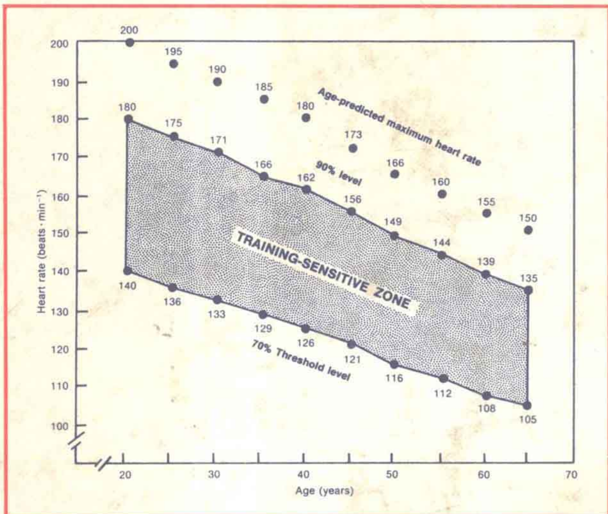
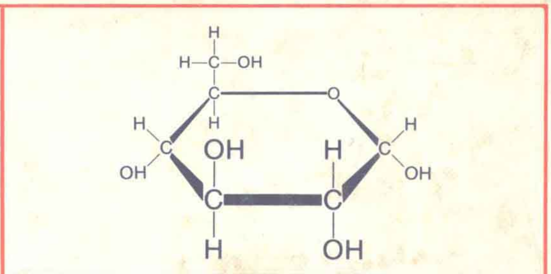
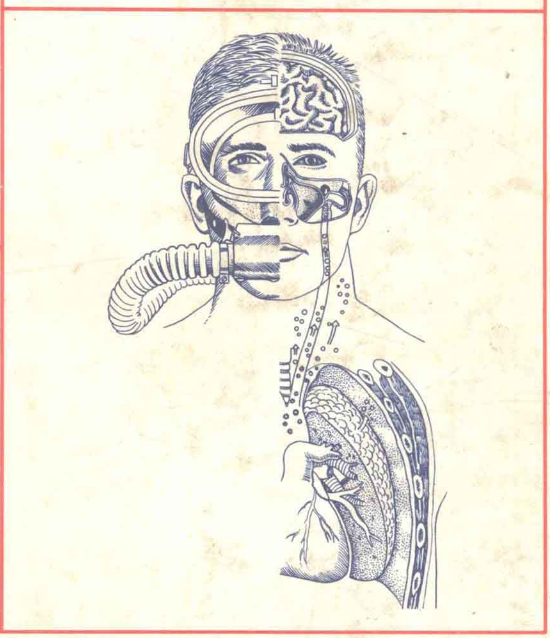
# EXERCISE PHYSIOLOGY

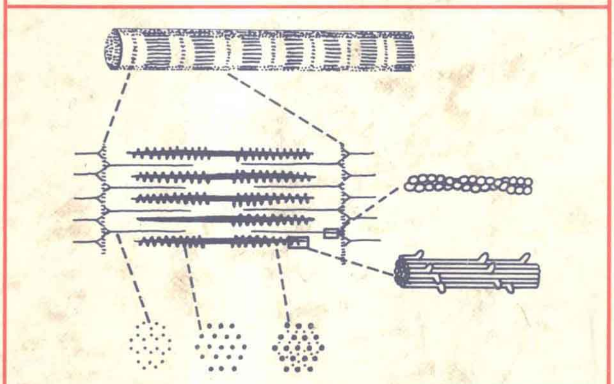
## Energy, Nutrition, and Human Performance

Second Edition







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# Exercise Physiology

## *Energy, Nutrition, and Human Performance*


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*To Kathy (and Theresa, Amy, Kevin, and Jennifer);*
*To Kerry (and David, Kevin and Ellen); and to Erika and Leslie,*
*whose lives give meaning to our own.*

# Preface

IN THE second edition of *Exercise Physiology: Energy, Nutrition and Human Performance,* we have continued our commitment to integrate basic concepts and relevant up-to-date scientific information to provide the foundation for understanding the physiology of exercise. As in the first edition, the main theme is that exercise performance is largely determined by one's capacity to generate energy. This capacity in turn, is intimately related to the food nutrients consumed in the diet and the metabolic and physiologic systems of energy delivery and energy utilization. Within this framework, the text materials are drawn from research in physical education, physiology, medicine, and nutrition. We have maintained our original seven main sections, each related to a central theme, and have added a chapter on the *Endocrine System and Exercise,* to bring the total to 30 chapters. All areas have been significantly updated with new and hopefully, relevant research.

Section I discusses food nutrients and optimal nutrition for exercise performance. In the 2nd edition, we have expanded and updated our discussion of dietary fiber, cholesterol and lipoproteins, and the role of carbohydrate feeding on human endurance capacity. In addition, we have expanded the presentation of minerals to include exercise-induced anemia and calcium, exercise, and osteoporosis. Section II deals with the energy for physical activity that includes energy metabolism relative to various modes of exercise. The presentation of blood lactate accumulation during physical activity has been further clarified and we have added a section on the maternal and fetal response to exercise. Also, a discussion of the economy of human movement is presented with comparisons between children and adults and trained and untrained individuals. The next section is concerned with the physiologic systems involved in energy delivery and utilization, emphasizing pulmonary ventilation, circulation, and neuromuscular integration. We have also broadened the presentation of exercise and pulmonary function and included a discussion of exercise and the asthmatic. A section is included that considers the onset of blood lactate accumulation (OBLA) during exercise as a determinant of endurance performance. In section IV the discussion moves to applied physiology in which topics related to training, fitness maintenance, and ergogenic aids are discussed with emphasis on the development of muscular strength and anaerobic and aerobic power. There is a new chapter that deals with the responses of the endocrine system to acute and long-term exercise. The chapter on ergogenic aids includes an update on red blood cell reinfusion and steroid use, and new presentations on the ergogenic effects of temporomandibular joint repositioning, caffeine, and pangamic acid. Section V deals with the environmental impact on exercise physiology and focuses specifically on diving, altitude, and thermal stress. A section on thermoregulation during cold weather exercise has been added in the second edition. Section VI is a particularly relevant section that focuses on the latest research and information that deals with body composition, obesity, and weight control. The concluding section presents the role of exercise as it relates to cardiovascular health and aging. These topics are germane to the established areas of adult fitness and cardiac prevention and rehabilitation programs.

As with the first edition, we have tried to balance our discussions between theoretical foundations and practical applications. Our aim is to provide a comprehensive teaching text that answers salient questions and provides the underlying reasons and rationale. Because many students enter exercise physiology with a minimal background in the sciences, the material assumes no previous specialization in topic areas. We have done our best to develop the basic introductory material into the complete picture required by the exercise specialist. We hope our text is useful to both undergraduate and graduate students, as well as students in "special topics" courses that deal with exercise and weight control, environmental physiology, nutrition and sport, and physical conditioning.

We want to say a special "thank you" to our teachers and colleagues (most notably J. Ball, A.R. Behnke, J.A. Faulkner, D. Fleming, G.F. Foglia, F.N. "Doc" Henry, H.J. Montoye, E.D. Michael, and G.Q. Rich, III) for the privilege of their close association; they each had a significant, positive, and lasting impact on our personal and professional lives. Without doubt, it was their unselfishness and commitment to the pursuit of excellence that provided the catalyst to spark our interest in physical education and to seek out and study the exciting area of human performance and exercise physiology. We wish to acknowledge our many undergraduate and graduate students, especially those who endured to pursue professional careers in the health and exercise sciences. We are also grateful to our many colleagues in the United States and abroad who provided constructive input and very helpful suggestions for the second edition. A final word of appreciation to the professionals at Lea & Febiger for their continued encouragement and support, especially J. Spahr, T. Colaiezzi, and M. Fraser.

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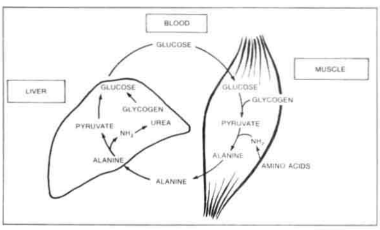
# Contents

## Exercise Physiology

### SECTION I

*Nutrition: The Base for Human Performance*





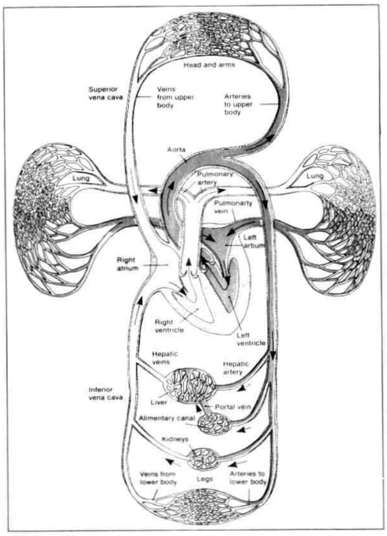

### SECTION II

*Energy for Physical Activity*



## SECTION III

*Systems of Energy Delivery and Utilization*

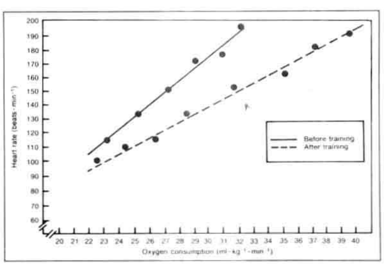





# Applied and Exercise Physiology

## SECTION IV

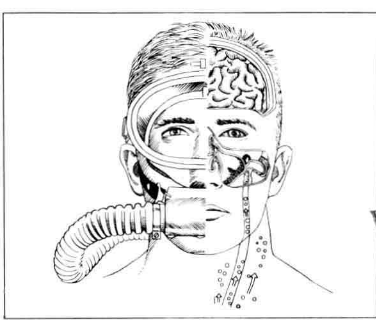
*Enhancement of Energy Capacity*

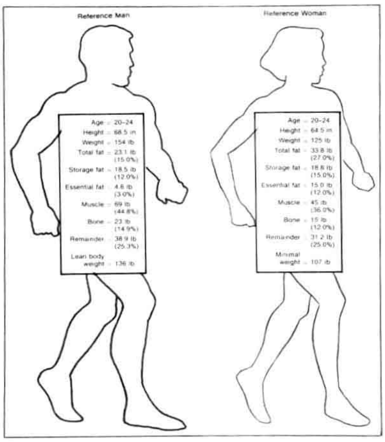





## SECTION V

*Work Performance and Environmental Stress*





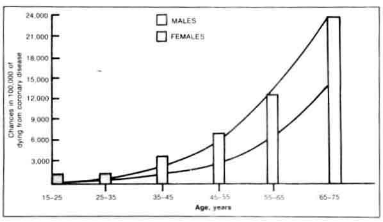

## SECTION VI

### *Body Composition, Energy Balance, and Weight Control*



## SECTION VII

### *Aging and Health Related Aspects of Exercise*



SECTION I

# Nutrition: The Base for Human Performance

In a textbook dealing with the physiology of human performance, it is uncommon to find a section devoted to the basics of human nutrition. We feel strongly that this topic is important and should serve as the starting point for this book.

Proper nutrition forms the foundation for physical performance; it provides both the fuel for biologic work and the chemicals for extracting and using the potential energy contained within this fuel. Food also provides the essential elements for the synthesis of new tissue and the repair of existing cells.

Some may argue that adequate nutrition for exercise can easily be achieved through the intake of a well-balanced diet and that it therefore is of little consequence in the study of exercise performance. We maintain, however, that the study of exercise, when viewed within the framework of energy capacities, must be based on an understanding of the sources of food energy and the role of nutrients in the process of energy release. With this perspective, it becomes possible for the exercise specialist to appreciate the importance of "adequate" nutrition and to evaluate critically the validity of claims concerning nutrient supplements and special dietary modifications for enhancing physical performance. Because various food nutrients provide energy and regulate physiologic processes associated with exercise, it is tempting to link dietary modification to improvement in athletic performance. Too often individuals spend considerable time and "energy" striving for the optimum in exercise performance, only to fall short due to inadequate, counterproductive, and sometimes harmful nutritional practices.

In the chapters that follow, we look at the six broad classifications of nutrients: carbohydrate, fat, protein, vitamins, minerals, and water. We attempt to answer the following questions: What are they? Where are they found? What are their functions? What specific role do they play in physical activity?

# 1

# Carbohydrates, Fats, and Proteins

The carbohydrate, fat, and protein nutrients consumed daily provide the necessary energy to maintain body functions both at rest and during various forms of physical activity. Aside from their role as biologic fuel, these nutrients (called macronutrients by nutritionists) also play an important part in maintaining the structural and functional integrity of the organism. In this chapter, each of these nutrients is discussed in terms of general structure, function, and source in specific foods in the diet. Emphasis is placed on their importance in sustaining physiologic function during moderate and more strenuous physical activity.

## Basic Structure of Nutrients

All biologic systems are composed of cells that engage in similar activities required to maintain the integrity and life of the cell. Although different cells possess specialized functions that necessitate special structures, the basic life-sustaining processes among all cells are similar. Cells with diverse functions also have similar chemical compositions. All cells are composed of essentially the same chemicals, differing only in the proportion and arrangement of these chemicals.

### *Atoms: Nature's Building Blocks*

Of the 103 different types of atoms or elements, hydrogen, nitrogen, oxygen, and carbon play the *major* role in the chemical composition of nutrients and comprise the structural units for most biologically active substances in the body. Hydrogen, with its relatively low atomic weight, accounts for 10% of the body weight and 63% of all the atoms in the body; carbon, for 18% of the body weight and 9% of all the atoms; nitrogen makes up 3% of the body weight and only 1% of the total number of atoms in the body; and the relatively "heavy" oxygen atom accounts for 65% of body weight yet only 26% of the total number of atoms.

*Molecules* are formed from the union of two or more atoms. The specific atoms as well as the arrangement of these atoms give the molecule its properties. Glucose is glucose because of the arrangement of 24 atoms of three different kinds within its molecule. *Chemical bonding,* e.g., between atoms of hydrogen and oxygen in the water molecule, involves a common sharing of electrons between atoms. *It is this force of attraction created between the positive and negative charges of atoms that forms the basis for bonding and provides the "cement" that keeps the atoms and molecules within a substance from readily coming apart.* When these forces are altered due to the removal, transfer, or exchange of certain electrons, energy is provided to power all cellular functions. When two or more molecules are chemically bound, a larger aggregate of matter or a *substance* is formed. This substance may take the form of a gas, liquid, or a solid, depending on the force of interaction between molecules.

### *Carbon: The Versatile Element*

All of the nutrients except water and minerals contain carbon. In fact, almost all of the biologic substances within the body are composed of compounds containing carbon. Carbon atoms have an almost unlimited ability to share chemical bonds with other carbon atoms and with atoms of other elements to form large carbon-chain molecules.

Fats and carbohydrates are formed from specific linkages of carbon atoms with atoms of hydrogen and oxygen. With the addition of nitrogen and certain mineral substances, a protein molecule is formed. These atoms of carbon, hydrogen, oxygen, and nitrogen are the *organic* building blocks from which the nutrients are made.

PART 1

# Carbohydrates

## The Nature of Carbohydrates

Carbohydrates, as the name implies, are composed of carbon and water. Atoms of carbon, hydrogen, and oxygen combine to form carbohydrate compounds. The basic chemical structure of a simple sugar molecule consists of a chain of from 3 to 7 carbon atoms with the hydrogen and oxygen atoms attached singly. The most typical sugar, *glucose,* is illustrated in Figure 1-1. The glucose molecule consists of 6 carbon, 12 hydrogen, and 6 oxygen atoms ($C_6H_{12}O_6$). Each of the carbon atoms has four bonding sites that can link to other atoms, including carbon atoms. Carbon atoms not linked to other carbons are "free" to hold hydrogen (which has only one bond site itself), oxygen (which has two bond sites), or an oxygen-hydrogen combination, termed a hydroxyl (OH).

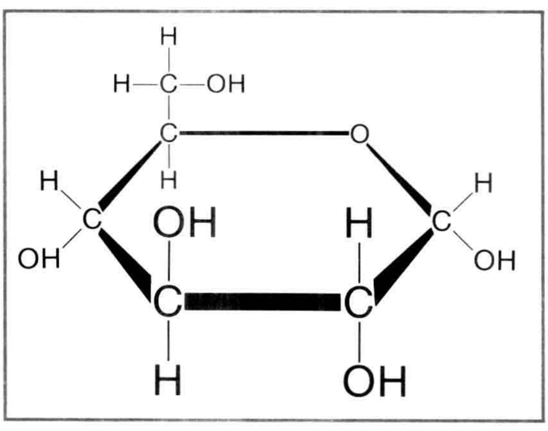



FIG. 1-1. *Three-dimensional structure of the simple sugar molecule glucose. The molcule resembles a hexagonal plate to which H and O atoms are attached.*

*Fructose* and *galactose* are two other simple sugars that have the same chemical formula as glucose, with a slightly different carbon-to-hydrogen-to-oxygen linkage. This alteration in atomic arrangement makes fructose, galactose, and glucose different substances.

## Kinds and Sources of Carbohydrates

The interaction of carbon dioxide in the atmosphere with water, solar energy, and the catalyst chlorophyll provides the necessary ingredients for plants to synthesize carbohydrates. In this process, oxygen is released into the atmosphere to be used by animals in the process of energy metabolism. The total process by which the energy from sunlight is harnessed by green plants in the production of carbohydrates is known as *photosynthesis.* This process of energy transfer is discussed more fully in Chapter 5.

There are three kinds of carbohydrates: *monosaccharides, oligosaccharides,* and *polysaccharides.* Each form of carbohydrate is distinguished by the number of simple sugars in combination within the molecule.

### *Monosaccharides*

More than 200 monosaccharides have been found in nature.[90] The most common of the monosaccharides or simple sugars, glucose, fructose, and galactose, were described previously. Glucose, also called dextrose or blood sugar, is formed as a natural sugar in food or is produced in the body as a result of digestion of more complicated carbohydrates. Glucose can be used directly by the cell for energy, stored as glycogen in the muscles and liver, or converted to fats for energy storage.

Fructose or fruit sugar is present in large amounts in natural form in fruits and honey and is the sweetest of the simple sugars. Although some fructose is absorbed directly into the blood from the digestive tract, it is all eventually converted to glucose. Galactose is not found freely in nature; rather, it must be produced from milk sugar in the mammary glands of lactating animals. In the body, galactose is converted to glucose for energy metabolism.

### *Oligosaccharides*

The major types of oligosaccharides are the *disaccharides* or double sugars, which are formed from the combination of two monosaccharide molecules.

The mono- and disaccharides collectively make up what is commonly referred to as the *simple sugars.* These sugars are packaged under a variety of guises—brown sugar, corn syrup, invert sugar, honey, and "natural sweeteners."

In the structure of each of the disaccharides, glucose is one of the simple sugars. The three principal disaccharides are:

*Sucrose* = glucose + fructose
*Lactose* = glucose + galactose
*Maltose* = glucose + glucose

*Sucrose* is the most common dietary disaccharide and contributes up to 25% of the total quantity of ingested calories in the United States. It occurs naturally in most foods containing carbohydrates, especially in beet and cane sugar, brown sugar, sorghum, maple syrup, and honey. Honey, while sweeter than table sugar owing to its greater fructose content, is no more superior nutritionally or as an energy source.

*Lactose* is found in natural form only in milk and is often called milk sugar. It is the least sweet of the disaccharides. Lactose can be artificially processed and is often found in carbohydrate-rich, high-calorie liquid meals.

*Maltose* occurs in malt products and in germinating cereals. It is considered a negligible carbohydrate in terms of its contribution to the carbohydrate content of the average person's diet.

### *Polysaccharides*

Three or more simple sugar molecules form a polysaccharide. In fact, from 300 to 26,000 monosaccharide molecules can be linked together or polymerized to form a polysaccharide. There are generally two classifications of polysaccharides, plant and animal.

PLANT POLYSACCHARIDES. Two common forms of plant polysaccharides are *starch* and *cellulose.*

*Starch* is the most familiar form of plant polysaccharide. It is found in seeds, corn, and in the various grains from which bread, cereal, spaghetti, and pastries are made. Large amounts are also present in peas, beans, potatoes, and roots, where it serves as an energy store for future use by plants. Starch granules of different sizes are encased within the cellulose walls of the plant cell. Potato starch granules, for example, are relatively large, whereas the starch granules within rice are small. Plant starch is still the most important dietary source of carbohydrate in the American diet, accounting for approximately 50% of the total carbohydrate intake. It is interesting to note, however, that starch intake has decreased about 30% since the turn of the century, whereas the consumption of more simple sugars such as sucrose has correspondingly increased from 31% to about 50%.

*Cellulose* and most other fibrous materials that are generally resistant to human digestive enzymes are another form of polysaccharide. They are found exclusively in plants and make up the structural part of leaves, stems, roots, seeds, and fruit coverings. The various fibers differ widely in physical and chemical characteristics and physiologic action; they are found mostly within the cellular walls as cellulose, hemicellulose, pectin, and the noncarbohydrate lignin, whereas other fibers such as mucilage and gums are found within the plant cell itself.

Although technically not a nutrient, dietary fiber has received considerable attention by researchers and the lay press. Much of this interest originated from studies that linked high levels of fiber intake with a lower occurrence of obesity, diabetes, intestinal disorders, and heart disease.[59,67] Because the Western diet is high in fiber-free animal foods and loses much of its natural fiber through processing, it is speculated that this accounts for the prevalence of intestinal disorders in this country compared to countries that consume a more primitive-type diet high in unrefined, complex carbohydrates.[79] For example, the typical American diet contains a daily fiber intake of about 20 grams (g)* whereas diets from Africa and India range between 40 and 150 g per day.[59] Fibers hold considerable water and thus give "bulk" to the food residues in the small intestines, often increasing stool weight and volume by 40 to 100%. This bulking action aids in gastrointestinal functioning by shortening the transit time for the passage of food residues (and possibly carcinogenic materials) through the digestive tract. This may reduce the chances of contracting various gastrointestinal diseases later in life.[17,32]

Fiber intake also lowers serum cholesterol in humans,[8,21,59,64] especially the water-soluble mucilagenous fibers such as pectin and guar gum present in oats, beans, peas, carrots, and a variety of fruits. For men with elevated blood lipids, for example, adding 100 g of oat bran to the daily diet caused a 13% reduction in serum cholesterol and favorably affected the ratio of the blood's lipoprotein components.[64] In contrast, the water-insoluble fibers, such as cellulose, hemicellulose, and lignin and cellulose-rich products like wheat bran showed no cholesterol-lowering effect.[59,94] The precise mechanism is unclear by which dietary fibers favorably affect serum cholesterol. Some fibers may hinder cholesterol absorption while others may reduce cholesterol metabolism in the gut.[21] These actions would depress the synthesis of cholesterol while at the same time facilitating the excretion of existing cholesterol bound to the fiber in the feces.[36]

Present nutritional wisdom maintains that a dietary fiber intake of about 30 g per day is an important part of a well-structured diet. Table 1-1 gives the fiber content of some common foods. Perhaps as research progresses and the analysis of the fiber content of various foods is refined, a recommended daily requirement for specific fibers may be established. Excessive fiber intake, however, is not prudent, especially for individuals with marginal levels of nutrition. Several reports show that increased fiber intake decreases the absorption of the minerals calcium, iron, magnesium, phosphorous, and certain trace minerals.[60]

ANIMAL POLYSACCHARIDES. *Glycogen* is the polysaccharide synthesized from glucose in the process of *glucogenesis* and stored in the tissues of animals. Glycogen molecules are usually large and range in size from a few hundred to thousands of glucose molecules linked together, much like the links in a chain of sausages. In well-nourished humans, approximately 375 to 475 g of carbohydrate are stored in the body. Of this, approximately 325 g are muscle glycogen, 90 to 110 g are liver glycogen, and only 15 to 20 g are present as blood glucose.[40] As each gram of glycogen contains 4 calories of energy, the average person stores between 1,500 and 2,000 calories of energy within the bonds of the carbohydrate molecule.

There are several factors that determine the rate and quantity of either glycogen synthesis or breakdown. During exercise, the carbohydrate stored as muscle glycogen is used as a source of energy for the specific muscle in which it is stored. In the liver, in contrast, glycogen is reconverted to glucose and transported in the blood for eventual use by the working muscles. The term *glycogenolysis* is used to describe this reconversion process, which provides a rapid supply of glucose for muscular contraction during all forms of work. When glycogen is depleted through dietary restriction or exercise, glucose synthesis from the structural components of the other nutrients, especially proteins, tends to increase. This process is termed *gluconeogenesis.* Hormones, especially insulin, play an important part in the regulation of liver and muscle glycogen stores by controlling the level of circulating blood sugar.

Because comparatively little glycogen is stored in the body, the quantity of liver and muscle glycogen can be modified considerably through the diet. For example, a 24-hour fast or low-carbohydrate, normal-calorie diet results in a large reduction in liver and mus-

* (Scientific measurement is generally presented in terms of the metric system. Appendix A shows the relationship between metric units and English units that are relevant to the material presented in this book. Also presented are some common expressions of work, energy, and power.)

**TABLE 1-1.** *Fiber content of some common foods listed in order of overall fiber content*

| | SERVING SIZE | TOTAL FIBER g | SOLUBLE FIBER g | INSOLUBLE FIBER g |
|---|---|---|---|---|
| 100% Bran cereal | ½ cup | 10.0 | 0.3 | 9.7 |
| Peas | ½ cup | 5.2 | 2.0 | 3.2 |
| Kidney beans | ½ cup | 4.5 | 0.5 | 4.0 |
| Apple | 1 small | 3.9 | 2.3 | 1.6 |
| Potato | 1 small | 3.8 | 2.2 | 1.6 |
| Broccoli | ½ cup | 2.5 | 1.1 | 1.4 |
| Strawberries | ¾ cup | 2.4 | 0.9 | 1.5 |
| Oats, whole | ½ cup | 1.6 | 0.5 | 1.1 |
| Banana | 1 small | 1.3 | 0.6 | 0.7 |
| Spaghetti | ½ cup | 0.8 | 0.2 | 0.8 |
| Lettuce | ½ cup | 0.5 | 0.2 | 0.3 |
| White rice | ½ cup | 0.5 | 0 | 0.5 |

cle glycogen reserves.[54] On the other hand, maintaining a carbohydrate-rich diet for several days enhances the body's carbohydrate stores to a level almost twice that obtained with a normal, well-balanced diet.[13] The effect of enhanced carbohydrate storage on exercise performance is discussed in a later section of this chapter.

## Recommended Intake of Carbohydrates

Almost all foods contain some carbohydrates, even if only trace amounts. Figure 1-2 illustrates the carbohydrate content of selected foods. Cereals, cookies, candies, breads, and cakes are rich carbohydrate sources. Because the values are based on carbohydrate percentage in relation to the total weight, including water content, fruits and vegetables appear to be less valuable sources of carbohydrates. The dried portion of these foods, however, is almost pure carbohydrate.

The typical American diet consists of approximately 40 to 50% of the total calories as carbohydrate. For a sedentary 70-kilogram (kg) person, for example, this amounts to approximately 147 g of carbohydrate per day. For active people and those involved in exercise training, about 55 to 60% of the daily caloric intake should be in the form of carbohydrates, predominantly of the complex variety.[55]

The main dietary carbohydrate source is generally fruits and vegetables. This in no way, however, represents the "state of affairs" for all individuals. A dietary survey of 16 moderately overweight females at the University of Michigan revealed that their daily carbohydrate intake of 375 g accounted for 53% of their total caloric intake. Fruits and vegetables represented only 20% of the carbohydrate intake, whereas cereals, bread, and especially sweets accounted for approximately 80%. Perhaps these findings should not be surprising because it has been estimated that the average American consumes about 50% of carbohydrate in the form of sim-

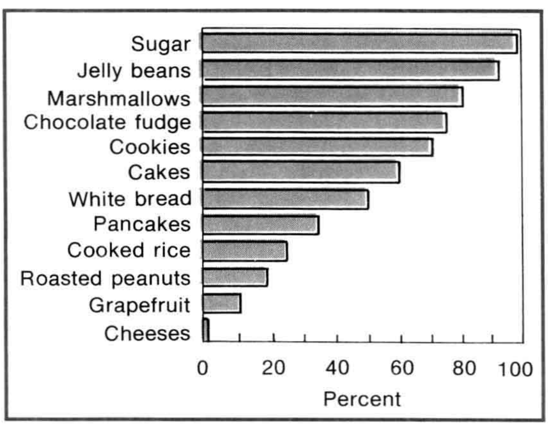



**FIG. 1-2.** *Percentage of carbohydrates in commonly served foods. (Adapted from Handbook No. 8: Composition of Foods. Washington, D.C., United States Department of Agriculture, 1963.)*

ple sugars. This amount represents more than 30 teaspoons a day or 115 pounds (lb) of table sugar each year as contrasted to a 4 lb-person intake 100 years ago!

Evidence is increasing to support the contention that an excessive frequency and quantity of fermentable carbohydrate, especially sucrose in the diet is a main *cause* of tooth decay.[31] In addition, in an as yet unexplained way, excessive dietary sugar is believed to be involved in a variety of other disease processes, most notably diabetes, obesity, and coronary heart disease.[86] One way recommended to reduce sucrose intake is to substitute fructose, the monosaccharide that is about twice as sweet as table sugar. This substitutes equal sweetness with fewer calories. In addition, fructose does not stimulate pancreatic insulin secretion and may be taken up by the muscle without assistance of insulin. As a result, blood-glucose level remains fairly stable after fructose ingestion.[75]

## Role of Carbohydrates in the Body

Carbohydrates serve several important functions related to exercise performance.

### *Energy Source*

*The main function of carbohydrate is to serve as an energy fuel for the body.* The energy derived from the breakdown of carbohydrate is ultimately used to power muscular contraction as well as all other forms of biologic work.

Carbohydrates must be broken down during digestion to a simple 6-carbon sugar before they can be absorbed by the blood and used by the body. It is important that adequate amounts of carbohydrates are ingested routinely to maintain the body's relatively limited glycogen stores. If too few carbohydrates are ingested, glucose is then obtained from glycogen breakdown and the carbohydrate reserves become depleted. In contrast, following a meal, excess carbohydrates may be readily converted to muscle and liver glycogen. Once the capacity of the cell for glycogen storage is reached, the excess sugars are converted and stored as fat. This action helps explain how body fat increases when excess calories in the form of carbohydrates are consumed. This process occurs even if the diet is low in fat.

Although the main function of carbohydrates is to provide energy to the body, certain sugars serve other important functions. The sugars ribose and deoxyribose are an integral part of the RNA and DNA molecules that form genes. These structures control heredity and exert powerful influences on all body processes.

### *Protein Sparing*

Carbohydrates also provide a "protein sparing" effect. Under normal conditions, protein serves a vital role in the maintenance, repair, and growth of body tissues, and to a considerably lesser degree, as a nutrient source of energy. When carbohydrate reserves are reduced, however, metabolic pathways exist for the synthesis of glucose from protein and the glycerol portion of the fat molecule. This process, termed *gluconeogenesis,* provides a metabolic option for augmenting carbohydrate availability in the face of depleted glycogen stores. This becomes increasingly important in prolonged endurance exercise. The price that is paid, however, is a temporary reduction in the body's protein "stores," especially muscle protein. In extreme conditions this can cause a significant reduction in lean tissue and an accompanying load on the kidneys as they excrete the nitrogen-containing byproducts of protein breakdown. Adequate intake and use of carbohydrates aid in the maintenance of tissue protein.

### *Metabolic Primer*

Another function of carbohydrates is to serve as a "primer" for fat metabolism. Certain food fragments from the breakdown of carbohydrate must be available to facilitate the metabolism of fat. If insufficient carbohydrate metabolism exists, either through limitation in the transport of glucose into the cell, which occurs in diabetes, or depletion in glycogen through improper diet or prolonged exercise, the body begins to mobilize fat to a greater extent than it can use. The result, both at rest and after exercise, is incomplete fat metabolism and the accumulation of acid by-products called *ketone bodies.*[65] This situation may lead to a harmful increase in the acidity of the body fluids, a condition called