing by-product  
- Reduces pH (increased acidity) which inhibits enzyme action  
- Stimulates pain receptors  
- Net effect is muscle fatigue and pain |
Fig 16.6 The aerobic energy system: a) Aerobic glycolysis; b) Kreb's Cycle
**Stage 2: Kreb’s Cycle**

The Acetyl CoA from Stage 1 combines with oxaloacetic acid to form citric acid. This is then further broken down in a series of complex reactions within the matrix of mitochondria, where four events take place:

1. CO₂ is produced and removed via the lungs
2. Hydrogen atoms are removed (oxidation)
3. Energy is produced to resynthesise two molecules of ATP
4. Oxaloacetic acid is regenerated.

Follow the four events above in Stage 2 of Figure 16.6b to identify how the Kreb’s cycle can continue to break down the Acetyl CoA produced from aerobic glycolysis in Stage 1.

**Exam Tip**

You should never write in an answer that aerobic glycolysis is the same as anaerobic glycolysis. You must write out the process again but add the changes that occur in the presence of oxygen.
**STAGE 3: ELECTRON TRANSPORT CHAIN (ETC)**

In Stage 3 the hydrogen atoms combine with the coenzymes NAD and FAD to form NADH and FADH, and are carried down the electron transport chain (ETC) where hydrogen is split into H⁺ and e⁻. This takes place within the cristae folds of the mitochondria, where three important events take place:

1. the hydrogen electron (e⁻) splits from the hydrogen atom and passes down the ETC
2. this provides sufficient energy to resynthesise 34 ATP
3. the hydrogen ion (H⁺) combines with oxygen to form H₂O (water).

The total energy produced via the aerobic system is therefore 38 ATP:

- 2 ATP from aerobic glycolysis
- 2 ATP from the Kreb’s cycle
- 34 ATP from the ETC.

This is summarised by an equation that represents aerobic respiration:

\[
\text{C}_6\text{H}_{12}\text{O}_6 + 6\text{O}_2 \rightarrow 6\text{CO}_2 + 6\text{H}_2\text{O} + \text{energy}
\]

Although seemingly complex, this equation is simply showing that glucose (C₆H₁₂O₆) is completely broken down by oxygen (6O₂) in the aerobic system into carbon dioxide (6CO₂) and water (6H₂O) to release sufficient energy to resynthesise 38 ATP.

**Exam Tip**

If the equation for aerobic respiration is too daunting, just remember to describe the process without the complex equation.

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**Table 4 The advantages and disadvantages of the aerobic system**

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Large potential glycogen and FFA stores available as an efficient energy fuel</td>
<td>Slower rate of ATP resynthesis compared with LA system due to points 2–4 below</td>
</tr>
<tr>
<td>Efficient ATP resynthesis when good O₂ supply guarantees breakdown of FFAs</td>
<td>Requires more O₂ supply (15 per cent more for FFAs)</td>
</tr>
<tr>
<td>Large ATP resynthesis: 38 ATP from one molecule of glucose compared to 2 ATP from LA system and 1 from ATP/PC</td>
<td>More complex series of reactions</td>
</tr>
<tr>
<td>Provides energy for low/m moderate-intensity high-duration exercise (3 minutes to 1 hour)</td>
<td>Cannot resynthesise ATP at the start of exercise due to initial delay of O₂ from the cardiovascular system</td>
</tr>
<tr>
<td>No fatiguing by-products; CO₂ and H₂O easily removed</td>
<td>Limited energy for ATP during high-intensity short-duration work</td>
</tr>
</tbody>
</table>
FATS
Triglycerides (fats) are broken down by enzymes termed lipases into free fatty acids (FFA) and glycerol and used as an energy fuel within the aerobic system. Although very complex, FFAs are simply broken down into Acetyl CoA, which enters and is broken down by the Kreb’s cycle and the ETC in a process termed beta-oxidation.

FFAs produce more Acetyl CoA and consequently produce far greater energy than the breakdown of glycogen/glucose. However, FFAs require approximately 15 per cent more oxygen than that required to break down glucose, and for this reason glycogen/glucose is the preferred energy fuel during moderate or high-intensity activity.

TRAINING EFFECTS
Specific ‘aerobic’ training causes a number of beneficial adaptations which help to improve the aerobic energy system’s efficiency to resynthesise ATP:

- increased storage of muscle and liver glycogen
- increased mobilisation of aerobic enzymes
- earlier use of FFAs as a fuel source thereby helping to conserve glycogen stores.

The net effect of the above adaptations is that they increase/prolong the aerobic threshold thereby increasing the potential intensity of performance. This delays muscle fatigue by increasing the intensity at which the onset of blood lactate accumulation is reached and by maximising its efficiency to remove lactate during periods of recovery.

REMEMBER
The energy from the breakdown of glycogen/glucose/fats in the aerobic system is not used for muscular work but to resynthesise ADP back into ATP in a coupled reaction.

Energy continuum
The energy continuum shows how the energy systems interact to provide energy for the resynthesis of ATP. It also highlights the predominance/percentage of each of the three energy systems related to the duration and intensity of the activity.

Each physical activity or sport an athlete participates in requires a different percentage of energy from each energy system, as they rarely work in isolation. Some activities/sports are mainly aerobic while others are anaerobic, but most use a combination of all three energy systems. Fig 16.7 shows a standard graph to represent the energy continuum in context of exercise duration. Fig 16.8 summarises how exercise intensity among other factors may affect which energy system is used. You will be required to explain how all the factors numbered in Fig 16.9 affect the energy system used.

TASK 5
The advantages and disadvantages also provide answers to explain when and why the aerobic system is used. For each of the advantages and disadvantages listed in Table 4, identify whether they explain when or why the aerobic system will be used.

APPLY IT!
The aerobic system is the primary energy system for ATP resynthesis during low/moderate-intensity, high-duration activity lasting from 3 minutes to several hours, for example team sports such as hockey and football and long distance cycling, swimming and marathon events. The aerobic system is also active during recovery and stoppages, even during anaerobic activity when it helps to restore ATP and PC stores.
Fig 16.7 Energy system interaction linked to exercise duration

Fig 16.8 Factors affecting the energy system/s utilised
Factors affecting the energy systems used

INTENSITY AND DURATION OF EXERCISE

Figs 16.7 and 16.8 show that it is a combination of both exercise intensity and duration that determines the predominant energy system/s being used. When the exercise intensity is anaerobic (high intensity, short duration) then the ATP/PC and LA systems will be the predominant systems, whereas if the intensity is aerobic (medium/low intensity, long duration) the aerobic system will be predominant.

When exercise intensity reaches a point that the aerobic energy system cannot supply energy quick enough, it has to use the lactic acid system to continue to provide energy for the resynthesis of ATP. You will remember that the LA system produces lactic acid as a by-product. During higher intensity exercise, lactate production will start to accumulate above resting levels and this is termed the ‘lactate threshold’. When blood lactate levels reach 4 mmol/L, the exercise intensity is referred to as ‘the onset of blood lactate accumulation’ (OBLA; see Fig 16.9). This 4 mmol/L is an arbitrary standard value for when OBLA is reached and in essence represents a point where the production of lactate exceeds the speed of its removal. OBLA will continue to increase if this exercise intensity is maintained or increased and will eventually cause muscle fatigue. Fig 16.10 shows that after training the intensity level for lactate threshold is increased and this subsequently delays the point that OBLA is reached and therefore increases the potential duration/threshold of the lactic acid energy system.

**APPLY IT!**

- A sprint athlete may have the potential to sprint at a higher/the same intensity for a longer duration before OBLA induces muscle fatigue.
- An endurance athlete can exercise just below the lactate threshold/OBLA at a higher pre-training intensity without inducing muscle fatigue.
EXERCISE AND SPORT PHYSIOLOGY

TASK 6

1 Make a copy of Table 5, including the headings as shown.

Table 5

<table>
<thead>
<tr>
<th>Activity</th>
<th>Percentage ATP/PC</th>
<th>Percentage Anaerobic</th>
<th>Percentage LA</th>
<th>Percentage Aerobic</th>
</tr>
</thead>
<tbody>
<tr>
<td>100m</td>
<td>70</td>
<td>90</td>
<td>20</td>
<td>10</td>
</tr>
</tbody>
</table>

2 Provide approximate percentages in columns 3 and 5 for the following activities/sports in respect of how much they are predominantly aerobic or anaerobic:

- triple jump
- marathon
- basketball
- 1500m
- badminton
- hockey
- netball
- golf
- gymnastics
- rowing
- skiing
- football
- swimming
- tennis
- rugby
- volleyball
- your own sport if not included.

3 Now split the anaerobic percentage between the ATP/PC and LA systems in columns 2 and 4.

4 Discuss why there may be varying percentage differences between you and your peers.

ENERGY SYSTEM THRESHOLDS

A threshold represents the point at which one energy system is taken over by another as the predominant energy system to provide the energy to resynthesise ATP. It shows the potential duration that each energy system can act as the predominant system and is summarised in Table 6.

It is important to note that the energy system threshold alters in response to a combination of both intensity and duration of exercise and will not always follow the route of ATP/PC, LA and then aerobic systems as depicted in Fig 16.7. For example, a cyclist cycling at a low intensity will be using the aerobic system as the predominant energy system, but upon reaching a steep hill for a couple of miles will exceed the intensity threshold of the aerobic system and the lactic acid system will take over as the predominant system. Similarly, a 200m sprinter may be running at an

Table 6 Energy system thresholds

<table>
<thead>
<tr>
<th>Performance duration</th>
<th>Energy system/s involved (predominant system in italics)</th>
<th>Practical example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Less than 10 seconds</td>
<td>ATP/PC</td>
<td>Triple jump/100m sprint</td>
</tr>
<tr>
<td>10–90 seconds</td>
<td>ATP/PC</td>
<td>200–400m sprint 100m swim</td>
</tr>
<tr>
<td>90 seconds to 3 minutes</td>
<td>LA, Aerobic</td>
<td>Boxing (3 minute rounds) 800m /1500m</td>
</tr>
<tr>
<td>3+ minutes</td>
<td>Aerobic system</td>
<td>Low-impact aerobics class Marathon</td>
</tr>
</tbody>
</table>
intensity of about 85 per cent of their maximal, whereas a 400m sprinter may be at 65 per cent and the 800m runner below this again. This shows that although all these events are predominantly LA/anaerobic (high intensity, short duration) events, by changing the intensity the duration before the threshold of the LA system is reached can be altered. Similarly, during team games a performer will be continually switching between all three energy systems and will not be limited to the times in Table 6, which assume that exercise continues to use the same energy system until it is completely exhausted. The ATP/PC system in particular demonstrates this as Table 6 suggests it can last for up to 10 seconds of flat-out sprint activity. However, during a team game the aerobic system is continually resynthesising ATP/PC during periods of recovery. This allows it to repeatedly be used intermittently during the game as the predominant system when explosive/short sprint-type movements are performed.

**EXAM TIP**

A common mistake is to think a threshold is when an energy system ‘stops’ providing energy to resynthesise ATP. If you do use the term ‘stop’, it is best to word your response as ‘stops being the predominant energy system’.

**OXYGEN AVAILABILITY**

As long as there is a sufficient supply of oxygen, the aerobic system can provide the energy to resynthesise ATP. If oxygen supply falls below that demanded for the exercise, then the aerobic system threshold is met and the LA system will begin to breakdown glucose anaerobically to resynthesise ATP. The availability of oxygen is dependent upon the efficiency of the respiratory and cardiovascular systems to supply oxygen to the working muscles and ultimately determines the efficiency and therefore threshold of the aerobic system to resynthesise ATP. Oxygen supply also affects which food fuels can be broken down to resynthesise ATP.

**FUEL AVAILABILITY**

As long as the body has sufficient stores of PC it is able to use the ATP/PC system for very high-intensity short-duration activity/movements. PC stores are limited but are available at the start and after recovery during exercise. If exercise intensity starts too high, then PC stores will quickly deplete and continued high-intensity explosive activity cannot be sustained. PC stores can be conserved by pacing and by resynthesising PC stores during periods of recovery using spare energy from the aerobic system.

Glycogen is the major fuel for the first 20 minutes of exercise, initially because oxygen supplies are limited as it takes 2–3 minutes for the cardiovascular systems to supply sufficient oxygen. Similarly, glycogen is readily available in the muscles, requires less oxygen and therefore is quicker/easier to break down than free fatty acids (FFAs), to allow a higher aerobic intensity of activity. After about 20–45 minutes there is greater breakdown of fats alongside glycogen as the energy fuel. Although FFAs are a more efficient fuel than glycogen, they require about 15 per cent more oxygen to break them down and will result in the athlete having to work at lower intensities. The greater the liver/muscle glycogen stores, then the longer the performer can work aerobically at a higher intensity.

When glycogen stores become almost fully depleted, after about two hours, FFAs have to be used for aerobic energy production, and unless exercise intensity is reduced it can bring on the sudden onset of fatigue which many athletes refer to as ‘hitting the wall’. Similarly, once the onset of blood lactate accumulation (OBLA) is reached the body has insufficient oxygen available to burn FFAs and therefore has to break down glycogen ‘anaerobically’ to continue resynthesising ATP. Generally it can be said that high-intensity short-duration activity will break down glycogen as the energy fuel, for example a team game player will use glycogen when sprinting. Low-intensity long-duration aerobic activity will break down FFAs and glycogen as energy fuel, for example in a team game a player will use FFAs to last the full duration of the game.
You will remember that enzymes are catalysts that activate the many reactions that help break down PC, glycogen, glucose and FFAs to provide the energy to resynthesise ATP. Hence, without enzymes there would be no reactions and therefore no energy for ATP resynthesis. Table 7 summarises the factors that activate the enzymes for each of the energy systems.

**ENZYME ACTIVATION LEVEL**

Generally, the more aerobically fit the performer, the more efficient their respiratory and cardiovascular systems are to take in, transport and use oxygen to break down glycogen and FFAs aerobically to resynthesise ATP. Aerobic athletes have also shown that they can start to use FFAs earlier during submaximal exercise and therefore conserve glycogen stores. The net effect is that the aerobic threshold in terms of intensity and duration can be increased as the lactate threshold/OBLA would be delayed. A typical untrained athlete would reach OBLA at approx 50/56 per cent of their VO2 max, whereas an aerobic-trained athlete wouldn’t reach OBLA until about 85/90 per cent of their VO2 max.

In the same way, an anaerobic-trained athlete will increase their ATP/PC, glycogen stores, anaerobic enzymes and tolerance to lactic acid, which would increase the threshold of both the ATP/PC and LA systems.

**FITNESS LEVEL**

A typical untrained athlete would reach OBLA at approx 50/56 per cent of their VO2 max, whereas an aerobic-trained athlete wouldn’t reach OBLA until about 85/90 per cent of their VO2 max.

**KEY TERM**

**VO2 max**

Maximum oxygen consumption attainable during maximal work.

On pages 488–491 we will be looking in more detail at the use of nutritional ergogenic aids before, during and after exercise in an attempt to overcome this problem of glycogen depletion.
TASK 7

Evaluation and planning for the improvement of performance.

1 Record two minutes of your A2 practical activity. If you are a continuous performer record the start, middle and finish of your event.
2 Now watch back the recording but identify when each of the energy systems is the predominant system being used.
3 Write a commentary on the two-minute clip, linking your descriptions of the actions taking place to the predominant energy systems you identified in question 2.
4 Show your clip to a peer/other person while providing an oral commentary.
5 Explain why each of the actions in the first two minutes of your A2 practical activity used the energy systems you linked them to in question 3 above. Use the factors affecting the energy system to guide you.
6 Repeat your oral commentary but now include your explanations from the previous question.

EXAM TIP

The oral commentaries in Task 7 are excellent preparation for your oral evaluation and appreciation talk which is part of your coursework in A2. Keep the recorded clip as you will need it for later tasks practising commentary work. So if you start to collate them you will have the major part of this coursework already prepared.

Recovery process

Before introducing what the recovery process is all about, it will be beneficial for you to have completed Task 8 below for you to acknowledge why an understanding of the processes involved are important for your own participation in physical activity and pursuing a healthy and active lifestyle.

TASK 8

Ensure all performers carry out the same, appropriate warm-up prior to completing the investigation.

In a group of six, working in pairs with one performing and one timing/recording, complete the following investigation:

- Each performer carries out three maximal sprint repetitions, with each sprint consisting of a 10 x 10-metre shuttle sprint (about the length of a badminton court; there and back counts as two).
- The timer records the total time and the recovery times for each of the three shuttle sprints as identified below:
  - Performer 1 is allowed 10 seconds recovery between each 10 x 10-metre shuttle sprint
The task investigation above highlighted that the recovery process is concerned with the events occurring in the body primarily after a performer has completed exercise. But when and why is it important for a performer/coach to have an understanding of the recovery process? It is important to maintain a performer’s readiness to perform:

- during exercise, to allow the performer to maintain performance, for example repeated sprints during a team game
- after exercise, to speed up their recovery in time for their next performance, for example the same or next day.

Task 9 identifies that the recovery process involves both the removal of the by-products produced during exercise and the replenishment of the fuels used up during exercise. We will identify the products that are removed and those that are replenished now as we look at the recovery process in more detail.

The main aim of the recovery process is to restore the body to its pre-exercise state; in other words, to return it to how it was before a performer started exercise.

---

**Table 8**

<table>
<thead>
<tr>
<th>Performer</th>
<th>First 10 shuttles</th>
<th>Second 10 shuttles</th>
<th>Third 10 shuttles</th>
<th>Total + / - sprint times from first shuttle</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td></td>
<td>(+/- )</td>
<td>(+/- )</td>
<td></td>
</tr>
<tr>
<td>2.</td>
<td></td>
<td>(+/- )</td>
<td>(+/- )</td>
<td></td>
</tr>
<tr>
<td>3.</td>
<td></td>
<td>(+/- )</td>
<td>(+/- )</td>
<td></td>
</tr>
</tbody>
</table>

Compare/discuss your results in relation to the rest/relief interval and each subject’s performance and answer the following questions.

1. What happened to the performance of each subject?
2. Do any of the relief intervals allow sufficient time for a full recovery?
3. If you were trying to improve your subject’s muscular endurance, which recovery time would you choose? Explain your answer.
4. If you were trying to improve your subject’s speed, which recovery time would you choose? Explain your answer.
5. List three opportunities within a team game of your choice where you can allow time for recovery.
6. How would knowledge of the recovery process be beneficial to you as a performer or a coach?

**Remember**

Remember the processes involved in the energy systems when considering the events taking place in the recovery process.
At AS-level you saw that the body does not immediately return to resting levels after exercise, but that respiration and heart rate remain elevated during recovery. This is the key process of recovery known as excess post-exercise oxygen consumption (EPOC; formerly termed the oxygen debt). This excess oxygen consumption, above that of a resting level during recovery, explains why respiration remains elevated after exercise to restore the body to its pre-exercise state. Figure 16.11 shows that EPOC is thought to consist of two stages, an initial rapid recovery stage, termed alactacid debt, and a slower recovery stage termed lactacid debt.

### KEY TERMS

**Excess post-exercise oxygen consumption (EPOC)**

The excess oxygen consumption, above that at a resting level, during recovery, to restore the body to its pre-exercise state.

**Alactacid**

The 'a' before lactacid signifies it is without lactic acid.

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**TASK 9**

An exhaustive bout of exercise like that completed in Task 8 causes many changes within muscle cells, for example an increase in lactic acid. Create a table using the following headings:

<table>
<thead>
<tr>
<th>1. Changing factor</th>
<th>2. Increase/decrease</th>
<th>3. Action to reverse change</th>
</tr>
</thead>
</table>

1. Make a list in the 'Changing factor' column of any additional internal changes that you think will take place (refer to the energy systems for some pointers to help you).
2. Indicate in the 'Increase/decrease' column if the change increases or decreases during exercise.
3. Indicate in the 'Action to reverse change' column what is required to reverse the changes you have identified.

At AS-level you saw that the body does not immediately return to resting levels after exercise, but that respiration and heart rate remain elevated during recovery. This is the key process of recovery known as excess post-exercise oxygen consumption (EPOC; formerly termed the oxygen debt). This excess oxygen consumption, above that of a resting level during recovery, explains why respiration remains elevated after exercise to restore the body to its pre-exercise state. Figure 16.11 shows that EPOC is thought to consist of two stages, an initial rapid recovery stage, termed alactacid debt, and a slower recovery stage termed lactacid debt.

---

**Fig 16.11 EPOC showing alactacid and lactacid stages of recovery process**
ALACTACID DEBT (RAPID RECOVERY STAGE)

The alactacid stage is also termed the restoration of phosphogen stores, as the elevated respiration primarily helps resynthesise the muscles’ store of ATP and PC. It also helps replenish the muscle stores of myoglobin and haemoglobin.

KEY TERM
Myoglobin
Red pigment in muscles that stores oxygen before passing it on to mitochondria for aerobic respiration.

The alactacid stage requires approximately 3–4 litres of oxygen and takes about three minutes to fully restore ATP/PC stores. However, approximately 50 per cent are restored within about 30 seconds and about 75 per cent in 60 seconds.

LACTACID DEBT (SLOW RECOVERY STAGE)

The lactacid stage is a slower process primarily responsible for the removal/re-conversion of lactic acid/lactate. Early research findings suggested that lactic acid is converted into either:

• pyruvic acid, to enter the Kreb’s cycle and to be used as a metabolic fuel
• glycogen/glucose
• protein.

However, it is now thought that a significant percentage of EPOC is to support the elevated metabolic functions taking place after exercise, namely:

• high body temperatures remain for several hours after vigorous exercise
• hormones, such as adrenalin, remain in the blood stimulating metabolism
• cardiac output remains high helping to reduce temperature.

The lactacid stage requires approximately 5–8 litres of oxygen and can remove lactic acid from between 1 and 24 hours after exercise depending upon the exercise intensity and the levels of lactic acid that have to be removed.

Fig 16.12 shows how the intensity of exercise can affect the rapid and slow stages of EPOC; a few points are worth noting. First, excess post-exercise oxygen consumption will always be present irrespective of exercise intensity. The oxygen deficit (shortage of oxygen supply during exercise) and EPOC are both lower during aerobic energy requirement of exercise.
activity than during anaerobic activity. Aerobic exercise shows a steady state where the oxygen supply (VO$_2$) meets the requirements of the exercise and therefore has a smaller EPOC, having only a small oxygen deficit and not producing high levels of lactic acid that require removal. Anaerobic exercise shows that a steady state of aerobic work cannot be maintained so the oxygen supply is lower than the exercise requirements. This increases the oxygen deficit and OBLA, producing high levels of lactic acid requiring removal and, consequently, a higher EPOC as it takes longer for oxygen consumption to return to pre-exercise levels.

**CO$_2$ REMOVAL**

Increased levels of CO$_2$, formed as a by-product of respiration during exercise, are carried by a combination of blood plasma within red blood cells as carbonic acid (H$_2$CO$_3$) and carbaminohaemoglobin (HbCO$_2$) to the lungs where it is expired. The high metabolic functions after exercise along with chemoreceptor stimulation of the cardiac and respiratory control centres ensure respiration and heart rate remain elevated to help aid the removal of CO$_2$.

**KEY TERMS**

- **Carbonic acid (H$_2$CO$_3$)**
  Carbon dioxide (CO$_2$) combined with water (H$_2$O).

- **Carbaminohaemoglobin (HbCO$_2$)**
  Carbon dioxide (CO$_2$) combined with haemoglobin (Hb).

**GLYCOGEN REPLENISHMENT**

The body’s store of muscle and liver glycogen can quickly deplete, and this is a major factor in muscle fatigue. Fig 16.13 shows that a large percentage of glycogen can be replaced up to 10–12 hours after exercise, but complete recovery can take up to two days in more prolonged endurance exercise. It has been shown that fast twitch muscle fibres can replenish glycogen stores quicker than slow twitch fibres. Fig 16.13 also shows that glycogen restoration can be almost completely recovered if a high carbohydrate diet is consumed, especially when eaten within the first two hours of recovery. Nutrition is considered in more depth in Chapter 19, but many athletes now replenish glycogen stores by consuming carbohydrate-rich drinks, which are thought to be quicker to break down and more easily ingested than large bowls of pasta immediately after exercise.

**KEY TERM**

- **VO$_2$**
  Volume of oxygen consumed.

**IMPLICATIONS OF THE RECOVERY PROCESS FOR PLANNING PHYSICAL ACTIVITY SESSIONS**

An understanding of the recovery process provides some guidelines for planning training sessions in respect of optimising both the work
Table 9 Total exercise, average $O_2$ uptake and blood lactate levels during continuous and work-relief training (Source: adapted from D. McArdle, Exercise Physiology, page 139)

<table>
<thead>
<tr>
<th>Work–relief ratio (same intensity/speed)</th>
<th>Total running distance (m)</th>
<th>Average $O_2$ uptake (L/min)</th>
<th>Blood lactate level (mg 100 ml blood)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 minute continuous to exhaustion</td>
<td>1422</td>
<td>5.6</td>
<td>150.0</td>
</tr>
<tr>
<td>10 seconds work 5 seconds relief (20 minutes work in 30-minute session)</td>
<td>7294</td>
<td>5.1</td>
<td>44.0</td>
</tr>
<tr>
<td>15 seconds work 30 seconds relief (10 minutes work in a 30-minute session)</td>
<td>3642</td>
<td>3.6</td>
<td>13.66</td>
</tr>
</tbody>
</table>

Table 9 above shows that a performer training at the same intensity, using work–relief ratios (rows 2 and 3) can train, for a longer distance, at a lower average $VO_2$ max and with a lower blood lactate level compared with continuous work, which causes exhaustion after only 4–5 minutes (row 1). Hence, work–relief interval training is more efficient as it increases the quality/intensity of training within a training session and consequently improves energy system adaptations. Similarly, by altering the work–relief intervals, the training can target specific energy systems appropriate to the performer.

- For training aimed at improving speed, using the ATP/PC system, the work ratio may be less than 10 seconds and the relief ratio is typically longer (ratio 1 : 3) to allow time for the ATP and PC stores to fully recover (2–3 minutes).

- Training aimed at improving the body’s tolerance to lactate to improve speed endurance using the lactic acid system, could either keep the work ratio less than 10 seconds but decrease the duration of the relief ratio (ratio 1 : 2 – i.e. 30 seconds relief only allows 50 per cent ATP/PC restoration) and/or increase the duration of the work ratio, which both increases lactate production and overloads the lactic acid system.

- For training aimed at improving a performer’s $VO_2$ max using the aerobic system, the work–relief ratio is normally longer in duration and intensity, just below the anaerobic threshold. The relief ratio is typically shorter (ratio 1 : 1), which helps reduce the OBLA and delay muscle fatigue and therefore prolong the aerobic system adaptations.

KEY TERM

Interval training
A form of training incorporating periods of work interspersed with periods of recovery.

APPLY IT!

Some elite marathon runners and cross-country skiers can perform at up to 90 per cent $VO_2$ max without significant lactic acid production (OBLA).
GENERAL RECOVERY TRAINING APPLICATIONS

- Complete a warm-up prior to training to increase respiration rate/O2 supply before exercise starts and thereby reduce the oxygen deficit.
- During anaerobic work, where lactic acid accumulates, an active recovery after training elevates respiration which helps speed up lactic acid removal (see Fig 16.14).
- A moderate intensity seems optimal for the active recovery but this can vary; for example, 35–45 per cent VO2 max for cycling and 55–60 per cent VO2 max for running.
- However, during steady state aerobic exercise, where little lactic acid is produced, a more passive recovery has been shown to speed up recovery more than an active recovery. In this case an active recovery actually elevates metabolism and delays recovery.
- Anaerobic speed/lactate tolerance training will both help to increase ATP and PC muscle stores.
- Use all available opportunities, breaks and time-outs, etc., to allow the restoration of ATP, PC and oxygen myoglobin stores during training/performance.
- Use tactics or pacing to control/alter intensity to meet the training objectives.
- Aerobic training will help improve oxygen supply during and after recovery from exercise.
- A mix of anaerobic and aerobic training will help delay the ATP/PC and lactic acid thresholds.
- Use heart rate as an indicator of exercise intensity, OBLA threshold and recovery state, as heart rate mirrors respiratory recovery.

TASK 10

Evaluation and planning for the improvement of performance

1. Locate the two-minute clip you used in Task 7 for your energy systems commentary. Read through your commentary while watching the clip again.
2. Now watch the recording but this time identify when the alactacid and lactacid stages of EPOC are taking place. This should include both during and after if applicable.
3. Write a commentary on the two-minute clip, linking your identification of when the recovery EPOC is taking place to the actual events taking place, for example myoglobin stores are starting to be replenished.
4. Show your clip to a peer/other person while providing your oral commentary.
5. Repeat your oral commentary but this time explain the link between the different energy systems used and the different stages of EPOC, including glycogen restoration. For example, how the ATP/PC system is linked to alactacid immediately recovery starts between or after activity.

**Fig 16.14 The effects of active recovery on lactic acid removal**
STRETCH AND CHALLENGE

Investigation into 'exercise-to-rest' interval training.

1. Work in groups of three, two performing and one recording. Performers 1 and 2 take turns to complete as many press-ups as they can in one continuous performance time. This is timed and counted (choose any appropriate method, for example bent-knee press-ups) to establish a base-level value.
2. Allow at least 5 minutes between task 1 and task 3 and 4.
3. Performer 1 adds twenty to their press-up base-level value total and then divides the total into 10-second work intervals, each followed by a 20-second relief interval.
4. Performer 2 divides their total base-level work time into 10-second work intervals and completes as many press-ups as they can in each 10-second work interval each followed by a 20 second relief interval.
5. For each performer, add up the total time on work and the number of press-ups completed.
6. Compare this with the work time and number of press-ups completed in task 1.
7. Discuss and compare the performers’ results.
8. What other types of performance could 'exercise-to-rest' interval training be applied to?

Example: Base-level value = 60 press-ups in 120 seconds. Add 20 = 80 press-ups; 8 press-ups in 10 seconds repeated 10 times. 80 press-ups completed in a total work time of 100 seconds compared with 60 press-ups in 120 seconds.
You should now have knowledge and understanding of:

- how to define energy, work and power
- the role of ATP; the breakdown and re-synthesis of ATP; coupled reactions and exothermic and endothermic reactions
- the three energy systems: ATP/PC; alactic; the lactic acid and aerobic system
- the contribution of each energy system in relation to the duration/intensity of exercise
- the predominant energy system used related to type of exercise
- the inter-changing between thresholds during an activity, for example the onset of blood lactate accumulation (OBLA), and the effect of level of fitness, availability of oxygen and food fuels, and enzyme control on energy system used
- how the body returns to its pre-exercise state: the oxygen debt/excess post-exercise oxygen consumption (EPOC); the alactacid and lactacid debt components; replenishment of myoglobin stores and fuel stores and the removal of carbon dioxide
- the implications of the recovery process for planning physical activity sessions.

**REVISE AS YOU GO!**

1. Define energy, work and power, giving the correct units for each.
2. What is ATP and why is it so important?
3. Briefly describe the processes involved in the three energy systems.
4. Explain the energy continuum and provide practical examples to show how the intensity and duration of exercise determine which energy system is predominant.
5. Define and explain the term OBLA.
6. Outline three factors which can affect which energy system is used.
7. Define oxygen debt/EPOC and explain the purpose of the recovery process.
8. Identify and outline the two components of oxygen debt/EPOC.
9. Describe how the store of oxygen myoglobin and glycogen are replenished and CO₂ removed after exercise.
10. How would knowledge of recovery process help a coach to plan a training session?

Ask your teachers for the answers to these Revise As You Go! questions.
During a hockey game, the three energy systems all work together to provide energy to resynthesise ATP in coupled reactions in what is known as the energy continuum. The ATP system is used when the goalkeeper dives explosively to save a low shot, whereas the lactic acid system is used for...
longer but less intense anaerobic sprints repeated for more
than 10 seconds – this is the ATP/PC system. The aerobic
energy system is used for exercise lasting more than 2–3
minutes. It allows the midfield player to last the duration
of the full game including all the aerobic jogging and non-
an aerobic sprinting-type work.

The ATP system is used at the very start of exercise
because there is insufficient oxygen available as it can work
anaerobically and PC is stored where we need it in the
muscles. The lactic acid system is used because the player
has run out of ATP/PC and needs continued sprints as it can
also work anaerobically, breaking down glucose via anaerobic
glycolysis. The aerobic system is used during the jogging
because there is lots of oxygen available and glucose and fats
can be used in aerobic glycolysis. This provides lots of energy
but only when running at a lower intensity than the lactic
acid and ATP/PC systems.

All three energy systems interact to allow the player to jog,
run, sprint and recover throughout the hockey game and
continually change throughout the game, the goalkeeper
would predominantly use the ATP/PC system and the
midfielder use a greater percentage of the aerobic system.

Although not concise, you have accurately
identified when
the three energy
systems are used
with a mixture of
descriptions, time
frames and good
practical examples
from hockey. Use of
the terms ‘intensity’
and ‘duration’ would
have helped clarify
your answer.

Excellent use of the
word ‘because’
throughout which is a
great way of ensuring
you do explain ‘why’
the energy systems
are used.

Although maximum marks would be awarded, you have a
tendency to answer with all the information you know and not
be as concise as you could be for a six-mark question. For
example, you wrote an irrelevant start and finish, and applied
examples twice for when and why rather than together.
Providing the same example to explain when and why for
each energy system mirrors the mark scheme and would help
you to answer in a more concise manner and save you time.