ADVANCED CARDIOVASCULAR EXERCISE PHYSIOLOGY

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Denise L. Smith

Bo Fernhall

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Preface

There have been remarkable advances in our scientific understanding of the function of the cardiovascular system in the last couple of decades, many of which have occurred as a result of scientific research aimed at understanding cellular and molecular aspects of the cardiovascular system. In addition to better understanding of the mechanisms of cardiovascular function, in recent years there has been extensive research and a concomitant increase in our understanding of how exercise affects the cardiovascular system. These research efforts have led to far better appreciation of the mechanisms by which exercise provides cardioprotection. Thus, the purpose of this text is to provide a single resource that (1) offers a clear and concise explanation of each component of the cardiovascular system—the heart, the vasculature, and the blood; and (2) systematically details the effect of acute exercise (aerobic and resistance) and chronic exercise training (aerobic and resistance) on each of the components of the system. An additional goal is to highlight the complex interaction of the components of the cardiovascular system, both at rest and during exercise.

This text relies heavily on the latest scientific and medical research to describe physiological functioning, exercise responses, and adaptations. The text is richly illustrated with figures to elucidate physiological mechanisms. Graphic presentations are extensively used to convey scientific data and to depict exercise responses and training adaptations. Although this text is intended primarily for graduate students (or advanced undergraduate students) who are studying the effects of exercise on the cardiovascular system, health care professionals and clinicians will also benefit from this compilation of research that documents the myriad effects of exercise on this system. In the text, specific attention is paid to the beneficial effects of exercise on the various components of the cardiovascular system and the mechanisms by which regular exercise provides cardioprotection. It is presumed that readers of this text will have had courses in basic anatomy, physiology, and exercise physiology.

This text is divided into two sections, one dedicated primarily to describing the structure and function of the cardiovascular system, and one devoted to detailing the effects of exercise on the system. The first section focuses on cardiovascular physiology and provides a concise description of the structure and function of each component of the cardiovascular system—namely, the heart, the vasculature, and the blood. The first chapter is an integrative chapter on the normal function of the cardiovascular system that provides a theoretical foundation for the detailed discussions that follow and emphasizes how the various components of the cardiovascular system function together as an intact and highly interdependent organ system, both at rest and during exercise. Chapter 2 presents the heart as a pump and emphasizes the role of the heart in delivering oxygen-rich blood to the body, as well as the need to regulate cardiac output to match the metabolic demands of the body. Chapter 3 details the structure and function of the myocardial cells, the myocytes, that are ultimately responsible for the contractile force of the heart. Chapter 4 addresses the electrical activity of the heart, both within the specialized conduction system of the heart and within the cardiac myocytes. Chapter 5 describes the standard electrocardiogram (ECG) and details the clinical relationship between electrical activity in the heart and the waveforms visible on the ECG. Chapter 6 provides an organ-level description of the function of the vasculature, discussing the important topics of hemodynamics in general and the regulation of blood flow and blood pressure in particular. Chapter 7 delves into the relatively new science of vascular biology and details the structure and function of the endothelium and the vascular smooth muscle. This chapter relies heavily on relatively recent discoveries to describe how substances released by the endothelium can control vessel diameter and, ultimately, blood flow. Chapter 8 details the hemostatic function of blood, describing platelet function, coagulation, and fibrinolysis. This chapter emphasizes the delicate balance that must be maintained between coagulation and fibrinolysis in order to prevent unnecessary blood clotting while simultaneously being able to prevent blood loss when a vessel is damaged.

The second section of the book systematically details the effect of exercise on the cardiovascular system—including acute response and chronic adaptations to aerobic and resistance exercise. Chapter 9 describes the effect of acute aerobic exercise on cardiac function, vascular function, and hemostatic variables. Chapter 10 presents the chronic effects of a systematic program of aerobic exercise training on cardiac structure and function, vascular structure and function, and hemostatic variables. Following the same pattern, chapter 11 describes the effect of an acute bout of resistance exercise on cardiac function, vascular structure and function, and hemostatic variables. Finally, chapter 12 documents the chronic effects of a systematic program of resistance exercise training on cardiac structure and function, vascular structure and function, and hemostatic variables.

While it is clear that a single textbook cannot comprehensively cover all that is known about the cardiovascular system, it is our hope that the information presented in this text will provide readers with a framework for understanding how all the components of the cardiovascular system function together to support exercise, and how those components adapt to a systematic program of exercise training. Students who wish to conduct research related to the effects of exercise on the cardiovascular system may find a direction for their research by noting gaps in our current knowledge as identified in the text.

Series Preface

Having a detailed knowledge of the effects of exercise on specific physiological systems and under various conditions is essential for advanced-level exercise physiology students. For example, students should be able to answer questions such as these: What are the chronic effects of a systematic program of resistance training on cardiac structure and function, vascular structure and function, and hemostatic variables? How do different environments influence the ability to exercise, and what can pushing the body to its environmental limits tell us about how the body functions during exercise? When muscles are inactive, what happens to their sensitivity to insulin, and what role do inactive muscles play in the development of hyperinsulinemia and type 2 diabetes? These questions and many others are answered in the books in Human Kinetics' Advanced Exercise Physiology Series.

Beginning where most introductory exercise physiology textbooks end their discussions, each book in this series describes in detail the effects of exercise on a specific physiological system or the effects of external conditions on exercise. Armed with this information, students will be better prepared both to conduct the high-quality research required for advancing scientific knowledge and to make decisions in real-life scenarios such as the assement of health and fitness or the formulation of effective exercise guidelines and prescriptions.

Although many graduate programs and some undergraduate programs in exercise science and kinesiology offer specific courses on advanced topics in exercise physiology, there are few good options for textbooks to support those classes. Some instructors adopt general advanced physiology textbooks, but such books focus almost entirely on physiology without emphasizing *exercise* physiology.

Each book in the Advanced Exercise Physiology Series addresses the effects of exercise on a certain physiological system (e.g., cardiovascular or neuromuscular) or in certain contexts (e.g., in various types of environments). These textbooks are intended primarily for students, but researchers and practitioners will also benefit from the detailed presentation of the most recent research regarding topics in exercise physiology.

Acknowledgments

There are many people who helped to make this book possible and we are indebted to all of them, but a few warrant special mention. Our acquisition editor, Mike Bahrke, provided the encouragement and insight expected from an editor, and also offered the kindness and patience of a friend throughout the preparation of the manuscript. Our developmental editor, Kevin Matz, provided good advice, offered consistant support, and effectively used his gentle nature to keep us organized throughout the last stages of preparing this text. Discussions with Tom Rowland helped frame our thinking in several places, and he kindly served as a reviewer of several chapters. Hannah Segrave has been indispensible in preparing the text; her skills strengthened the manuscript, and her good humor made the project much more fun.

We would like to acknowledge the role of our students in pushing us to frame a logical approach to understanding the complex and intricately interrelated components of the cardiovascular system and the effects of exercise upon those various components. Furthermore, we gratefully recognize the central role that our students have played in providing us with the inspiration and the motivation to pursue the daunting task of writing this text.

Finally, we would like to thank our families for their unwavering support and encouragement through the long process of preparing this text, a process that kept us from them for more than we would have liked.

Contents

SECTION I

Cardiovascular Physiology

The cardiovascular system is composed of the heart, the vasculature, and the blood. The cardiovascular system responds to exercise in a complex and integrated way that allows it to meet the metabolic needs of the working muscles, preserve needed levels of homeostasis for bodily function, and respond to potential bodily threats.

Section I provides a concise explanation of the structure and function of each component of the cardiovascular system (the heart, the vessels, and the blood), placing considerable emphasis on how the cells of organs function and how their functions are controlled. The second section of the book describes how all the components of the cardiovascular system respond in an integrated fashion to aerobic and resistance exercise and to training programs. It is useful to keep the integrated response to the stress of exercise in mind throughout each chapter in Section I.

CHAPTER 1

Essentials of the Cardiovascular System

The human cardiovascular system is a fascinating system that has inspired awe and provoked serious investigation among clinicians and researchers for hundreds of years. In ancient times, the heart was seen as the seat of our emotions, and even today the image of the heart is tied to the notion of sentimental feelings. In 1628, William Harvey proposed that the heart propelled blood through a closed vascular circuit (Fye, 2006). Today, every high school student has a rudimentary understanding of the role of the cardiovascular system in sustaining life. Nonetheless, researchers continue to make exciting new discoveries about the cardiovascular system every day, with recent discoveries focused largely on cellular and molecular aspects of cardiovascular function.

The cardiovascular system is a complex organ system that functions with multiple other physiologic systems in an integrated way. The cardiovascular system is composed of three overlapping and interrelated components: the heart, the vasculature, and the blood. Together, these components provide the basic function of the cardiovascular system: the delivery of oxygen and nutrients to the cells of the body and the elimination of waste products from the cells. The cardiovascular system serves multiple functions, which may be categorized into several major and sometimes overlapping categories as follows:

1. Transport and delivery
    - The transport and exchange of respiratory gases (oxygen and carbon dioxide)
    - The transport and exchange of nutrients and waste products
    - The transport of hormones and other chemical messengers
2. Hemostatic regulation
    - Fluid balance among various fluid compartments

- The maintenance of pH balance
- The maintenance of thermal balance
- The regulation of blood pressure

3. Protection
    - Prevention of blood loss through hemostatic mechanisms
    - Prevention of infection through white blood cells and lymphatic tissue

These essential functions are achieved because of the close functional relationships between the cardiovascular system and other major systems of the body, notably the neural, respiratory, endocrine, digestive, urinary, skeletal, and integumentary systems. As seen in the schematic presented in figure 1.1, the cardiovascular system provides blood flow to the pulmonary circulation and the systemic circulation. The pulmonary circulation delivers partially deoxygenated blood from the right ventricle to the pulmonary capillaries, where it becomes oxygenated and is returned to the left atrium. The pulmonary circulation highlights the important interrelationship between the cardiovascular system and the respiratory system. In short, the respiratory system is responsible for bringing oxygen into the alveoli, whereas the cardiovascular system is responsible for distributing oxygen to the cells of the body. Likewise, the cardiovascular system delivers carbon dioxide that is produced at the cellular level to the pulmonary capillaries, where it diffuses into the lungs to be exhaled. The systemic circulation

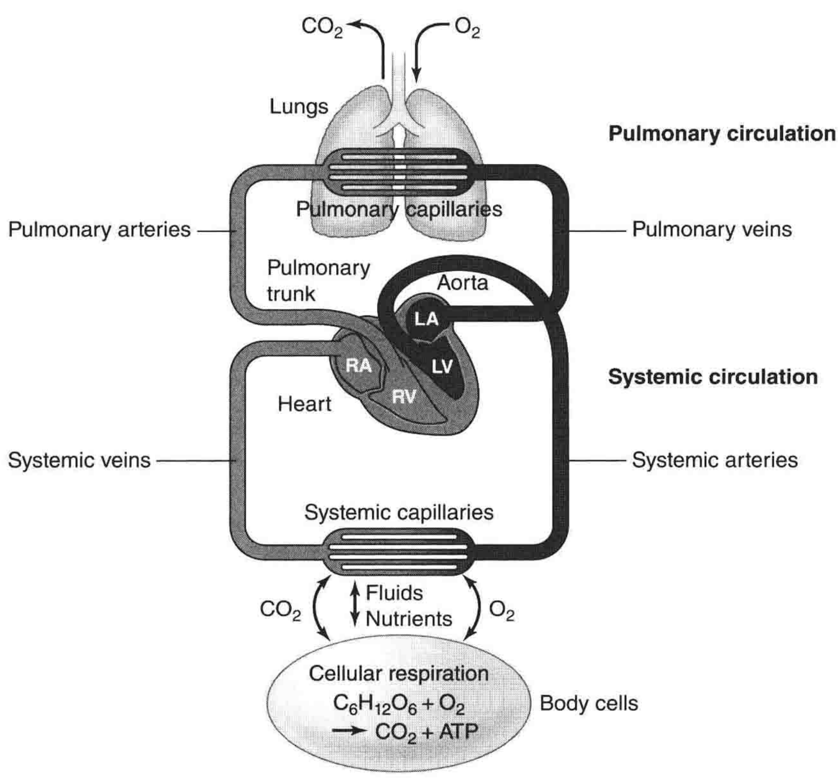

Figure 1.1 Overview of pulmonary and systemic circulations. The pulmonary circulation delivers blood to the lungs in order to eliminate carbon dioxide and oxygenate hemoglobin.

distributes blood to all the major systems and tissues of the body. The systemic circulation interacts extensively with other bodily systems, notably the digestive, urinary, and integumentary systems, to accomplish the major functions of the cardiovascular system.

Many of these functions play an important role in homeostatic balance, including maintenance of adequate blood pressure to perfuse body tissues and thus supply optimal levels of oxygen; maintenance of pH balance within tight limits; thermal regulation, through both the formation of sweat (derived from plasma) and increase in cutaneous blood flow; and metabolic regulation, particularly in terms of blood glucose levels.

COMPONENTS OF THE CARDIOVASCULAR SYSTEM

This chapter briefly reviews the structure and function of the components of the cardiovascular system to provide the reader with an appreciation of the extent to which all the components of the system must operate together to achieve the functions just described. Subsequent chapters will discuss the structure and function of each component in greater detail and explain how each component responds to the stress of exercise.

Heart

The cardiovascular system is composed of the heart, the vasculature, and the blood. The heart serves as the pump for the system and provides the contractile force necessary to distribute blood to the various organs (figure 1.2 provides a schematic of the heart structure). The atria serve as the receiving chambers, receiving blood from the superior and inferior vena cava. The right ventricle pumps blood to the lungs (pulmonary system), whereas the left ventricle pumps to the entire body (systemic circulation). The muscular wall of the heart is termed the myocardium, meaning "heart muscle." Properly functioning valves ensure the one-way flow of blood through the heart. Although the heart is a relatively small organ, weighing approximately 300 to 350 g in healthy adults, it receives about 4% of resting blood flow and accounts for approximately 10% of resting oxygen consumption.

MAXIMAL OXYGEN CONSUMPTION ($\dot{V}O_2MAX$)

Maximal oxygen consumption ($\dot{V}O_2max$) is one of the most common measures of an individual's overall fitness. It is also a functional measure of the entire cardiovascular system. Maximal oxygen consumption reflects the capacity of the cardiovascular system to deliver blood (and the oxygen it contains) to working muscle and the ability of that muscle to use the oxygen delivered. This requires an increase in the total amount of blood pumped by the heart (increased cardiac output) and a redistribution of the blood so that a greater percentage is directed to the exercising muscle and a lesser percentage to the non-exercising muscle and organs that do not require as much oxygen at that time (e.g., kidney and gastrointestinal tract). Cardiac output at rest is approximately 5 L/min; during maximal exercise it may increase to values over 30 L/min. Equally impressive is how the cardiac output is distributed in each case. In particular, at rest, approximately 20% of the cardiac output (or 1 L/min) is distributed to skeletal muscle. During maximal exercise, approximately 90% of cardiac output (or 27 L/min) is directed to the skeletal muscle.

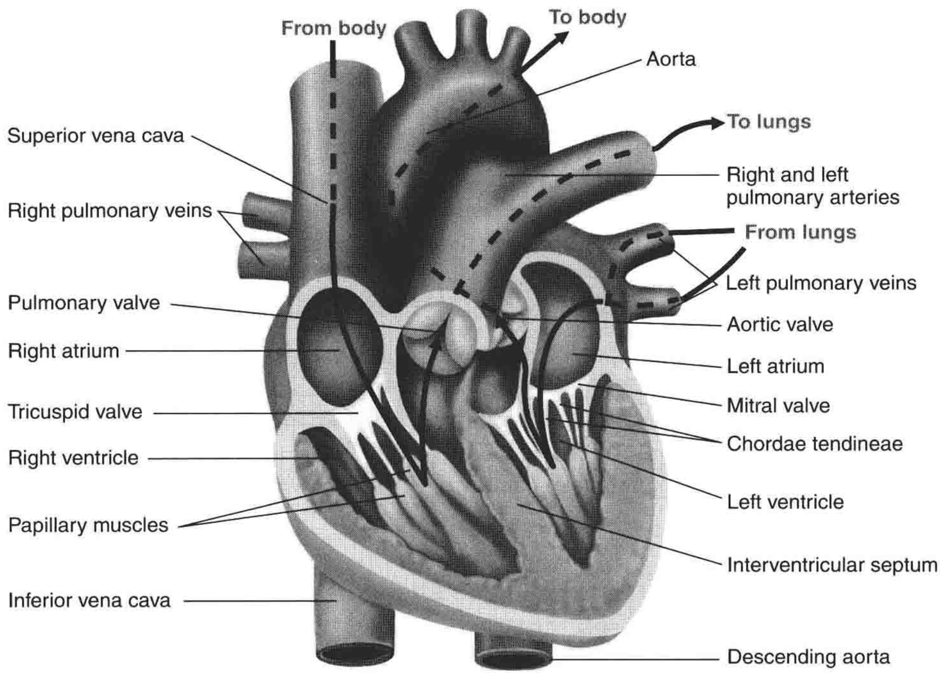

Figure 1.2 Heart structure. Valves play a major role in ensuring one-way flow of blood through the heart.

Reprinted, by permission, from J.W. Wilmore, D.L. Costill, and W.L. Kenney, 2008, *Physiology of Exercise and Sport*, 4th ed. (Champaign, IL: Human Kinetics), 125.

Cardiac output is the amount of blood ejected from the ventricles in one minute. It is a measure of the heart's ability to pump blood to support the needs of the body on a per minute basis. Cardiac output is determined by the product of heart rate (number of beats per minute) and stroke volume (amount ejected per beat). Under normal, resting conditions, cardiac output is approximately 5 L/min, depending largely on body size, but this value can change quickly to meet the changing needs of the body. For instance, during strenuous exercise, cardiac output may increase four to five times to meet the metabolic demands of working muscles.

Vessels

The vessels are responsible for distributing oxygen, nutrients, and myriad other substances throughout the body. Figure 1.3 provides a schematic view of the circuitry of the cardiovascular system. Although circulation to most of the organs is in parallel, the liver and renal tubules are in series. The relative distribution of blood that is delivered to each of the circulations is intricately controlled by the degree of vasoconstriction or vasodilation in the arterioles that supply the organs. The degree of smooth muscle contraction is, in turn, determined by extrinsic (neurohormonal) and local control (i.e., the metabolic needs of the tissue).

Far from being simple conduits, the vessels are dynamic organs that constantly alter their diameter to change blood flow to meet their requirement for blood flow. The vessel wall also releases a number of chemical mediators that participate in blood clotting and the inflammatory response.

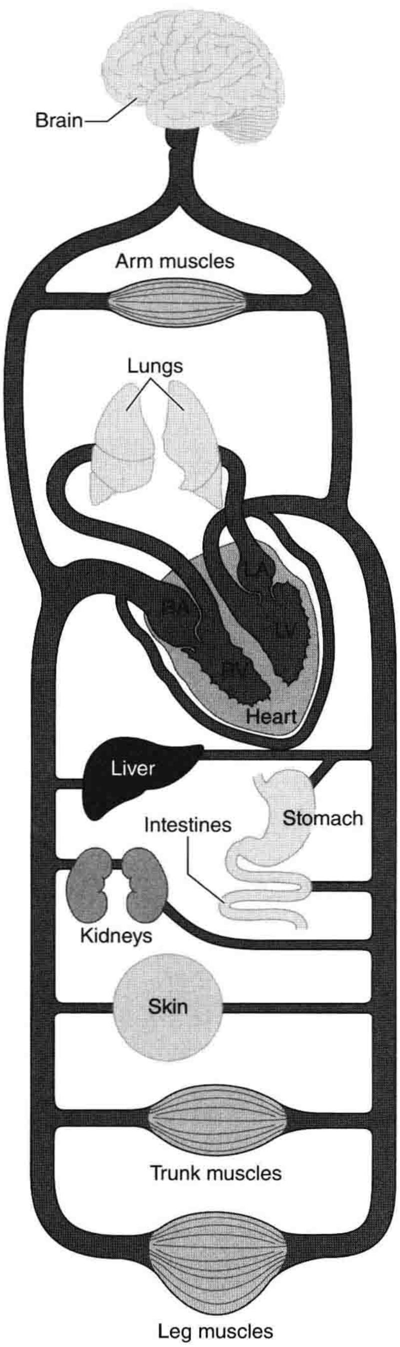

Figure 1.3 Schematic of the major circuitry of the cardiovascular system. Circulation to most systemic organs is in parallel, but the liver and kidney tubules are in series.

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Blood Velocity and Pressure Through the Vascular System

Figure 1.4 presents a schematic of velocity, blood pressure, and resistance of blood flow through the systemic circulation and relates these variables to the cross-sectional area of the vessels. On an individual basis, the aorta (the largest artery in the body) is larger than regular arteries, arteries are larger than arterioles, and arterioles are