Characteristics of the aerobic system

- Much slower energy production than that of the anaerobic systems
- Lag of 2–5 minutes until the individual reaches a 'steady state' (where the respiratory system's increased oxygen intake meets the activity's oxygen demands). The aerobic production of ATP plateaus at the required exercise intensity level (figure 2.13).
- Dominant contributor to ATP production only at sub-maximal exercise conditions.

**Figure 2.13:**
When you begin to exercise, the more quickly responding anaerobic systems contribute the bulk of ATP production until the aerobic system reaches its steady state 2–5 minutes later.

### Table 2.2

**Summary of the three energy systems**

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Phosphate energy</th>
<th>Anaerobic glycolysis</th>
<th>Aerobic system</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Energy source for ATP production</td>
<td>Phosphocreatine</td>
<td>Carbohydrate</td>
<td>Carbohydrate</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Glycogen</td>
<td>Fat</td>
</tr>
<tr>
<td>2. Number of ATP molecules made from one molecule of energy source</td>
<td>Phosphocreatine:</td>
<td>Glucose:</td>
<td>Glucose: thirty-eight</td>
</tr>
<tr>
<td></td>
<td>less than one</td>
<td>approximately two</td>
<td>Fat: more than 100</td>
</tr>
<tr>
<td>3. Maximal rate of ATP production (molecules/minute)</td>
<td>3.6</td>
<td>1.6</td>
<td>1.0</td>
</tr>
<tr>
<td>4. Duration of peak energy production</td>
<td>5–10 seconds</td>
<td>30–45 seconds</td>
<td>3–7 minutes (time above the lactate inflection point; see pages 75–6)</td>
</tr>
<tr>
<td>5. Percentage contribution at 25 per cent of VO₂ max</td>
<td>Less than 5 per cent</td>
<td>Approximately 15 per cent</td>
<td>Approximately 80 per cent</td>
</tr>
</tbody>
</table>
### Summary of the three energy systems

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Phosphate energy</th>
<th>Anaerobic glycolysis</th>
<th>Aerobic system</th>
</tr>
</thead>
<tbody>
<tr>
<td>6. Percentage contribution at 65 per cent of VO₂ max</td>
<td>Approximately 5 per cent</td>
<td>Approximately 45 per cent</td>
<td>Approximately 45 per cent</td>
</tr>
<tr>
<td>7. Percentage contribution at maximal sprint</td>
<td>55 per cent</td>
<td>40 per cent</td>
<td>5 per cent</td>
</tr>
<tr>
<td>8. Recovery time until repeat effort</td>
<td>Phosphocreatine replenishment: 3–5 minutes  • 50 per cent recovery in first 30 seconds  • Rest recovery best</td>
<td>Depends on time above lactate threshold. Removal of lactic acid to rest levels:  • with active recovery:  – 50 per cent removal: 15 minutes  – 95 per cent removal: 30 minutes  • with passive recovery:  – 50 per cent removal: 30 minutes  – 95 per cent removal: 60 minutes</td>
<td>Restoration of body glycogen stores:  • after competition of more than 1 hour: 24–48 hours  • after hard interval training: 6–24 hours</td>
</tr>
<tr>
<td>9. Limiting factor when operating maximally</td>
<td>Depletion of phosphocreatine</td>
<td>Lactate and hydrogen-ion accumulation</td>
<td>Lactate and hydrogen-ion accumulation  • Glucose and glycogen stores  • Overheating (hyperthermia)</td>
</tr>
<tr>
<td>10. Intensity and duration of activity where the system is dominant ATP provider</td>
<td>Maximal intensity (&gt;95 per cent) and duration of 1–10 seconds</td>
<td>High, sub-maximal intensity (85–95 per cent) and duration of 10–30 seconds</td>
<td>Sub-maximal intensity (&lt;85 per cent) and duration of &gt;30 seconds</td>
</tr>
<tr>
<td>11. Specific sporting examples</td>
<td>• Any athletic field event  • Elite 100 m athletic sprint  • Golf drive  • Gymnastic vault  • Volleyball spike  • High mark and long kick in AFL  • Tennis serve  • Water polo centre forward–centre back contest</td>
<td>• 200–400 m in athletics  • 50 m swim  • Consecutive basketball fast breaks  • High intensity 15–20 second squash rally  • Repeated leads by AFL full forward  • Elite netball centre in close game  • Quadriceps in downhill skiing  • Water polo consecutive fast breaks and defends</td>
<td>• Marathon  • Cross-country skiing  • Triathlon  • AFL mid field  • Hockey wing  • All elite team players  • Rowing 2000 m race  • Water polo game</td>
</tr>
<tr>
<td>12. Everyday activity examples</td>
<td>• Running up one flight of steps  • Carrying heavy shopping from car to house  • Sprinting for train</td>
<td>• Running up four flights of stairs  • Running 200 m to catch bus  • Chopping wood  • Moving heavy furniture</td>
<td>• Shopping  • Going to the cinema  • Gardening  • Dancing  • Ironing  • Studying</td>
</tr>
</tbody>
</table>
**Key knowledge**

- Characteristics and interplay of energy systems for physical activity and recovery in relation to duration, intensity and type of activity
- Fuels required for physical activity and the conversion of food to energy
- Muscular fatigue mechanisms, specifically fuel depletion, metabolic by-products, and dehydration

**Key skills**

- Describe the interplay of the energy systems, using correct terminology.
- Analyse the relationship between energy systems and physical activity.
- Identify and explain the relationship between physical activity, muscular fatigue and recovery.

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**Activity 6**

**Data analysis exercise**

**Phosphate energy efforts linked to the other energy systems**

Watch a replay of any high-level team game (either a professional recording or one you have filmed yourself). Assign groups to record all phosphate efforts by the players.

a. Assess the average length of each effort and the average recovery time between each.

b. Determine the relative importance of each of the three energy systems to the game.

---

**ATP production — different exertion conditions**

The length and intensity of physical exertion determine which of the energy systems is the dominant contributor to ATP production (figure 2.14). As the activity time increases, the influence of the aerobic system on ATP production also increases. However, the relative contribution of each of the three energy systems varies according to the intensity and duration of the activity.

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**Figure 2.14:**

*The average energy contributions of different energy systems during high-intensity competition*

**Source:**

The contribution of either carbohydrate or fat to ATP production varies according to the activity intensity. This is usually measured against the maximum oxygen uptake (VO₂ max = the maximum volume of oxygen that the body can use, measured in millilitres per minute per kilogram — see chapters 6 and 8). A low-intensity activity such as walking uses about 25 per cent of maximum oxygen uptake and elicits high levels of fat mobilisation from around the body to generate ATP. This is one reason for prescribing long walking sessions as a valuable exercise for weight control. Walking mobilises only small amounts of carbohydrates, with blood glucose supplies meeting the body’s carbohydrate needs.

Figure 2.15 indicates that an activity performed at 65 per cent of maximum oxygen uptake (such as easy jogging) produces significant rates of fat oxidation to create ATP; at an activity level of 85 per cent of maximum oxygen uptake (a level at or above the lactate threshold for non-elite athletes), fat contributions decline and carbohydrate assumes dominance in ATP production.

### Lactate inflection point

The term lactate inflection point (LIP) is now the preferred term used to represent a number of previously used terms such as anaerobic threshold, lactate threshold and OBLA (onset of blood lactate accumulation).

The LIP can be established by graphing the results of blood testing during incremental exercise (exercise that progressively increases in intensity). The LIP occurs where there is a sudden exponential or non-linear increase in the lactate concentration in the blood (refer Figure 2.16). The LIP reflects the balance between lactate entry into the blood (commonly referred to as lactate appearance) and lactate removal from the blood (lactate disappearance). The sudden increase occurs when the rate of lactate appearance exceeds the rate of lactate removal or disappearance.

The LIP establishes the exercise intensity beyond which a given exercise intensity or power output cannot be maintained. Exercise intensities beyond the LIP are associated with a shortened time to exhaustion. The higher the exercise intensity beyond the LIP, the more rapid the onset of fatigue. This decreased time to exhaustion is mainly associated with the accumulation of the by-products of anaerobic metabolism, namely lactate and hydrogen ions.

### Determining LIP

Athletes, coaches and exercise physiologists have used the LIP concept to help determine appropriate training intensities for endurance events. By using the LIP results obtained during incremental exercise tests and VO₂ max results (see below and refer to Chapter 8), specific training intensities can be determined that may result in an athlete improving their endurance performance. Training at an intensity that is above the LIP has been shown to result in an improved performance in endurance sports compared to training at the LIP.

Several tests exist to determine LIP. However, as these tests have varying testing protocols and criteria to assess LIP, the estimated intensity at which the LIP occurs may be different for each test, underlining the importance of using the general term LIP. Following are three terms that can reflect the balance between lactate entry into and removal from the blood.

### Lactate threshold (LT)

The lactate threshold is defined as the exercise intensity associated with a substantial increase in blood lactate during a single incremental test. Several specific criteria have been developed to detect the LT. These include...
departure from linearity in the graph of blood lactate concentration and an increase in blood lactate concentration of 1 mmol/L above resting concentrations. It is a more time efficient (or quicker) test than the MLSS test (see below) but has a high correlation with the MLSS tests results.

**Onset of blood lactate accumulation (OBLA)**

OBLA is defined as the intensity of exercise at which blood lactate concentration reaches 4 mmol/L during an incremental test. This is a clear objective outcome and can be accurately assessed, but it does not consider varied individual tolerances to lactic acid. For example, some trained endurance runners have been unable to sustain work rates at OBLA, while some sedentary individuals have been reported to have sustained exercise intensities above OBLA for 50 minutes.

**Maximal lactate steady state (MLSS)**

The MLSS represents the exercise intensity at which equilibrium is observed between lactate transport into and out of the blood. Blood lactate concentration is measured over a series of 20–30 minute constant rate exercise bouts, with each bout increasing by 4–5 per cent. The MLSS can vary from 3–9 mmol/L, and this variation can be found both in trained and untrained individuals. Assessment of MLSS is very time consuming and laboratory dependent, but appears to provide the most accurate estimation of LIP.
Once the athlete passes the lactate inflection point and continues the activity until reaching exhaustion, all energy systems are still functioning but the body’s increasing reliance on the anaerobic glycolysis system results in increasing H+ levels that curtail the activity.

Figure 2.16 on the preceding page indicates there is no exact physical state at which the lactate inflection point occurs. It will differ with each individual, the individual’s state of fitness and the intensity of the activity. However, some indicators (which vary in their precision) provide coaches and athletes with a means of assessing the effort required by a work-out (table 2.3).

### Table 2.3

<table>
<thead>
<tr>
<th>Ways of determining the lactate inflection point</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Method</strong></td>
</tr>
<tr>
<td>1. Percentage of maximum heart rate</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>2. Percentage of maximum oxygen uptake</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>3. Blood lactate levels</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>4. Conversation during exercise</td>
</tr>
<tr>
<td>5. Respiration</td>
</tr>
</tbody>
</table>

### Key knowledge

- Characteristics and interplay of energy systems for physical activity and recovery in relation to duration, intensity and type of activity
- Muscular fatigue mechanisms, specifically fuel depletion, metabolic by-products, and dehydration

### Key skills

- Describe the interplay of the energy systems, using correct terminology.
- Analyse the relationship between energy systems and physical activity.
- Perform, observe, analyse and report on laboratory exercises designed to explore the relationship between energy systems during physical activities.
- Identify and explain the relationship between physical activity, muscular fatigue and recovery.

### Activity 7  Laboratory report

#### The aerobic glycolysis system

Select two high-level endurance athletes from the class and obtain a medical clearance for each.

a. Carry out an aerobic power laboratory test, such as the Multi-Stage Fitness Test, or the Phosphate Recovery Test (see chapter 6).

b. Ensure you can record accurate heart rates.

c. Predict when the lactate inflection point is likely to occur for each of the two subjects.

d. Have the subjects perform the test to exhaustion, recording as many body responses as possible during the test.

e. Try to pinpoint when the lactate inflection point occurs. Give reasons for your decision.

f. How long after this was each individual able to continue working?

g. Assess the value of the test and answer questions your teacher will prepare. Some possible areas to investigate include:

- levels of oxygen consumption during the test
- the percentage contributions of each energy system
- differences in the lactate inflection point for each subject
- reasons for respiration rates and other body responses to the test.
Most sports participants specifically target their lactate inflection point in training in order to improve their aerobic delivery of energy (by reducing or delaying their reliance on anaerobic metabolism). As a result, trained athletes can generally tolerate higher levels of lactic acid in their working muscles (see page 76, and chapters 7 and 9 for more detail).

**Lactic acid removal**

Existing exertion levels determine the rate of lactic acid removal. An active recovery provides the best conditions, with exertion levels less than the level of the lactate inflection point and with a heart rate ideally 15–30 beats per minute lower than that at the lactate inflection point. With blood flow greater than at rest levels, the blood flow through the muscle capillaries is still substantial enough to disperse lactic acid.

The bulk of lactic acid is converted back to pyruvic acid then oxidised inside the mitochondria via the citric acid cycle, ultimately creating new ATP supplies. During exercise and depending on the aerobic levels of activity, lactic acid can serve as a ‘metabolic precursor’ (or energy source). If there is ‘spare’ oxygen due to the aerobic exercise levels being below the lactate inflection point, the body can clear lactic acid through neighbouring muscle fibres in less active muscle groups, as well as through the heart, liver and spleen. Once exercise is finished, the liver can also reconvert lactic acid to glycogen.

**Lactic acid levels during changes in exercise intensity**

Increases in exertion levels may occur at different times in sport, such as:
- with tactical surges during 1500 to 10,000-metre athletic races
- while pushing hard up a hill during a triathlon cycle leg
- when running ‘on the ball’ in Australian Football
- while closely following a talented wing attack for half of a netball game.

With sudden increases in intensity, the quickest responding energy system is anaerobic glycolysis. When this increase in exertion is passing the lactate inflection point the quick accumulation of lactate and H\(^+\) will require a following rest period to allow levels to fall below the threshold. Depending on how long each excursion is beyond the lactate inflection point, this pattern has to continue throughout the activity for the athlete to achieve optimal performance. The aim is to avoid too much lactate and H\(^+\) accumulation which demands longer periods of rest before the effort can be repeated.

---

**Key knowledge**
- Muscular fatigue mechanisms, specifically fuel depletion, metabolic by-products, and dehydration

**Key skills**
- Analyse the relationship between energy systems and physical activity.
- Identify and explain the relationship between physical activity, muscular fatigue and recovery.

**Activity 8 Structured questions**

**The lactate inflection point**

1. What sporting examples (other than those detailed above) exemplify times when athletes reach the lactate inflection point?
2. How is each example a debilitating influence on the performer’s ability to complete the event?
3. Can athletes train to delay the lactate inflection point?
**Lactate as an energy source**

Recent research has focused less on the inhibiting effects of lactic acid and more on the ability of the body to metabolise lactic acid as a source of ATP production for muscular effort.

When the demand for ATP reduces, lactic acid can be broken down by the body to create replenished ATP supplies. This situation of sufficient oxygen availability is most readily found during team games or long-distance endurance events that may be punctuated by spurts of anaerobic effort. For example, triathlons, marathons, long-distance athletic track events, or cycling tours.

These sporting situations will see high level anaerobic efforts followed by a recovery phase of aerobic effort. As long as this ‘recovery’ level is below the individual’s lactate inflection point, then the excess oxygen will be able to metabolise the extra lactic acid accumulated from the burst of higher effort.

Accompanying this change of emphasis has been greater acknowledgement of the inhibiting effects of increased muscle acidity during anaerobic work. The rising levels of hydrogen ions (H+) within the anaerobically working muscle are now recognised as the more significant inhibitor to effective muscle contraction. Increased acidity upsets the normally smooth interaction between the actin and myosin within the muscle cell’s sarcosome. It also interferes with energy generating chemical pathways of each of the energy systems.

**Figure 2.17:**
*Blood lactate levels with varying levels of intensity from the beginning of exercise. Note the existence of blood lactic acid before exercise begins.*

| Line A | start of exercise, which is maintained at levels lower than lactate inflection point |
| Line B | exercise intensity at levels above that of the lactate inflection point |
| Line C | exercise intensity at levels at the lactate inflection point |
| Line D | exercise intensity at levels oscillating above and below the lactate inflection point, given the competition demands and available aerobic recovery periods |

**Figure 2.18**
*Cadel Evans in the 2005 Tour de France — knowledge of his lactate inflection point is crucial to his race strategy and pace.*
Evidence mounts that lactic acid helps, not hinders, athletic performance

By Justin Kemp and Damian Farrow

Sally Robbins stopped rowing because of it. Paula Radcliffe ended her Olympic marathon due to it. And the Australian 4 x 400 metres relay team claims that a silver medal helped cure its ill-effects. One chemical appears to be solely responsible for all the fatigue and discomfort felt when exercising to the limit — lactic acid. But is this really true?

There are many types of fatigue and the causes vary depending on the duration and intensity of the activity. Acute alterations to nerve and muscle function, to the metabolic environment in cells, to the availability of fuel for energy supply and to hormonal levels may all act to slow us down.

The brain, too, plays its part in perceiving these signals and acting to protect the body from damaging over-exertion. But because lactic acid production increases with ever-heavier exercise, it has become the common scapegoat to explain declines in performance at the muscle level.

When lactic acid is generated in human cells, it immediately separates into two components: (1) the lactate ion, and (2) a hydrogen ion (which reflects an increased acidosis). These two are often touted to inhibit the force and speed of muscle contraction, disrupt the ionic balance of the cells and slow the work-rate of the muscle’s energy-supplying pathways.

Many studies have explored the impact that both lactate and acidosis has on muscle performance and this work is now trumpeting the virtues of lactic acid.

When lactic acid is produced during exercise and transported from working muscles into the bloodstream as lactate, the heart, neighbouring and distant muscle fibres and even the brain can use it as an energy source. Furthermore, the liver and kidney can convert lactate back to glucose, demonstrating that lactate is not the negative by-product of metabolism that it is so often labelled. It is actually a mobile fuel appreciated by other tissues.

In truth, lactate is an indispensable intermediary molecule involved in many physiological processes, including a role in maintaining muscle force. Professor Graham Lamb’s team at La Trobe University has shown that high concentrations of lactate have little inhibitory effect on activation and contraction within single muscle fibres.

Meanwhile, scientists at Aarhus University in Denmark demonstrated that lactate acidosis may even protect against potential losses in the ability to activate muscles (called muscle excitability) and enforce output that can take place because of inevitable potassium escape from exercising muscle fibres.

A subsequent collaboration between these Danish and Australian research teams also has provided evidence that lactate production decreases muscle acidosis.

The accumulation of lactate in the muscle and blood during exercise might still be a good marker to indicate the onset of fatigue, but this in no way declares that lactic acid causes muscle fatigue.

There is now overwhelming evidence from myriad experimental protocols expounding lactate as being not harmful, and even beneficial, to exercise performance, compared with limited evidence to the contrary.

Source:
The Age, 4 September, 2004
Key knowledge
• Characteristics and interplay of energy systems for physical activity and recovery in relation to duration, intensity and type of activity
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• Perform, observe, analyse and report on laboratory exercises designed to explore the relationship between energy systems during physical activities.
• Identify and explain the relationship between physical activity, muscular fatigue and recovery.

Chapter summary
• The energy for physical activity is released by the catabolism (breaking down) of adenosine triphosphate (ATP). This energy source is stored in only small amounts within muscles.
• ATP is produced via three energy pathways:
  — the phosphate energy system, which uses phosphocreatine to create new ATP supplies without using oxygen
  — the anaerobic glycolysis energy system, which uses glycogen but no oxygen
  — the aerobic energy system, which uses oxygen and primarily glycogen and fat (and protein under extreme conditions) to create ATP.
• The phosphate energy system can create ATP very quickly, with a major energy contribution to powerful exertions of up to around 10 seconds’ duration. It depletes quickly, taking around 3–5 minutes to fully replenish.
• The anaerobic glycolysis system takes longer to create ATP. It is the major contributor to high-level exertions of 10–30 seconds, but creates lactate and hydrogen ions as by-products. The lactate inflection point is the stage when lactate acid concentrations within the blood reach the level at which continued high-level muscle activity cannot continue. It can take up to 60 minutes to restore lactic acid to resting levels.
• The aerobic glycolysis system becomes the major contributor to muscle activity from around 30 seconds into a sustained sporting performance. It relies on an efficient circulo-respiratory system. The creation of ATP within the muscle occurs in the mitochondria.

Review questions
1. Define in your own words the key terms listed below, all of which appear in this chapter. When you have finished, check your definitions with those in the glossary on page 435.
   adenosine triphosphate  aerobic energy
   anaerobic glycolysis  carbohydrate
   citric acid cycle  electron transport chain
   energy substrates  fat
   fat oxidation  free fatty acids
   glucose  glycogen
   hydrogen ions  lactate
   lactate inflection point  lactic acid
   maximal lactate steady state  mitochondria
   mmol/L  muscle acidity
   OBLA  phosphate energy system
   phosphocreatine  protein
   steady state  triglycerides

2. Construct pie charts showing percentage energy contributions of each of the three energy systems for the following activities:
   (a) walking  (d) 1500-metre athletic race
   (b) a slow jog  (e) 10 000-metre athletic race
   (c) 400-metre athletic race  (f) the Hawaii triathlon.
   Give reasons for your energy breakdowns.
3. (a) To which myofilament are the cross bridges attached? 
(b) How do the cross bridges facilitate muscle contraction?

4. (a) On the following diagram of a sarcomere at rest, where do these features appear?

```
Z line   A band   I band   H zone
```

(b) What happens to each of these features during muscle contraction?

5. (a) Calcium is released during muscle contraction. From where is it released? 
(b) How does the release of calcium assist muscle contraction?

6. Name activities or sports best suited to each of the bars within the graphs in figure 2.14 (page 74).

7. Study the bar graph in figure 2.15 (page 75).
   (a) Why is exercise at 25 per cent of VO₂ max more useful for weight control than exercise at higher intensity levels? Give the physiological reasons.
   (b) Why does the carbohydrate proportion increase so markedly at 85 per cent of VO₂ max?

8. Study the graph in figure 2.16 (page 75).
   (a) Draw the graph and add the probable lactate inflection point for an elite AFL player (in mmol/L of blood) to the vertical axis.
   (b) Why does the contribution of anaerobic glycolysis to ATP production increase after the athlete reaches the lactate threshold?
   (c) Define the ‘lactate threshold’. How is the term ‘onset of blood lactate accumulation’ different?

9. Study the graph in figure 2.17 (page 78).
   (a) What different sporting activity is representative of each situation in lines A–D?
   (b) Why do you think that not all the lines begin at the junction of the X and Y axes?
   (c) Why does line A have a hump?

10. Examine the data in figure 2.20 on the following page, showing times for the four individual 100-metre splits of the three medallists in the women’s 400-metre event at the Sydney Olympics. Answer the following questions:
    (a) State the physiological factors that explain Cathy Freeman’s much faster third and fourth 100s when compared with Graham and Merry.
    (b) Which energy system is most important to the runners over the first 50 metres?
    (c) Give reasons for your answer to question (b) above.
    (d) From the data in table 2.4, use evidence to show at what point you believe lactate levels have become an influencing factor in the run.
(e) Define OBLA. Is it the reason for athletes to stop their performance efforts?

(f) Understanding that there is a ‘usual’ circulatory system lactic acid level where the MLSS is said to occur in most people, what could Freeman’s lactate levels have been at the end of the race? Give your answer in mmol/L.

(g) What is the ‘usual’ level of LA for other LIPs to occur? Give your answer in mmol/L.

(h) Discuss the probable differences in the 400-metre race between Freeman’s reaction to her LIP and an unfit individual’s reaction.

(i) Draw three pie charts. In the first, give your estimates of percentage contributions from each of the three energy systems for the first 200 metres of the race. In the second pie chart, give the estimated percentage contributions for the second 200 metres of the race. In the third, give the percentage contributions from each of the three energy systems for the total race.

(j) Provide reasons for the divisions in each of the pie charts in (i) above.

11. (a) Describe the intensity and duration of a sporting activity where phosphocreatine is the predominant fuel source.

(b) Name a specific sporting activity/situation that clearly illustrates the use of phosphocreatine as the predominant fuel source.

(c) List one advantage and one disadvantage in using phosphocreatine as a fuel.