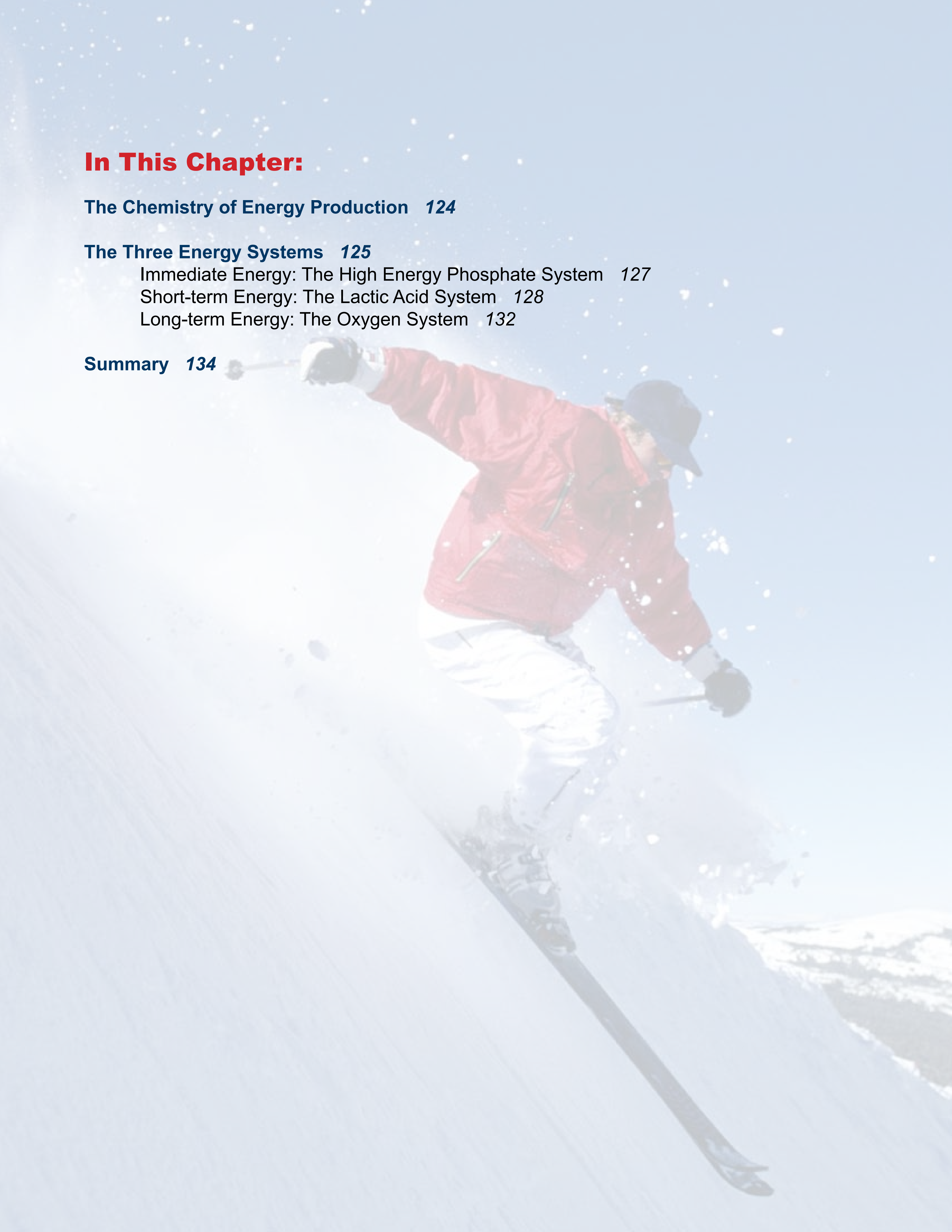


In This Chapter:

Energy for Muscular Activity

After completing this chapter you should be able to:

- use and understand the basic terminology of human metabolism related to exercise;
- describe the basic chemical processes the body uses to produce energy in the muscles;
- demonstrate an understanding of the body's three energy systems and their contribution to muscular contraction and activity;
- discuss the effects of training and exercise on the energy systems.

Humans are capable of performing amazing physical feats. Sprinters run down the track with astonishing speed and power; power lifters hoist hundreds of pounds of weight, making it look effortless; swimmers traverse an entire lake or channel against the elements; hurdlers gracefully clear all obstacles in their way; and basketball players seem to defy the laws of gravity in their flight to the basket. While various combinations of physical ability, skill, and training are required to accomplish these feats, the common denominators in each case are the muscle activation patterns described previously and the development of energy at rates, and in sufficient quantity, to meet the needs of the activity.

The energy needs for endurance events performed at relatively low intensity levels significantly differ from those requiring immediate power output performed at highest intensity levels. For effective planning of training programs, coaches need to know the energy demands of their sport.

The production of a movement during contraction occurs as the muscle pulls on the bones through the tendinous attachments to the bones. Even a single contraction requires a significant input of energy. Just as a car requires the appropriate fuel to run efficiently, so too do our muscles require energy for maximal performance. However, depending on the activity in which you are engaged, the body will make use of different energy systems that have been adapted for supplying energy at the required rate and in the necessary amount for that particular activity (i.e., the body will produce energy at a higher rate – but for a shorter duration – during an activity demanding power than one requiring endurance, where energy is required in greater quantities but at a lower rate).

What are the body's primary sources of energy? What other fuels do we use? Why do our muscles produce energy differently under varying circumstances? These are some of the many questions that will be answered in this chapter. We will also explore some methods of testing and assessing energy production as well as the way the body adapts to exercise.

The Chemistry of Energy Production

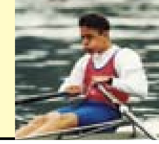
All energy in the human body is derived from the breakdown of three complex nutrients: carbohydrates, fats, and proteins. The end result of the breakdown of these substances is the production of various amounts of the molecule **adenosine triphosphate (ATP)**, the energy currency of the body. ATP provides the energy for fueling all biochemical processes of the body such as muscular work or digesting food. The capacity to perform muscular work depends on sufficient energy supply at the required rate for the duration of the activity.

Energy is liberated for muscular work when the chemical bond between ATP and its phosphate subgroup is broken through **hydrolysis** according to the following biochemical reaction:

$$\text{ATP} \longrightarrow \text{ADP} + P_i + \text{Energy}$$

The breakdown of ATP into **adenosine diphosphate (ADP)** and a **free phosphate group (Pi)** is the fuel for contractile activity (i.e., the formation of cross bridges in working muscles) (see Chapter 4, Muscle Structure and Function). The amount of energy released is about 38 to 42 kilojoules (kJ) or 9 to 10 kilocalories (kcal) per mole of ATP (Note: a **kilocalorie** is the amount of heat energy needed to raise 1,000 grams of water by 1 degree Celsius).

When the body performs physical work, it needs a continuous supply of ATP. The muscle has a small supply of ATP stored within it, satisfying initial requirements of the body, but the initial stores of ATP in the muscles are used up very quickly. Therefore, if activity is to continue, ATP must be regenerated. ATP is a renewable resource that can be regenerated by the recombination of ADP with a free phosphate. The metabolic process that results in the recombination of ADP and P_i to form ATP is termed **ATP resynthesis**.



This reaction can occur at a very fast pace in the body. The resynthesis of ATP is described by the following reaction:

$$ADP + P_i + \text{Energy} \longrightarrow ATP$$

The regeneration of ATP, however, requires the addition of energy, which is supplied through the breakdown of complex food molecules, such as carbohydrates and fats.

The Three Energy Systems

The production of ATP involves three energy systems, each of which produces ATP at a distinct

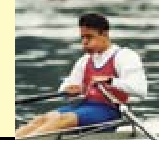
Figure 6.1 **A.** Immediate energy system activity. **B.** Short-term energy system activity. **C.** Long-term energy system activity.

Table 6.1 The roles of the three energy systems in competitive sport.

Energy Pathways	Anaerobic Pathways			Aerobic Pathway	
Primary Energy Source	ATP produced without the presence of O_2			ATP produced with the presence of O_2	
Energy System	Immediate Alactic	Short-term Lactic		Long-term Oxygen	
Fuel	ATP, CP	Glycogen, glucose		Glycogen, glucose, fat, protein	
Duration	0 s 10 s	40 s	70 s 2 min	6 min 25 min	1 hr 2 hr 3 hr
Sport Event	Sprinting 100-m dash Throwing Jumping Weightlifting Ski jumping Diving Vaulting in gymnastics	Track 200-400 m 500-m speed-skating Most gym events Cycling, track 50-m swimming	100-m swimming 800-m track Floor exercise gymnastics Alpine skiing Cycling, track: 1,000 m and pursuit	Middle-distance track, swimming, speedskating 1,000-m canoeing Boxing Wrestling Rowing Figure skating Synchronized swimming Cycling, pursuit	Long-distance track, swimming, speedskating, canoeing Cycling, road racing Triathlon
	Most team sports/racket sports/sailing				

rate and for a given maximal duration: (1) the immediate or high energy phosphate system (anaerobic alactic system); (2) the short-term or glycolytic system (anaerobic lactic system); and (3) the long-term or oxygen system (aerobic system) (Figure 6.1). The main roles of the three energy systems in competitive sport are summarized in Table 6.1.

The three energy systems are designated as **aerobic** or **anaerobic**, depending on whether oxygen is needed by the system in the production of the energy. While oxygen is not needed by either the **high energy phosphate** or **glycolytic** systems, the **oxidative phosphorylation** system depends on oxygen to produce energy. Similarly, the two anaerobic systems can be separated on the basis of whether or not lactic acid is produced during the energy production. With the glycolytic system, lactic acid is produced as part of energy production (hence **anaerobic lactic**), but no lactic acid is produced during energy production by the high energy phosphate system (hence **anaerobic alactic**).



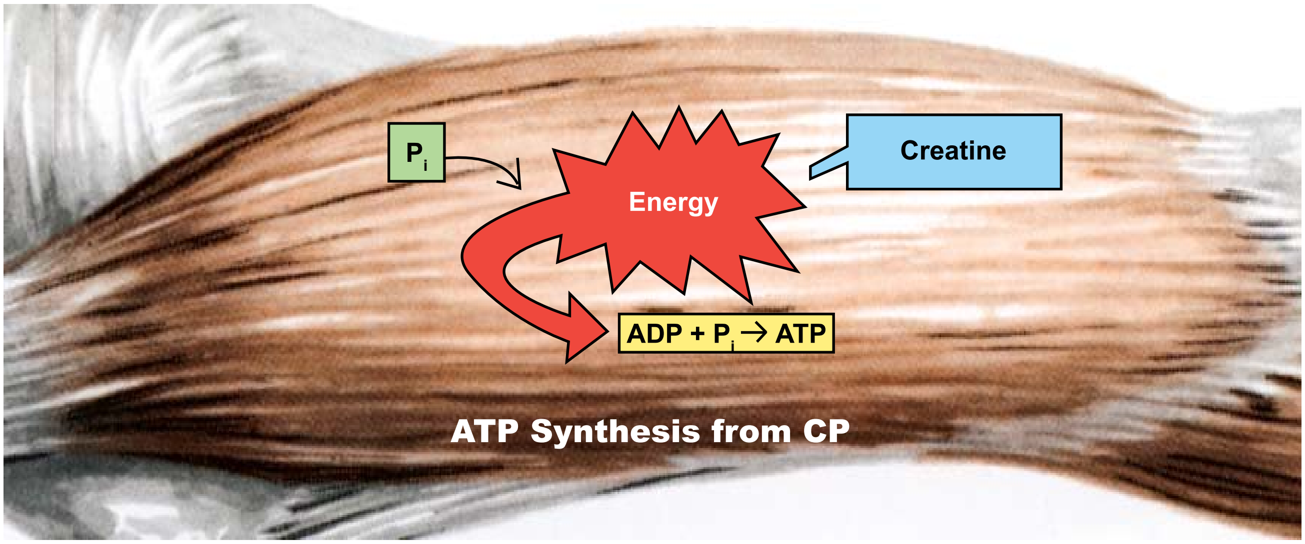


Figure 6.2 The immediate (alactic) energy system.

Immediate Energy: The High Energy Phosphate System

Many sporting activities, such as weightlifting, high jump, long jump, 100-meter run, or 25-meter swim, sometimes described as **high power output activities**, require an immediate high rate of energy production as intensive muscle activity is done over a short time interval. The primary fuel source for these activities is the **immediate** or high energy phosphate system. Under these conditions, creatine phosphate (CP), another high-energy compound in the muscle cell, can be broken down to produce phosphate and creatine. The free phosphate then bonds with ADP to reform ATP (Figure 6.2). As there is only a small amount of ATP and CP stored within each muscle fiber, and because this system produces energy at a very high rate, this system can only provide immediate energy for muscles in the initial 7 to 12 seconds of high-intensity activity.

This system is also known as the alactic energy source or the ATP-CP system.

Characteristics of the High Energy Phosphate System

The utility of the high energy phosphate system is that (1) it can produce very large amounts of energy in a short amount of time and (2) its rate of recovery is relatively rapid. The system can supply energy only until the intramuscular stores of ATP are exhausted, and thereafter, for as long as there is a sufficient local supply of creatine phosphate to resynthesize ATP from ADP. However, the total muscle stores of ATP are very small and are depleted after only a few seconds of high-intensity work. Because the store of creatine phosphate in muscle is also small, it too is depleted rapidly during high-intensity work.

The initial concentrations of high energy phosphates in the muscle are limiting factors in an individual's ability to perform short-term high-intensity work. If the athlete must continue the activity for a period longer than 7 to 12 seconds of very highly vigorous work, or for 15 to 30 seconds of moderately intensive work, the high energy phosphate supply cannot provide all the energy for the activity. It is for this reason that a 100-meter runner often loses speed after only 80 meters as the store of high energy phosphates is exhausted and the body begins using another energy source, the short-term or glycogen energy source (Table 6.1 and Figure 6.3).

Similarly, in weight training, short-term sets (three of 30-second duration) during maximal strength and power training are dependent on stored ATP and CP as the primary energy source.

Short-term Energy: The Lactic Acid System

A second energy system results in the production of ATP at the expense of producing lactic acid, an unwanted by-product. This process is called **anaerobic glycolysis**. It involves the breakdown of glycogen (stored carbohydrate in the muscle) into pyruvic acid and ATP (Figure 6.3).

The **lactic acid system** uses a complex biochemical process called anaerobic glycolysis to release energy in the form of ATP by a stepwise breakdown of the carbohydrate fuels glycogen and glucose. During glycolysis, each step in the sequential breakdown (a total of 10 steps; Figure 6.4) involves a specific **enzyme** breaking down the chemical bonds of glycogen or blood glucose in the absence of oxygen (hence the term *anaerobic*). The last product in the series of breakdowns is termed **pyruvate**. When the rate of work is high, the pyruvate is converted into **lactic acid**. The exercise intensity at which lactic acid begins to accumulate within the blood is known as the **anaerobic threshold**. The anaerobic threshold can be thought of as the point during exercise when you begin to feel discomfort and a burning sensation in the muscles.

The source of substrates for the anaerobic energy system is carbohydrate. Glycogen (stored form of carbohydrate in the muscles and the liver) and blood glucose (circulating form of carbohydrate) are derived from the carbohydrates that make up one's diet. Carbohydrates (pasta, rice, bread, potatoes, starchy foods, sweets; Figure 6.5) are the primary dietary sources of glucose and serve as the primary energy fuels for the brain, muscles, heart, liver, and various other organs. Once ingested, these foods are broken down into glucose by the digestive system. Glucose then enters the bloodstream and is circulated around the body. Some glucose stays in the blood, but most is stored in the liver and the muscles as glycogen. Glycogen consists of hundreds of glucose molecules linked together to form a chain. The process of forming glycogen from glucose is termed **glycogenesis**.

Characteristics of the Lactic Acid System

Lactic acid is the substance that makes your muscles "burn" when you exercise intensely

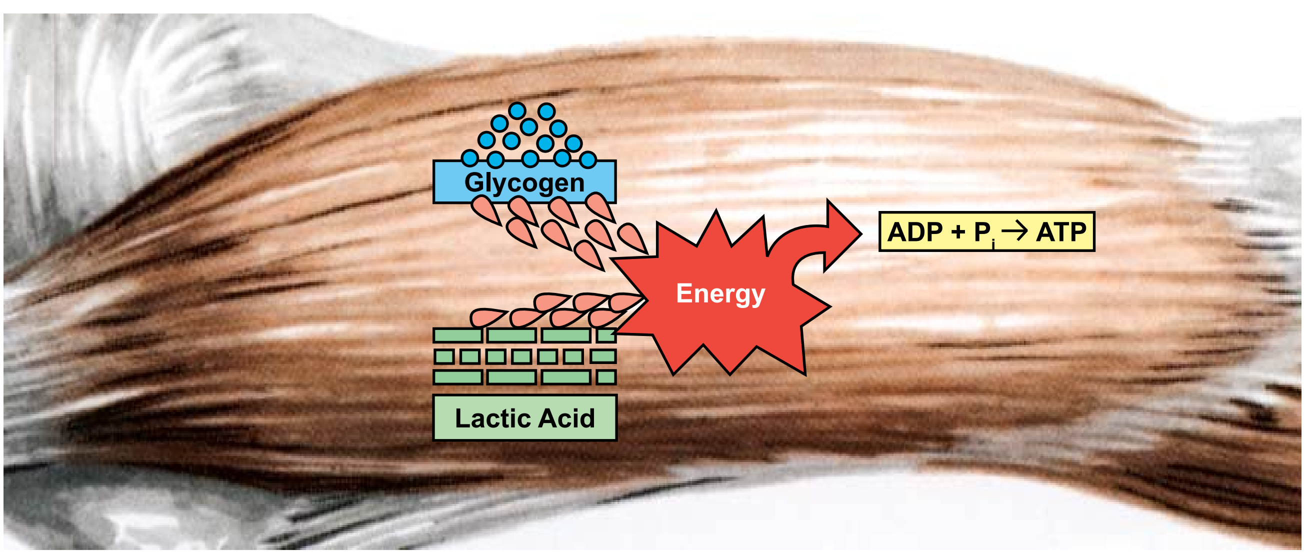
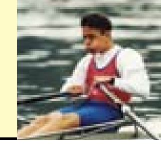


Figure 6.3 The short-term (lactic acid) energy system.



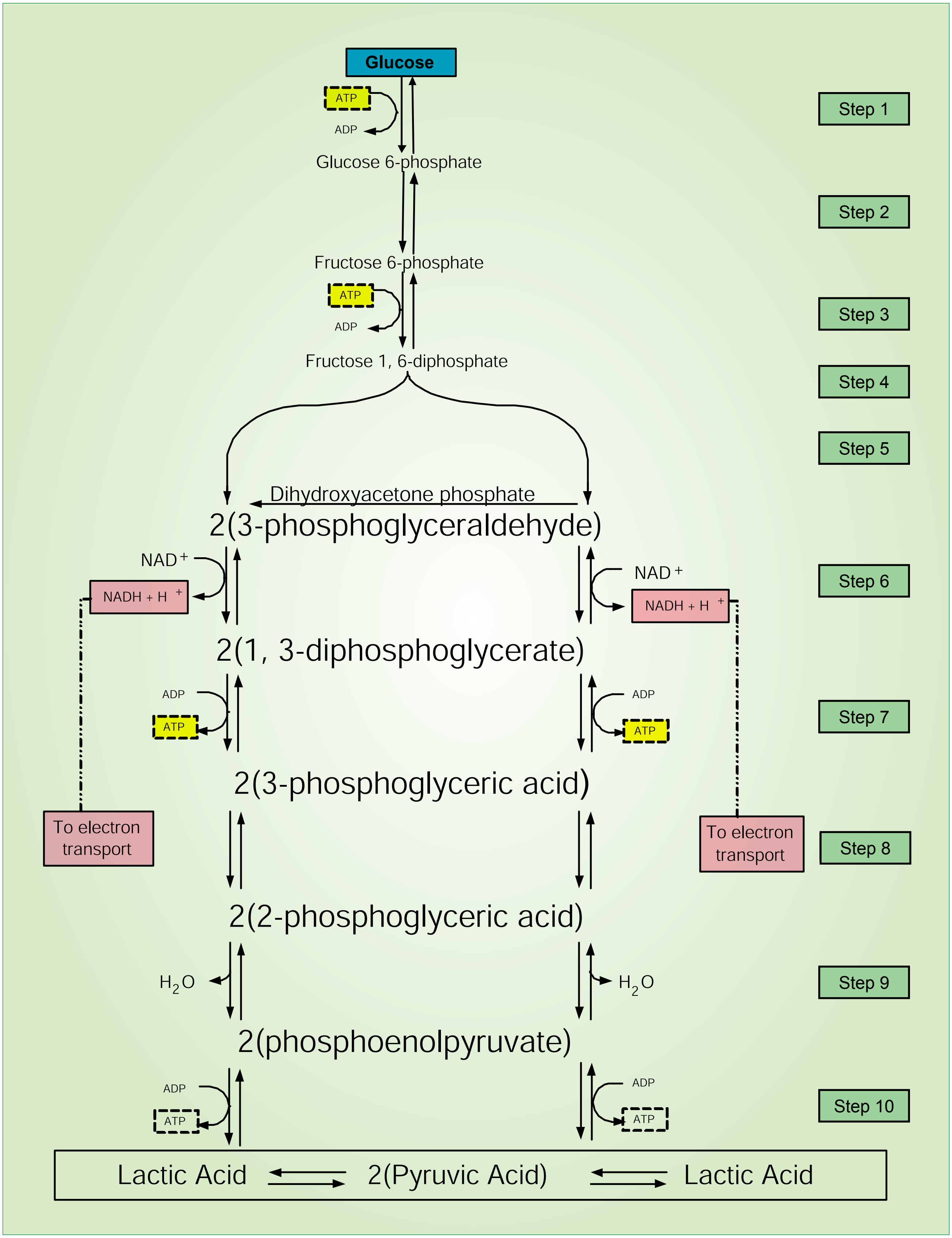


Figure 6.4 The highly complex metabolic pathways of glycolysis.