ebsite **www.jaypeebrothers.com,** for detailed information on nutrition books, visit our website **www.jaypeebrothers.co**

Under the Aegis of
Sports Authority of
Andhra Pradesh

NUTRITIONAL GUIDELINES
for Sportspersons

Geetanjali Bhide
Subhadra Mandalika

Forewords
G Subbulakshmi
Maj Gen MA Naik
Dr (Col) Rana K Chengappa

JAYPEE

Contents

Section I: Concepts of Sports Nutrition

Section II: Sports Specific Nutrition and Dietary Guidelines

CHAPTER 2

Fuel for Exercise and Sport: Bioenergetics of Exercise

JAYPEE BROTHERS

ABSTRACT

Energy to fuel varied functions, activity and exercise is derived from substrates carbohydrates, fats and proteins. The three energy pathways are phosphocreatine system; anaerobic glycolysis and aerobic/oxidative pathway produce ATP, the energy currency of the cells through a series of reactions. The reactions can occur with or without oxygen and are catalyzed by specific enzymes. The phosphocreatine system fuels short burst activities like kicking a ball, throwing, and a 100-meter sprint/dash. Anaerobic glycolysis fuels an 800-meter run or a 400-meter swim. The oxidative pathway fuels a marathon race. The tricarboxylic acid (TCA) cycle is the key metabolic pathway that connects carbohydrates, fat and protein metabolism. The three energy systems work in unison and at a time only one system usually predominates, except when there is transition from predominance of one energy system to other. The dependence on each of the energy system during an activity depends on the nature of the sport, intensity and duration. The energy metabolism is regulated by coordinated integration of intracellular factors, sympathetic nervous system (epinephrine and norepinephrine) and other hormones.

INTRODUCTION

Energy is the capacity to do work and also the basic necessity of life. A brisk walk to hop on to a bus, climb up stairs, workout at a gym and performing routine household chores, all need a constant supply of energy. Energy is also essential to synthesize new biochemical compounds in the body, transfer chemical molecules across the body compartments, supply blood to various organs and tissues; and even to maintain erect posture while not at work. Energy is revealed only when a change occurs but cannot be explained in concrete terms as mass, size or shape. Energy is measured as the amount of work performed during a given change.

Energy is primarily obtained from food. Macronutrients—carbohydrates, fat and proteins in food have to be transformed into usable form of energy through a series of biochemical reactions. Human body continuously extracts energy from macronutrients and channels it to perform physical activity and complex biological functions. It is important to understand the role and metabolism of each macronutrient in energy production along with its effect on exercise performance. Maximal exercise performance depends on how well and how much energy is produced in the working muscles. The present chapter elaborates the bioenergetics of exercise, energy transfer, energy systems, use of macronutrients as substrates to derive energy and regulation of energy metabolism.

BIOENERGETICS IN EXERCISE

Bioenergetics is a science of energy formation, transfer and use in a biological system. It is body's capacity to extract energy from food nutrients (carbohydrates, fats, proteins) and transfer it to contractile elements in skeletal muscles. It determines an individual's capacity to exercise, i.e. to swim, jog, and cycle or perform various routine activities.

Energy is classified as Potential energy and Kinetic energy. *Potential energy* is inactive or stored energy, readily available at any moment to do work such as energy stored in a battery, petrol or a rock at the top of the hill. When the potential energy is released it transforms into *Kinetic energy*, e.g. lighting a torch with the battery, burning petrol to run a vehicle and a rock rolling down the hill.

Bioenergetics is based on the law of thermodynamics. **The first law of thermodynamics** states "energy cannot be created or destroyed but can be changed from one form to another". Our body does not produce, consume or use up energy; it merely transforms energy from one form to another as physiological systems undergo continuous change.

The second law of thermodynamics, states that the process of energy transformation results in loss of large amounts of energy as heat. All forms of biological work, i.e. mechanical (muscle contraction), chemical (synthesis of cellular molecules) and transportation (transfer of diverse substances as per concentration) produce an enormous amount of energy released as heat. The released heat helps to maintain body temperature and increases the rate of chemical reactions of the body.[1]

Energy transfer involves thousands of complex reactions using a balanced mixture of macronutrients. Energy is produced in the presence (**aerobic)** or absence (**anaerobic)** of oxygen. Quick energy for intense activities as short sprints, kicking a ball, stop and go activities in hockey is obtained anaerobically. While, energy for routine and long duration repetitive endurance activity is obtained aerobically.

JAYPEE BROTHERS

Movement is a remarkable feat of the body. Skeletal muscles enable movement during activity and exercise. In order to understand the mechanics of muscle movement during exercise and the methods of energy production to support the exercise, it is essential to understand the structure, composition and classification of muscles.[1-3]

STRUCTURE OF SKELETAL MUSCLE

Muscle is composed of many long, cylindrical cells or fibers. These fibers contain internal organelles and structures that allow muscles to contract and relax. Each muscle fiber is enveloped by a plasma membrane called sarcolemma (Fig. 2.1). Sarcolemma encloses the cytoplasm (*sarcoplasm*) of muscle cell. Within the sarcoplasm are present many *nuclei, mitochondria and myoglobin*. The red color of the muscles is due to myoglobin, the oxygen transporting protein. The sarcoplasm has an extensive network of transverse tubules (T-tubules) and longitudinal tubules (*sarcoplasmic reticulum*). These tubules allow communication and transport of substances. Sarcoplasm stores calcium—necessary for muscle contraction, and energy substrates—fat, glycogen, phosphocreatine and adenosine triphosphate (ATP).

The functional unit of muscle responsible for muscle contraction. Sarcomeres are joined end-to-end to form Z disks. Between every pair of Z disks are found the light zone (I band) and dark zone (A band).

Myofibrils are composed of overlapping thin and thick filaments. The arrangement of these filaments gives the skeletal muscle a striated appearance. The thick filaments are composed of **myosin** molecules, each of which

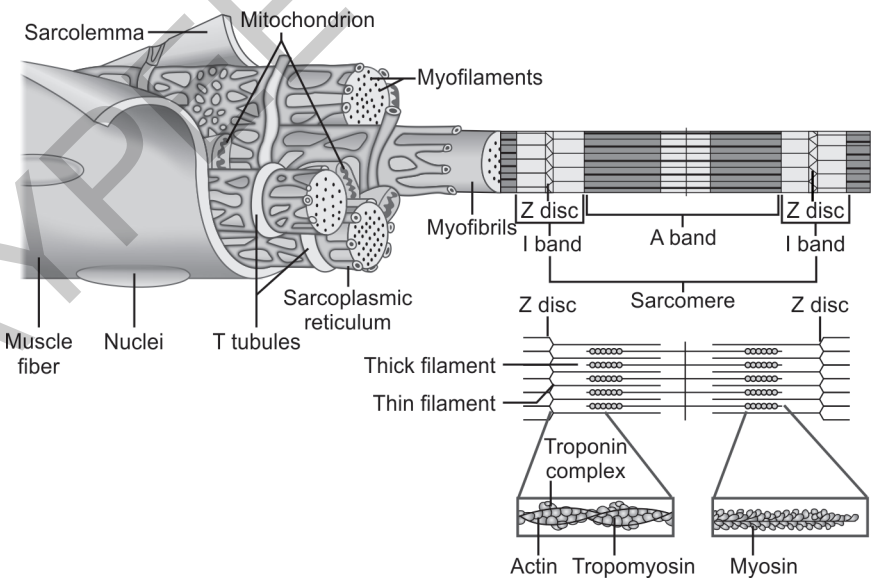

Fig. 2.1: Structure of skeletal muscle.[3,4]

JAYPEE BROTHERS

consists of a rod like tail and a globular head. The head contains ATPase and actin binding sites. The thin filaments are composed of **actin** molecules, tropomyosin and troponin. Actin strands are twisted like a rope.

PROCESS OF MUSCLE CONTRACTION

The process of muscle contraction is initiated by a nerve impulse or signals. The impulse travels to the sarcolemma, T-tubules and causes release of calcium ions from sarcoplasmic reticulum into sarcoplasm. Calcium binds to troponin of thin filaments. Troponin moves the tropomyosin and exposes the myosin binding sites. Myosin heads of the thick filament bind with actin in the thin filament resulting in cross bridge formation. The pulling of thick and thin filaments enables contraction of muscles. ATP provides energy for the process. ATP is converted to ADP by the enzyme adenosine triphosphatase (ATPase) that is present in the myosin heads. At the end of muscle contraction, calcium is pumped back into sarcoplasmic reticulum. This causes relaxation of muscles. The cycle continues throughout the muscle activity and facilitates a well-timed sequence of contraction and relaxation along with added control over the magnitude and speed of muscle force development. Muscles act like cables and pull bones to produce movement.

TYPES OF MUSCLE FIBERS

Muscle fibers are broadly classified as type I or type II based on their metabolic characteristics, ability to generate speed, power or endurance. The proportion of these two types of muscle fibers determines success in athletic activities.

Type I (Slow twitch) fibers are small diameter red cells that contain relatively less active actin-myosin ATPases and hence contract slowly. The red color of the cells is due to high myoglobin (the oxygen carrying protein), mitochondria and capillary network. Slow twitch muscle fibers are enriched with enzymes involved in oxidative metabolism, resistant to fatigue and are specialized for repeated contractions over prolonged periods.

Type II (Fast twitch) muscle fibers contain less myoglobin, few mitochondria and have a poor capillary network. Due to the presence of fast acting actin-myosin ATPases, they exhibit quick contraction and relaxation. These fibers also contain greater glycogen and phosphocreatine stores along with the enzymes that promote glycogenolysis and glycolysis. The type II fibers are further classified as type IIA and B. The characteristics of these muscle fibers and their capacity to produce energy are given in (Table 2.1).

Normally, each and every muscle contains combination of all the muscle fibers. However, their predominance differs with the type of activity. Athletes who have a higher percentage of type I fibers have an advantage in prolonged endurance events, while predominance of type II fibers is better suited for high intensity short duration explosive activities.

JAYPEE BROTHERS

Table 2.1: Characteristics of muscle fibers.[2,5]

Characteristics	*Type I (Slow twitch oxidative)*	*Type IIA (Fast twitch, oxidative glycolytic)*	*Type IIB (Fast twitch, glycolytic)*
Structure	Small muscle fibers enriched in mitochondria, myoglobin, capillary network	High mitochondria, myoglobin, intermediate capillary density	Less mitochondria, myoglobin, capillary density
Color	Dark red	Pink	White
Size of motor neuron	Small	Medium	Very large
Contraction time	Slow	Moderately fast	Very fast
Force production	Low	Medium	High
Energy (ATP) production	Aerobic	Long-term aerobic	Short-term anaerobic
Maximum duration	Hours	<30 min	< 1 min
Major substrate stored	Fat: Neutral lipids, Triglycerides Carbohydrates: Elevated levels glycogen, glucose	Phosphocreatine, Glycogen	Phosphocreatine, Glycogen
Resistance to fatigue	High	Fairly high	Low
Effect of training	-	Hypertrophy	Hypertrophy
Activities	Maintaining posture	Walking, jogging, running	Weightlifting, sprinting, hurdles, kicking a football, jumping

JAYPEE BROTHERS

Energy Currency: Adenosine Triphosphate

Adenosine triphosphate (ATP) powers all forms of biological work, hence is the energy currency of the cell. ATP molecule consists of adenine joined to a ribose molecule that is linked to three phosphate molecules. ATP rapidly releases free energy (approximately 7.3 kcal per mole of ATP) when it is hydrolyzed in the presence of an enzyme adenosine triphosphatase (ATPase) to form adenosine diphosphate (ADP). The energy released initiates muscle force generation or movement.

$$ATP + H_2O \xrightarrow{ATPase} ADP + P - 7.3 \text{ kcal per mole}$$

ADP that is a relatively low energy compound can be converted to ATP through *phosphorylation*, i.e. addition of a phosphate group. Synthesis of ATP independent of or in the absence of oxygen occurs through *substrate level phosphorylation* while in presence of oxygen, it occurs through *oxidative phosphorylation.*

Key Terms: Review of reactions in energy metabolism[1,6]

Phosphorylation: addition of phosphate group to a relatively low energy compound.

Oxidative phosphorylation: The process in which NADH +H+ and FADH2 are oxidized in the electron transport system and the energy released is used to synthesize ATP from ADP and Pi.

Substrate level phosphorylation: The transfer of Pi directly from a phosphorylated intermediate or substrates to ADP without any oxidation occurring.

Oxidation: Gain of oxygen or loss of hydrogen or the direct loss of electrons by an atom or substance.

Reduction: Loss of oxygen or gain of electrons or gain of hydrogen by an atom or substance.

Redox reactions: Oxidation and reduction reactions are coupled.

Reducing agent: Donates or loses electrons as it oxidizes.

Oxidizing agent: Accepts electrons being reduced.

Transamination: Transfer of the NH_2 group from an amino acid to a keto acid.

The body store of ATP is limited. It needs to be continually synthesized to fuel basal metabolism as well as physical activity. ATP is generated through three energy pathways or systems.

a. Phosphocreatine (ATP-CP) system.
b. Anaerobic system—glycolysis (breakdown of glucose)
c. Aerobic/Oxidative system—breakdown of carbohydrates, fat and protein in the presence of oxygen.

Table 2.2 depicts the site, duration and activities of the body that the various energy pathways/systems support.

JAYPEE BROTHERS

Table 2.2: Characteristics of the three energy pathways/systems.[1,2,6]

Energy system	*Site*	*Substrate*	*Rate of ATP generation*	*Capacity to generate ATP*	*Duration of activities*	*Activities*
ATP-PC system (Anaerobic)	Cytoplasm	Phosphocreatine	Very fast	Very limited	5–15 seconds	Powerful-short burst activities
Glycolysis (Anaerobic and aerobic)	Cytoplasm	Glucose, glycogen	Fast	Limited	1–3 minutes	Short duration all out activity
Oxidative system-citric acid cycle	Mito-chondria	Carbohydrates, fats, proteins	Very slow	Unlimited	30 minutes and above	Long duration steady state activities

JAYPEE BROTHERS

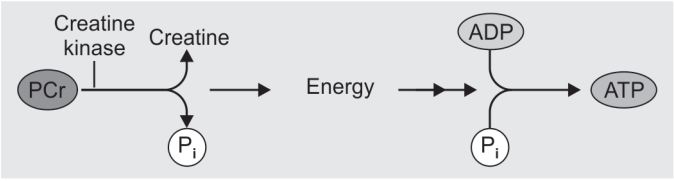

Fig. 2.2: Regeneration of ATP from phosphocreatine.[6]

PHOSPHOCREATINE (ATP-CP) SYSTEM (FIG. 2.2)

Cells store very small amounts of energy in the form of ATP. This limited store of ATP of 80–100 g can fuel activity only for a few seconds that is sufficient only for short duration intense activities such as a 100 meter sprint or kicking a football or tennis serve. The cells also store another high energy molecule creatine phosphate or phosphocreatine (PCr). Phosphocreatine is broken down to creatine and phosphate in the presence of an enzyme *creatine kinase*. The phosphate group is picked up by low energy ADP to be converted to high energy ATP (Fig. 2.2).

The process of ATP regeneration is rapid and does not require oxygen. However, the capacity of the body to maintain ATP levels through this mechanism is limited. ATP and phosphocreatine together help to sustain the energy needs of the muscle for about 3 to 15 seconds. Beyond this time, muscles have to generate energy (ATP) from other metabolic processes, i.e. glycolysis and oxidative breakdown of macronutrients—carbohydrates and fats.

ANAEROBIC GLYCOLYSIS

Glucose is the most readily available source of energy. It is obtained from the diet and also from breakdown of muscle and liver glycogen. The metabolic pathway that produces energy by oxidizing the glucose is termed glycolysis. The site for glycolysis is cytoplasm. In this energy system, the reactions of glycolysis proceed in the absence of oxygen hence termed anaerobic glycolysis.

Anaerobic glycolysis fuels exercise activities that require maximal effort for a short duration up to 2 minutes and also the early minutes of long duration exercise.

The first stage of glycolysis begins with the conversion of glucose to **glucose-6 phosphate** using one ATP molecule as a phosphate donor. Alternatively, glycogen is degraded to glucose 1 phosphate that isomerizes to glucose 6-phosphate with the help of an enzyme *phosphorylase*. However, this conversion does not require ATP (Fig. 2.3).

Glucose-6-phosphate is converted to fructose-6-phosphate, which then uses a molecule of ATP to form **fructose 1,6-bisphosphate**. This reaction is catalyzed by an enzyme *phosphofructokinase* (PFK). PFK regulates the rate of glycolysis during maximal effort exercise. Fast twitch muscle fibers that

JAYPEE BROTHERS

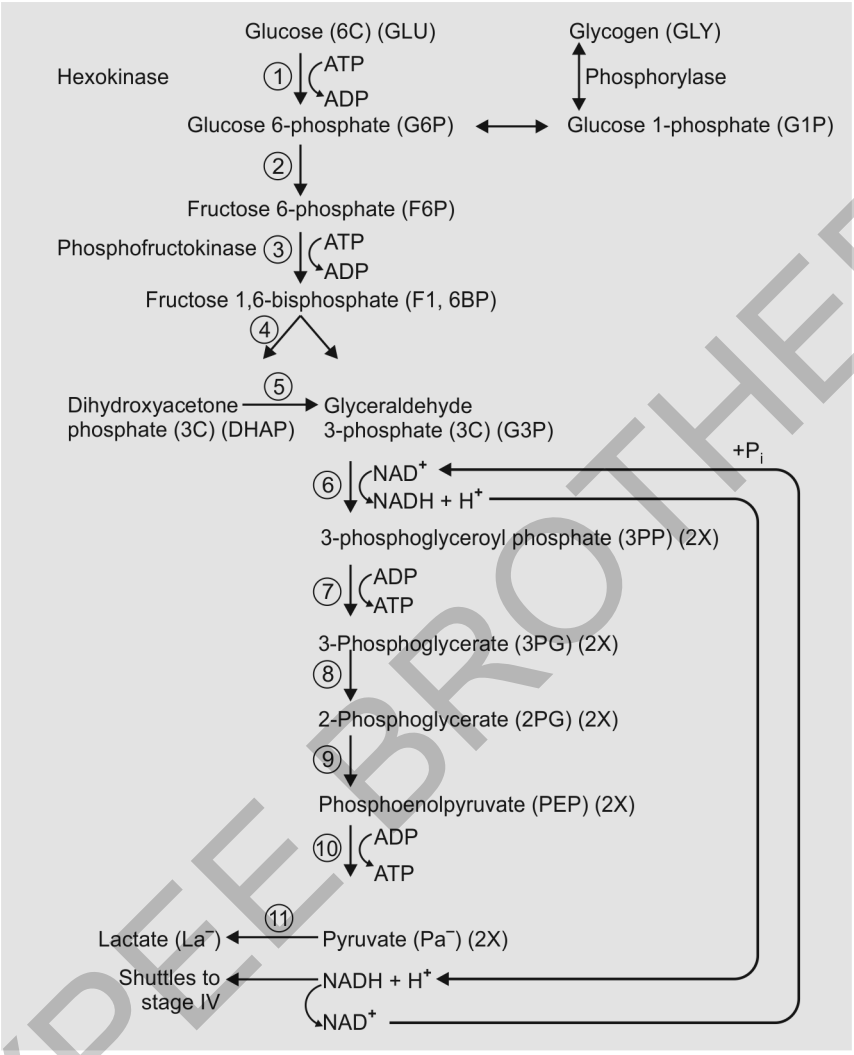

Fig. 2.3: Anaerobic breakdown of glucose.[6]

are essential for short burst activities (sprinting, weightlifting) contain high amounts of PFK. Fructose 1,6-bisphosphate then splits into two trioses, i.e. **dihydroxyacetone phosphate** (DHAP) and **glyceraldehyde 3-phosphate** (G3P). DHAP is isomerized to G3P during progression of the pathway.

The second stage of glycolysis is the conversion of each of the two molecules of G3P finally to pyruvate and then to lactate. Energy is released to form NADH and ATP. When G3P is converted to **1,3-bisphosphoglycerate**, nicotinamide adenine dinucleotide (NAD^+) is reduced to NADH by accepting electrons. With the loss of a phosphoric acid group, 1,3-bisphosphoglycerate is converted to 3-phosphoglycerate generating two molecules of ATP.

JAYPEE BROTHERS

The 3-phosphoglycerate is then converted to 2-phosphoglycerate with the shifting of phosphoric acid group from third to second position, which is then converted to phosphoenolpyruvate. Pyruvic acid is produced from phosphoenolpyruvate with the loss of the phosphoric acid group to ADP resulting in the production of another two molecules of ATP, thus resulting in a total production of four ATP molecules.

Thus, under aerobic conditions, the net effect of glycolysis on conversion of glucose to pyruvate is formation of two NADH (each NADH can be oxidized in the electron transport chain in the mitochondria to produce 3 ATPs resulting in the total production of 6 ATP molecules) and four ATP molecules resulting in a total yield of 10 ATP molecules. Since two ATPs are used up in the initial phosphorylation of glucose molecule, the net production would be 8 ATP molecules. However, under anaerobic conditions both the pyruvic acid molecules are converted to lactate utilizing the NADH molecules produced earlier. Hence, finally only two ATPs are produced on breakdown of glucose (if available directly), while three ATPs are produced if glucose is available to the cell from the breakdown of glycogen.

Although, the net energy production in anaerobic glycolysis is limited, energy is released rapidly and fuels intense activities. Activities like a 800 meter running, 50 and 100 meter sprint or swim that require maximal effort in short time, sprinting to the finish line at the end of mile run and power events like throwing depend on anaerobic glycolysis for energy.

The fate of pyruvate produced during glycolysis depends on exercise intensity and oxygen availability. In strenuous exercise when oxygen supply is limited, pyruvate is converted to lactate. Lactate accumulates temporarily in the muscle fibers. This lowers the pH of muscles and consequently inhibits the enzymes *phosphorylase* and *phosphofructokinase* essential for glycolysis to proceed. Thus, accumulation of lactate interrupts breakdown of glucose for energy and thereby reduces the calcium binding capacity of muscles and muscle contraction.

LACTATE AS A SOURCE OF ENERGY: CORI CYCLE

Lactate produced in the anaerobic glycolysis should not be considered as a waste product. It is released into blood and carried to the liver and converted back to pyruvate by an enzyme lactate dehydrogenase. This cycle is called **Cori cycle** or **Lactic acid cycle** (Fig. 2.4).

It is an important pathway as it prevents accumulation of lactate in the muscle and blood (lactic acidosis), and produces glucose or glycogen from pyruvate (gluconeogenesis in liver) that can be used as energy source.

THE ALANINE GLUCOSE CYCLE

The alanine cycle is similar to the Cori cycle. Alanine is a nonessential amino acid which also serves as an indirect source of energy. Active skeletal muscles

JAYPEE BROTHERS

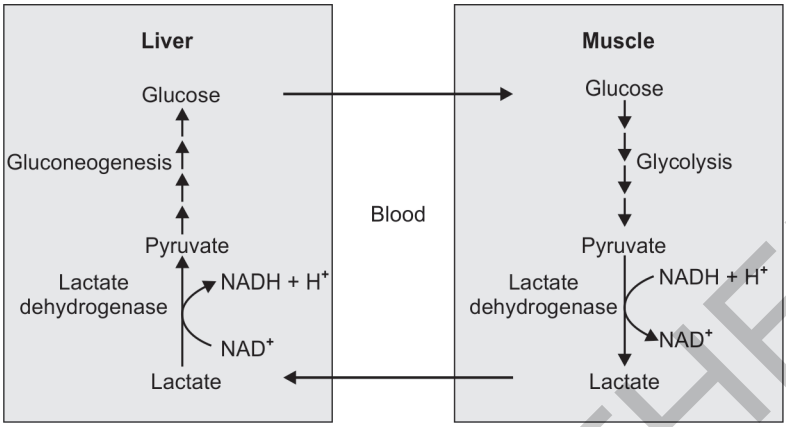

Fig. 2.4: Cori cycle.[6]

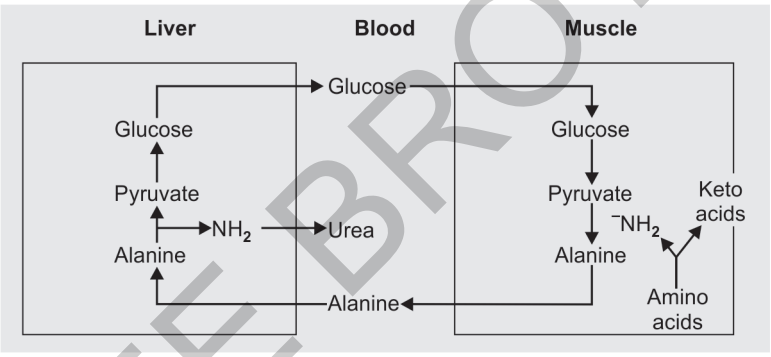

Fig. 2.5: Alanine glucose cycle.[7]

synthesize alanine from glucose derived pyruvate via transamination and transport it to the liver where it is deaminated. The carbon skeleton of alanine is then converted to glucose and supplied to the working muscle through blood for energy production (Fig. 2.5).

The series of reactions involved in this process are termed as ***Alanine-glucose cycle***. During prolonged exercise, alanine glucose cycle generates 10–15% of the total energy requirement. Glucose produced from alanine is also used to fuel nervous system.

OXIDATIVE SYSTEM: AEROBIC BREAKDOWN OF CARBOHYDRATES

Anaerobic breakdown of glucose yields only 10% of potential energy from glucose. When adequate oxygen is available and exercise progresses at a steady state, pyruvate is transported in the mitochondria and is converted to

JAYPEE BROTHERS

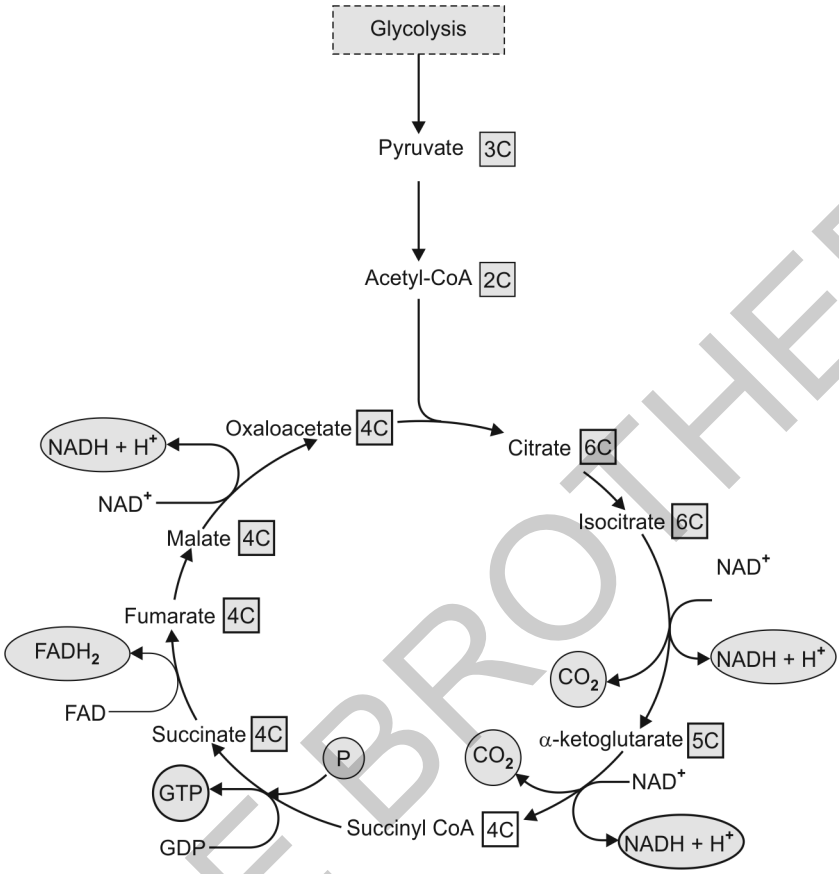

Fig. 2.6: Tricarboxylic acid cycle.[6]
Source: Adapted from Sax PE, 2012-www.jwatch.org[10]

an important intermediate compound Acetyl-CoA. The conversion is catalyzed by an enzyme complex of *pyruvate dehydrogenase,* producing NADH. This reaction requires the coenzymes synthesized form various B-complex vitamins such as thiamin, riboflavin, niacin and lipoic acid.

$$\text{Pyruvate} + \text{NAD} + \text{CoA} \xrightarrow{\text{TPP, FAD, Lipoate}} \text{Acetyl-CoA} + CO_2 + \text{NADH} + H^+$$

Acetyl-CoA is also obtained as a product of fatty acid oxidation. Acetyl-CoA is finally oxidized to CO_2 in a series of reactions termed as *citric acid cycle* or *tricarboxylic acid cycle (TCA)* (Fig. 2.6). This pathway is also known as the Krebs cycle in the honor of the scientist Hans Krebs who discovered it.

The TCA begins with formation of citrate, a 6-carbon tricarboxylic acid, when acetyl portion of acetyl-COA combines with oxaloacetate. Citrate is isomerized to isocitrate. It then undergoes two successive decarboxylations (removal of CO_2) to yield 4 carbon **succinate** in subsequent reactions.

JAYPEE BROTHERS

Succinate is converted back to oxaloacetate in further reactions to accept acetyl fragments and again enter the TCA.

Four pairs of hydrogen atoms are stripped off in the cycle on conversion of *isocitrate to* α *Ketoglutarate*, α *Ketoglutarate to succinate, succinate to fumarate,* and *malate* to *oxaloacetate.* The hydrogen atoms are accepted by coenzymes NAD and FAD to form NADH and $FADH_2$. One molecule of GTP (guanosine triphosphate) is also produced on conversion of succinyl-CoA to succinate. GTP is readily converted to ATP to yield energy.

Summary of TCA:

$$\text{Acetyl CoA} + \text{ADP} + \text{Pi} + 3\text{NAD} + \text{FAD} + 3H_2O \rightarrow 2CO_2 + \text{CoA} + \text{ATP} + 3\text{NADH} + 3H + FADH_2$$

Thus, TCA produces two molecules of carbon dioxide, three NADH, one $FADH_2$ and a molecule of ATP on breakdown of acetyl-CoA. NADH and $FADH_2$ release their hydrogens and electrons to flow to O_2 in the electron transport chain. The actual use of oxygen in the aerobic breakdown of glucose takes place in the electron transport chain.

ELECTRON TRANSPORT CHAIN (ETC)

Hydrogen ions released in glycolysis and TCA cycle combine with coenzymes to form NADH and $FADH_2$. These two carry the hydrogen atoms to the electron transport chain, in the inner mitochondrial membranes.

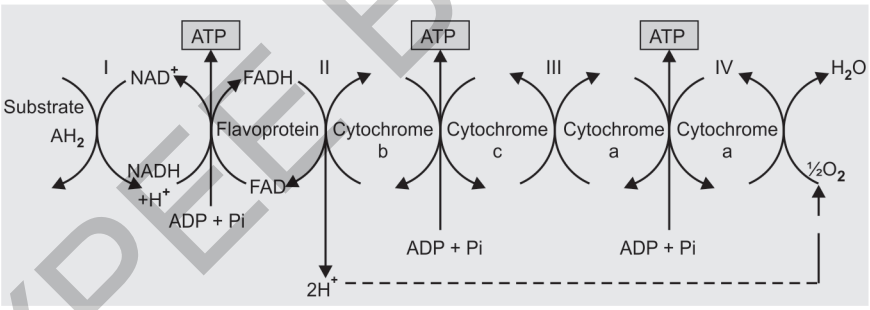

Fig. 2.7: Electron transport chain.[6]

Electron transport chain (Fig. 2.7) comprises of a series of iron containing proteins called cytochromes. The cytochromes are essential for a series of oxidation reduction reactions. The iron portion of each cytochrome exists in either oxidized (ferric - Fe^{3+}) or reduced (ferrous - Fe^{2+}) form. Hydrogen atoms released are split into protons and electrons. The electrons released are accepted by the ferric portion of a specific cytochrome to be reduced to its ferrous form. Ferrous ions then donate the electrons to the next cytochrome and so on down the line.

Finally, the electrons extracted from hydrogen are passed on to oxygen. For each pair of hydrogen atoms, two electrons flow down the chain and

JAYPEE BROTHERS

reduce one atom of oxygen to form water. The metabolic use of oxygen in energy pathways occurs in the electron transport chain. Energy released in the electron transfer is used to synthesize ATP in the process of *Oxidative phosphorylation*.

$$NADH + H^+ + 3\ ADP + 3P + ½\ O_2 \rightarrow NAD^+ + H_2O + 3\ ATP$$

$NADH_2$ generates 3 ATP molecules and $FADH_2$ generates 2 ATP molecules. NAD^+ and FAD^+ thus formed are recycled for further use in energy metabolism.

ENERGY YIELD FROM COMPLETE OXIDATION OF CARBOHYDRATE

The complete oxidation of one molecule of glucose or glycogen under aerobic conditions yields 36 to 39 molecules of ATP respectively. When the process starts with breakdown of glucose one ATP is used up to convert glucose to glucose 6 phosphate and yields 2 ATP molecules whereas glycogen yields three (Fig. 2.3). NADH produced in glycolysis yields only 2 ATP molecules as NADH produced in the cytoplasm cannot enter the mitochondria, but can transfer electrons and hydrogen to proteins in the outer mitochondrial membrane, which then shuttles them to NAD^+ or FAD molecules already in the mitochondria. Conversely, if NADH produced in the cytoplasm enters the mitochondria through malate shuttle, it yields 3 ATP molecules (Table 2.3).

The overall reaction on complete oxidation of glucose is

$$Glucose + 6O_2 + 38\ ADP + 38Pi \rightarrow 6CO_2 + 6H_2O + 38\ ATP$$

With the deduction of 2 ATP used in the preparatory phase of glycolysis, the net yield would be 36 ATP under aerobic conditions.

OXIDATION OF FAT

Body fat is an abundant source of energy. Muscle and liver glycogen and circulating blood glucose provide only 2000–2500 kcal of energy, whereas fat can provide 60,000 to 100,000 kcal of energy. Fat is stored in the body as triglycerides, phospholipids and cholesterol. Triglycerides stored in adipose cells and within skeletal muscle fibers are the major source of energy. To derive

Table 2.3: Energy yield from carbohydrate.[3,9]

Source	*ATP synthesized*
Glycolysis	2–3
Glycolysis—oxidative phosphorylation of NADH	4(6)
TCA cycle—oxidative phosphorylation of NADH	24
TCA cycle—oxidative phosphorylation of $FADH_2$	4
GTP	2
Total	36–39

JAYPEE BROTHERS

energy from fat, triglycerides should be broken down to glycerol and three fatty acids. The process of breakdown of triglycerides is lipolysis, and the reaction is promoted by lipases. The activity of lipases depends on intracellular mediator *cyclic AMP* and *hormones.* The hormone insulin promotes synthesis of triglycerides while epinephrine, norepinephrine, glucagon, growth hormone and cortisol stimulate lipolysis.

$$\text{Triglyceride} + 3H_2O \rightarrow \text{Glycerol} + 3 \text{ fatty acids}$$

Glycerol released on breakdown of triglycerides is converted to glyceraldehyde 3-phosphate, enters anaerobic glycolysis and is converted to pyruvate. Hydrogen atoms are passed on to NAD^+ to further yield ATP. Glycerol can be also converted to glucose in the process of gluconeogenesis. Synthesis of glucose from glycerol is necessary when glycogen stores are depleted due to prolonged intense training or starvation.

The free fatty acids (FFA) released on lipolysis are the primary source of energy. The FFA's released from glycerol enter the blood and are transported throughout the body by simple or facilitated diffusion. The rate of entry of free fatty acids into muscle fibers depends on the concentration, i.e. greater the concentration of FFA higher is their transport into muscle fibers.

The rate of lipolysis and entry of fatty acids into circulation depends on exercise intensity and training. Intense exercise restricts the blood flow to adipose tissues and thereby the release of fatty acids into circulation is limited. Also, accumulation of lactate that occurs during anaerobic conditions inhibits breakdown of triglycerides and thereby availability of fat for energy production to the working muscle. Conversely, exercise at low to moderate intensity increases the level of hormones that promote lipolysis and use of fat as a source of energy. Production of energy from fat occurs through a process known as β **oxidation**.

β OXIDATION OF FATTY ACIDS

The use of fatty acids to yield energy as ATP occurs in the mitochondria. The fatty acids that enter the muscle fibers are transported into mitochondria with the help of L-carnitine with the help of *carnitine acyl-CoA transferase*. Once in the mitochondria, the fatty acid is cleaved at β carbon atom to two carbon acetyl fragments which are eventually get converted to acetyl-CoA. β oxidation proceeds only when oxygen combines with hydrogen. On availability of oxygen, β oxidation continues till the entire fatty acid molecule is degraded into acetyl-CoA.

Each acetyl-CoA molecule that is produced in β oxidation is further oxidized completely to carbon dioxide and water in TCA cycle and subsequent electron transport chain, producing enormous amount of energy.

The number of acetyl-CoA molecules released on β oxidation of fatty acid depends on the fatty acid chain length. For example, when a fatty acid like

JAYPEE BROTHERS

palmitic acid that contains 16-carbon atoms is degraded, it undergoes seven cycles of β oxidation to yield 8 molecules of acetyl-CoA and 14 pairs of hydrogen atoms. The 14 pairs of hydrogen atoms removed in β oxidation of palmitic acid enter the mitochondrial electron transport chain, to form 7 pairs of $FADH_2$ and 7 pairs of NADH. On passage of electrons from $FADH_2$ and NADH to oxygen, two and three ATP molecules are released respectively. Thus, five molecules of ATP are produced when one acetyl-CoA is cleaved to enter into TCA cycle.

$$\text{Palmitoyl-CoA} + 23O_2 + 131\ \text{ADP} + 131\ \text{Pi} \rightarrow \text{CoA} + 16CO_2 + 146H_2O + 131\ \text{ATP}$$

It is to be noted that one molecule of ATP is required to activate the fatty acid initially. Hence, complete oxidation of one molecule of palmitic acid yields 130 ATP molecules. Thus, energy produced from a molecule of fatty acid is many times greater than that from a molecule of glucose.

FATS BURN IN THE FLAME OF CARBOHYDRATE

The use of fat as a source of energy also depends on the carbohydrate breakdown. Acetyl-CoA enters the TCA cycle by combining with oxaloacetate generated from pyruvate, a product of glycolysis (breakdown of carbohydrate). Degradation of acetyl-CoA released from fatty acids depends on the availability of oxaloacetate. When carbohydrate levels in the body are reduced, oxaloacetate level may become inadequate. Fat then cannot be further metabolized to derive energy in the TCA cycle, hence the term "fats burn in carbohydrate flame".[3]

OXIDATION OF PROTEIN

Carbohydrates and fats are the preferred sources of energy during exercise. Protein is used as an energy source in endurance activities and intense training. Proteins are catabolized to amino acids, the nitrogen (amine) group of the amino acid is removed (deamination) and the carbon skeleton is used to derive energy.

Some glucogenic amino acids are converted to glucose via gluconeogenesis (synthesis of glucose from noncarbohydrate source). Alternatively, some amino acids are converted to intermediates of oxidative metabolism of carbohydrates or fat oxidation (Fig. 2.8). They are metabolized to derive energy in the TCA cycle. The amino acids that are mostly oxidized for energy production in the skeletal muscle are branched amino acids-isoleucine, leucine and valine along with glutamate and aspartate. The exact location that the amino acid enters the oxidative metabolism depends on the number of carbon atoms in the molecule. The other amino acids such as glycine are ketogenic and when deaminated yield intermediates of acetyl-CoA or acetoacetate. These either enter the TCA cycle or are converted to fat.

JAYPEE BROTHERS

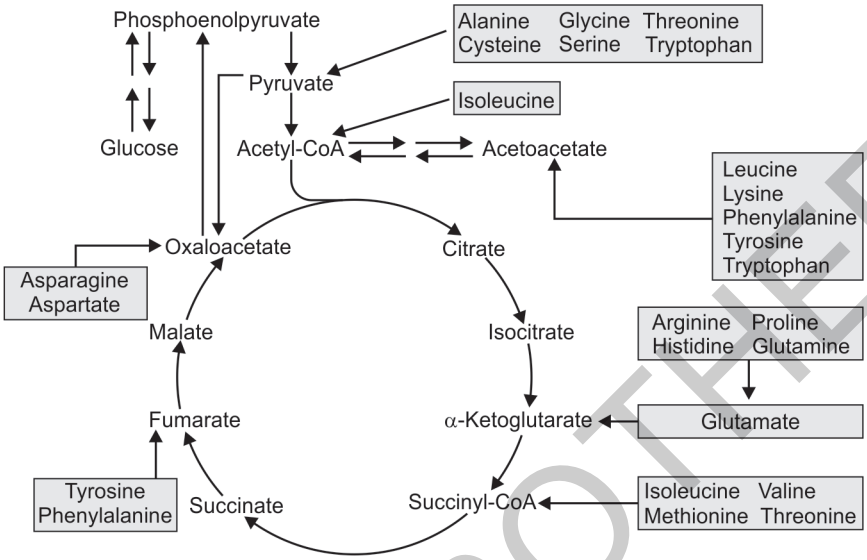

Fig. 2.8: Oxidation of amino acids.[6]
Source: Image adapted from www.archive.cnx.org

Nitrogen released on deamination in skeletal muscles is either used to synthesize fresh molecules of amino acids or carried to liver, converted to urea and excreted in urine. This conversion also requires some energy in the form of ATP. The energy produced from amino acid oxidation is thus difficult to determine. The rate of protein oxidation is assessed by measuring the amount of nitrogen intake and its excretion. This aspect is discussed in the chapter on proteins and exercise.

When protein is degraded for energy, nitrogen containing amine groups and other solutes are released as waste products. These are water soluble and excreted through urine. Excessive protein catabolism for energy thus results in loss of water, and causes dehydration.

Key Terms: Review of pathways[1,6]

Phosphagen system: Regeneration of ATP via phosphocreatine hydrolysis and ADP.
Glycolysis: Reactions involving breakdown of glucose to pyruvate.
Glycogenolysis: The process by which stored glycogen is broken down to provide glucose.
Tricarboxylic acid cycle: Mitochondrial reactions involving the addition of acetyl-CoA to oxaloacetate, and the eventual release of carbon dioxide, electrons, and hydrogen's during the reformation of oxaloacetate.

JAYPEE BROTHERS

Gluconeogenesis: The creation of glucose in the liver from noncarbohydrate sources, particularly glycerol, lactate or pyruvate and alanine.
Electron transport chain: The series of electron receivers located along the inner mitochondrial membrane that sequentially receive and transfer electrons to the final electron receiver—molecular oxygen.

THE METABOLIC MILL

The TCA cycle is the vital link between food (macronutrient) energy and the chemical energy of ATP (*see* Fig. 2.6). It is a major site for energy production. Pyruvate from glycolysis, fragments of fat and protein breakdown, deaminated excess amino acids all enter the TCA cycle to yield energy. The TCA cycle is also a "metabolic hub" where important conversions among macronutrients occur. The predominant conversions are:

- Carbohydrates to fats or nonessential amino acids
- Fats to nonessential amino acids
- Proteins to Carbohydrates or fats.

Only the fatty acids cannot be converted back to glucose, as conversion of pyruvate to acetyl-CoA is irreversible.

INTERACTION OF THE THREE ENERGY SYSTEMS

The main purpose of the three energy systems is to use chemical energy to produce ATP, the energy currency of the cells (*see* Table 2.2). As discussed earlier, the energy system used by the body varies with the type of exercise/sports activity. For example, energy for a short sprint is obtained from ATP-PC system; for an 800-meter run is anaerobic glycolysis and a marathon race derives energy from oxidative phosphorylation. However, these energy systems do not work like a switch on and off mode. The three systems work in unison and at a time only one system usually predominates, except when there is transition from predominance of one energy system to another. The reliance on each of the energy systems during an activity depends on the nature of sport, intensity and duration. Table 2.4 lists the sports and approximate contribution of each of the energy systems to the energy requirement.

REGULATION OF ENERGY METABOLISM DURING EXERCISE

As the body transits from the resting state to an active state, the rate of energy metabolism increases. ATP, the energy currency needs to be continually regenerated to support the increasing activity. This is possible due to a coordinated integration of intracellular factors, sympathetic nervous system and hormones.

JAYPEE BROTHERS

Table 2.4: Contribution of energy systems in different sports.[8]

Sport	*ATP-PCr glycolysis*	*Glycolysis and oxidative*	*Oxidative*
Basket ball	60	20	20
Fencing	90	10	0
Field events	90	10	0
Golf swing	95	5	0
Gymnastics	80	15	5
Hockey	50	20	30
Rowing	20	30	50
Distance running	10	20	70
Skiing	33	33	33
Soccer	50	20	30
Swimming (distance)	10	20	70
Swimming (50 m freestyle)	40	55	5
Tennis	70	20	10
Volleyball	80	5	15

Intracellular Factors

Several intracellular factors, compounds and enzymes are responsible for the continual energy supply. The concentration of ADP/ATP in the cells has a great influence on the energy pathways that extract energy from macronutrients. Reduced concentration of ADP initiates extraction of energy from anaerobic and oxidative pathways, while high concentration of ATP inhibits further extraction. The other compounds that impact energy metabolism are levels of phosphate, cyclic AMP, calcium, NAD^+, citrate and pH.

These intracellular compounds inhibit or activate enzymatic reactions involved in phosphocreatine, carbohydrate and fat degradation and utilization.

Sympathetic Nervous System

The adrenal glands produce and release two hormones—epinephrine and norepinephrine, which are collectively called catecholamines. The catecholamines work as neurotransmitters in the sympathetic nervous system. There is a remarkable rise in the levels of norepinephrine and epinephrine within minutes of the initiation of exercise or stress. These two hormones prepare a person for instant action, and hence their release is termed as the fight or flight response. They have many systemic effects in relation to exercise and energy metabolism.

- Increase in heart rate and force of muscle contraction
- Increase in rate of energy metabolism

JAYPEE BROTHERS

- Promote liver and muscle glycogenolysis to release glucose for energy
- Promote lipolysis and availability of FFA to derive energy
- Redistribution of blood to the skeletal muscles through dilation and constriction of blood vessels
- Increase in blood pressure and rate of respiration.

The synthesis and action of these hormones is influenced by changes in body composition, psychological stress, and exercise.

Hormones

Several hormones play an important role in exercise metabolism. Hormones are responsible for contraction of muscles, cardiorespiratory functions, water balance, temperature control and also energy metabolism during exercise. The functions of major hormones that regulate energy metabolism are discussed below.

Insulin: Secreted by the β cells of islets of Langerhans in the pancreas. Insulin secretion is stimulated by increase in blood glucose levels and amino acids. Insulin stimulates glucose uptake and utilization by the cells, inhibits lipolysis, glycogenolysis, gluconeogenesis. It also promotes uptake of amino acids and inhibits protein breakdown and thus insulin is described as an anabolic hormone.

Glucagon: Secreted by the α cells of islets of Langerhans in the pancreas. Glucagon secretion is stimulated by decrease in blood glucose levels. It stimulates gluconeogenesis, glycogenolysis, lipolysis and mobilization of fat from adipose cells.

Cortisol: Secreted by adrenal cortex. Cortisol secretion is related to exercise intensity. In prolonged strenuous exercise cortisol secretion is increased. It stimulates gluconeogenesis, promotes mobilization of free fatty acids and amino acids.

Growth hormone: Secreted by anterior pituitary gland. Growth hormone secretion is stimulated by stress of exercise. It stimulates lipolysis and mobilization of fatty acids from adipose tissues.

STUDY QUESTIONS

1. Explain the terms oxidative phosphorylation.
2. Differentiate between the three types of muscle fibers.
3. Describe in detail the energy system and fuel source used in throwing events.
4. Hockey as a sport involves different activities—standing, walking, cruising, jogging, and short burst activities. Explain how different energy systems fuel these activities.
5. Discuss the factors that regulate energy metabolism in the body.

JAYPEE BROTHERS

REFERENCES

1. Robergs RA, Roberts SO. Metabolic adaptations to exercise. Fundamental Principles of Exercise Physiology: For Fitness, Performance and Health. McGraw-Hill Education (ISE Editions); International Ed edition, 1999.
2. Wilmore JH, Costill DL, Kenney WL. Physiology of Sport and Exercise, Structure and Function of Exercising Muscle. Human Kinetics, Champaign 2008.
3. McArdle WD, Katch FI, Katch VL. Nutrient bioenergetics in exercise and training. In: Sports and Exercise Nutrition, 3rd edition. Lippincott Williams and Wilkins, Baltimore: Wolters Kluwer; 2009. pp. 125-53.
4. Plowman SA, Smith DL. Exercise physiology for health, fitness, and performance, ed 2, San Francisco, 2003, Benjamin Cummings https://musculoskeletalkey.com/understanding-muscle-contraction/
5. Lakshmi NS. Textbook of Therapeutic Exercises. New Delhi: Jaypee Brothers Medical Publishers; 2005.
6. Lehninger, Nelson DL, Cox MM. Principles of Biochemistry. New York: W.H. Freeman; 2005.
7. Mallette LE, Exton JH, Park CR. Effects of glucagon on amino acid transport and utilization in the perfused rat liver. J Biol Chem. 1969;244(20):5724-8.
8. Foss ML, Keteyian SJ. Fox's Physiological Basis for Exercise and Sport. Ann Arbor, MI: McGraw-Hill; 1998.
9. Jeukendrup A, Gleeson M. Fuel sources for muscle and exercise metabolism. In: Sports Nutrition. An Introduction to Energy Production and Performance. USA: Human Kinetics; 2004. pp. 31-60.
10. Sax PE. ID Case Conference Discussant Types, NEJM Journal Watch(Internet) 2012 https://blogs.jwatch.org/hiv-id-observations/index.php/id-case-conference-discussant-types/2012/01/18/.

JAYPEE BROTHERS

or detailed information on nutrition books, visit our website **www.jaypeebrothers.com,** for detailed information on nutrit

NUTRITIONAL GUIDELINES
for Sportspersons

Key Features

- Relevant concepts of physical activity- exercise, health, fitness, types of sports, physical activity guidelines in terms of frequency, intensity, type and duration of exercise
- Bioenergetics—Fuel utilization by working muscles and Fuel shifts
- Body weight and Body composition variations in athletes of various categories and impact on sports performance
- Role of macronutrients (carbohydrates, fats and proteins) and micronutrients in exercise, altered nutrient needs and recommended allowances for athletes
- Importance of fluids and electrolytes, suitable hydration strategies for sportspersons
- Essentials of diet planning for sportspersons including concepts of physical fitness components of sport, phases of training, dietary practices, body weight and body composition, biochemical parameters, and nutrition periodization
- Practical nutrition guidelines, inclusion of nutritional supplements in the diets of sport persons—endurance, power/strength, team events, racket sports, weight class and combat sports; explanation with the help of well designed sample case studies
- Nutritional supplements—detailed review on the classification, composition, dose, effects, efficacy, and safety
- A nutrition spotlight that highlights current concepts; key terms; recent researches; and study questions in every chapter.

Target audience: Helpful for students of nutrition, coaches, sports medicine specialists and sportspersons.

Geetanjali Bhide MSc PhD is practicing Sports Nutritionist at Lakshya Sports Foundation, Brand Nutritionist for Diabetic Food International, and visiting faculty for sports and exercise nutrition and research guide at College of Home Science, Nirmala Niketan. She was invited as an expert panel member for a webcast—on adolescent athlete at GSK Human Performance Lab, UK in June 2016.

She has the expertise and experience of nutrition assessment, counseling and develops nutrition and supplement strategies for national and international athletes from varied sports disciplines. She regularly conducts many invited sports nutrition workshops/seminars for practicing nutritionists/dietitians, athletes, coaches and sports medicine specialists.

She set-up the Sports Nutrition department of the Army Sports Institute, Pune. Her research on Indian athletes is presented and published at national and international conferences. She won the Young Scientist Nutrition Society of India award and JN Bose memorial award by Indian Dietetic Association, in 2004. She has earlier worked as Assistant Lecturer at SNDT Women's University, Pune, and Consultant Nutritionist with GSK Consumer Health Care. Her experience as a sports nutritionist, academician, speaker, researcher and writer spans over 15 years.

Subhadra Mandalika MSc PhD is an Associate Professor of Nutrition at the college of Home Science, Nirmala Niketan, affiliated to the University of Mumbai. She has got around 27 years of professional experience in teaching and research in various academic institutions. She is a PhD guide, recognized by the University of Mumbai and successfully guided 4 PhD scholars so far. She is also an external PhD referee for University of Kerala, Saurashtra, Nagpur and Pune; and SNDT Women's University, Mumbai. She has coordinated minor as well as major research projects sponsored by UGC, University of Mumbai and DAE/BRNS. Her research outcome on 'Antiestrogenic activity of phytosterols from fenugreek seeds' has been patented (Patency No. 225689). Her interest in dissemination of scientific information is evident through the number of research presentations in various National and International Conferences and Symposia organized by NSI, IDA, AFSTI, AIAARO, ICMR, ILSI, ICDA, etc. She has also published number of research papers in various peer reviewed national and international journals. In addition, she has published two Reference Books in Nutrition and Co-edited a book on Methodologies for Fitness Assessment. Dr Subhadra has been an external member on the editorial team of national and international journals. Recognizing her academic and research expertise, the Rotary International has selected Dr Subhadra as an Ambassador of Goodwill to take up an academic assignment at the University of Mauritius for 3 and half months which was highly appreciated by the host institute. Dr Subhadra is a life member of reputed organizations including Nutrition Society of India (NSI), Indian Dietetic Association (IDA), Association of Food Scientists and Technologists of India (AFSTI), All India Association of Advanced Research in Obesity (AIAARO). Recently she has been elected as the convener of Nutrition Society of India, Mumbai Chapter. Her areas of interest include Clinical Nutrition, Nutritional Food Product Development, Food Science and Technology, Biochemistry, Micronutrients, Antioxidants, Community Nutrition and Sports Nutrition.

Available at all medical bookstores
or buy online at www.jaypeebrothers.com

JAYPEE BROTHERS
Medical Publishers (P) Ltd.
www.jaypeebrothers.com

Join us on facebook.com/JaypeeMedicalPublishers

Shelving Recommendation
NUTRITION

ISBN 978-93-5270-345-6