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BIOFLUID DYNAMICS: BLOOD FLOW IN ARTERIES AND VEINS

Dr.Ranveer Singh, Associate Professor of Mathematics, Govt. Science College, Siker (Rajasthan). Email: ranveersinghchoudhary149@gmail.com

Abstract

The field of study known as biofluid dynamics may be characterized as the investigation of fluid flow, fluid-structure interaction, and the transport of heat and mass in mammalian systems as well as in medical devices. The flow of blood through the arterial system of the human body may be thought of as a fluid dynamics issue. A deeper insight into the workings of the human body's physiology may be gained through the simulation of blood flow in the arterial network system. Because of this, hemodynamics plays a significant part in the development and progression of arterial stenosis, which ultimately results in dysfunction within the cardiovascular system. Simulation studies of blood flow in a sick condition may rapidly diagnose a health problem and have various applications in fields such as the planning of surgical procedures and the creation of medical equipment. This is one of the many benefits of doing these studies. This paper presents a review on the existing scenario of the simulation studies of blood flow. It begins with a brief overview of the structure and function of arteries and veins, and it is then followed by a discussion on pressure wave propagation, blood flow models, and Fluid Structure Interaction in the arterial system. Finally, the paper concludes with a discussion on some potential future directions for these simulation studies. The study of biofluid dynamics is an intriguing topic since it captures the interest of people from a variety of backgrounds, including that of the scientific community and the public.

keywords: *Biofluid, Dynamics, Blood, Arteries*

Introduction

In much of the western world, occlusion of the arteries, also known as occlusive arterial disease, is one of the leading causes of mortality. It is nearly certain that a constriction or stenosis in an artery will disrupt the normal flow of blood through the channel, leading to areas with high fluid stress, increased wall shear stress, and recirculation of flow. These flow conditions have the potential to eventually produce major pathological issues within the artery, including damage to the endothelium, hemolysis, thrombosis, and other types of injury. Therefore, it should not come as a complete surprise that the study of blood flow via stenosed arteries has been the focus of a significant number of research over the course of the last several decades. However, despite the enormous number of research that have been conducted in this field, the factors that lead to arterial stenoses are still largely a mystery. A significant amount of research applying epidemiological methods has been carried out to identify the variables that are related with vascular illnesses. A high cholesterol level is associated with several risk factors, including age, gender, smoking cigarettes, hypertension, and an overall high level of cholesterol. However, these investigations have only been able to show a correlation between the parameters in question and arterial disorders. They provide us with no information whatsoever on the factors that contribute to the disorders.

dynamics of blood flow, with the goal of better comprehending the relevance of this phenomenon in the development and progression of vascular illnesses. Such research, which can take the form of either an experiment or a mathematical model, often involves simulating the flow of blood through a tube, which may or may not be partially blocked. These models include the making of measurements of flow variables including pressure, shear stress, and flow velocity, as well as the analysis of those measurements.

Numerous in experimental investigations have yielded a significant amount of knowledge. Some of these studies make use of flow visualization tools, which might provide important qualitative information such as regions of recirculation and flow separation. However, to gather quantitative information, some of these models may require the installation of a probing device of some kind (like a pressure probe, for instance) within the vessel to carry out a variety of measurements. Because it is not possible to place probes over the whole flow domain, the use of these physically based measures is severely restricted. In addition, the installation of probes has the potential to significantly modify the natural circumstances of the flow, which can at times lead to erroneous data being obtained. The use of a laser Doppler anemometer or ultrasound methods to detect the velocity of flow also has a limitation in that measurements can only be taken at certain sites within the flow domain. This makes it difficult to generalize the results of the measurements. Furthermore, it is extremely difficult to accurately detect shear forces by experimental means. The study of blood flow via arteries may be done in a way that is less expensive and does not need any intrusive procedures with the use of mathematical models. However, because of the complexity of the model's extremely non-linear and linked governing equations, accurate analytic solutions for the flow models have not yet been established. This is preventing the models from being fully understood. To discover analytical solutions to the problem, early researchers in this subject tended to simplify the equations. During this process, assumptions and simplifications were typically made in the models. In recent years, as high-speed digital computers have become more widely available, an increasing number of academics have begun to focus on numerical approaches for predicting blood flow. In more recent times, computer algorithms that use computational fluid dynamics (CFD) have also been utilized successfully to analyze problems of this nature.

In the process of modelling blood flow, either experimentally or mathematically, the primary goal is to gather qualitative or quantitative information on flow properties of blood as it passes through a vessel by means of a realistic simulation. This may be done either by observing the flow of blood or by simulating it. The pressure drops, flow velocities, and shearing stresses on the vessel walls are typically the flow parameters that are of interest. The resistance to flow that exists within the vessel is directly connected to the pressure decreases that occur throughout its length. Therefore, information on how pressure drops are altered by specific physiological parameters represented in the model will convert into information on how the flow of blood may be hampered. This information will be useful in determining whether the model is accurate. There is a correlation between the volume flow rate and the velocity of the flow, also known as the average velocity. The amount of blood that is delivered to the vital organs will be directly proportional to this quantity. Additionally, anomalies in the arteries may result in abnormalities in the velocity profile, and vice versa. It is therefore of significant interest to investigate, using a model, the ways in which altering circumstances in the model could influence the flow velocities. In a laboratory setting, it is difficult to accurately assess the shearing forces that are placed on the artery walls. Experiments are frequently used to make estimates of them, or mathematical or numerical models are utilized to ascertain their values. The amount of shear stress that the artery walls are subjected to may have a direct influence on the creation or rupture of plaques in the walls, which can then lead to a variety of clinical issues. Studies that utilize modelling therefore constitute an essential component of the ongoing research in the field of blood flow. It is crucial to get important insight into how the dynamics of blood flow might be connected to arterial illnesses, and information on the flow characteristics can assist to give such important knowledge. In turn, this will help cardiologists understand the pathogenesis and course of these disorders, which will be of great assistance to them.

L.2 Some Early Studies in Blood Flow Problems

During the last several decades, a great number of experimental research have been carried out to construct models of the flow of blood through arteries. studies like these, which may take place either in vivo or in vitro, are often carried out with the purpose of measuring certain essential flow parameters including pressure drops and blood flow velocities. These studies can take place either in vivo or in vitro. Researchers such as Mann et al (L938) and Shipley and Gregg (1944) were responsible for carrying out a few of the earliest experiments that were conducted to explore the characteristics of blood flow in arteries. This experimental researchhas mostly focused on estimating the decrease in blood flow that occurs because of a decrease in the lumen of a vessel as a result of an external compression. Shipley and Gregg discovered that the only time there was a substantial reduction in the flow of blood through an artery was when there was a 50–70 percent reduction in the cross-sectional area of the lumen. Although there were some questions raised about the methods of measurement used in these early experiments, because ofthis research, a foundation was formed for more experimental investigations in the future. In the years that followed, researchers such as May et al (1963), Fiddian et al (1964), Rodbard (1966), and Kindt and Youmans (1969) did additional experimental work to investigate the dynamics of blood flow in stenotic arteries. May et al (L963) conducted an experiment on animals in which they increased the amount of constriction placed on their iliac arteries. They discovered that a consistent drop in blood flow was not evident until the degree of stenosis reached 80 percent. In addition, the researchers discovered via their trials that an increase in the length of the stenotic segment from one cm to four cm brought about an average flow reduction of 24.8 percent. Fiddian et al. (1964) conducted a series of studies on dogs to explore the factors that affect the flow of blood: the diameter of the stenosis, the length of the stenosis, the viscosity of the fluid, and the peripheral resistance. Their trials not only confirmed the findings of Shipley and Gregg, but they also demonstrated that the duration of a stenosis has a disproportionately modest impact on the amount of blood that is allowed to flow through the artery. In the experiment that Kindt and Youmans (1969) conducted to investigate the impact of stricture length on critical arterial stenosis, they employed a total of fourteen canines for their research. To partially obstructing the flow of blood through a vessel, clamps of the same diameter but varied lengths were created and employed. According to the findings of their investigation, an increase in stenotic length that was eight times greater was necessary to achieve a reduction in flow that was only fifty percent as great. As pressure drops are connected to the resistance to flow, most of these early studies were designed to measure or estimate the pressure drop across a stenosed artery because pressure dips are related to resistance. The most fundamental conclusion that can be derived from these investigations is that in general, a rather severe reduction in the cross-sectional area of the lumen is required (approximately 70 to 80 percent), to generate a considerable drop in the blood flow in the channel. The shearing loads that are placed on the artery wall are yet another significant flow feature. The measurement of the wall shear stress is a highly challenging undertaking, which is unfortunate. Fry (1968) devised an indirect approach for measuring shearing stresses and carried out a remarkable experiment to explore the acute vascular endothelial alterations associated with an increase in flow velocity. To ascertain the normal limiting wall shear stress levels at which endothelial failure will occur, Fry conducted in uiuo tests on the thoracic arteries of anaesthetized mongrel dogs. These investigations looked at the mongrel dogs' thoracic arteries. According to the findings of his research, being subjected to an averaged wall shear stress that was higher than roughly 380 dynes f cm2 for periods of time as brief as one hour might result in a significant degradation of the endothelium surface.

THE CIRCULATORY SYSTEM IN THE HUMAN BODY

The removal of waste and carbon dioxide from the body for excretion through the kidneys and the lungs, respectively, and the regulation of body temperature by adverting the heat that is generated and transferring it to the environment outside the skin are the primary roles that the cardiovascular system plays in the body. The circulatory system of a healthy human body (as well as the circulatory systems of other vertebrates and a small number of other animals) may be thought of as a closed system. This means that the blood never exits the network of blood vessels that makes up the circulatory system. The existing pressure gradient serves as the driving force behind the circulation of blood. There are three sub-systems that may be explored when discussing the circulations that are involved with the cardiovascular system. The systemic circulation, the pulmonary circulation, and the coronary circulation are the three types of circulation that are shown in Figure 1. Blood travels throughout the body via the systemic circulation, which delivers it to all the organs and tissues except for the lungs. When the left ventricle of the heart contracts, it pumps blood that is rich in oxygen to a relatively high pressure, and then the blood is ejected via the aortic valve into the aorta. Blood is carried from the aorta to all the body's organs by means of the systemic arteries and the branch arteries.

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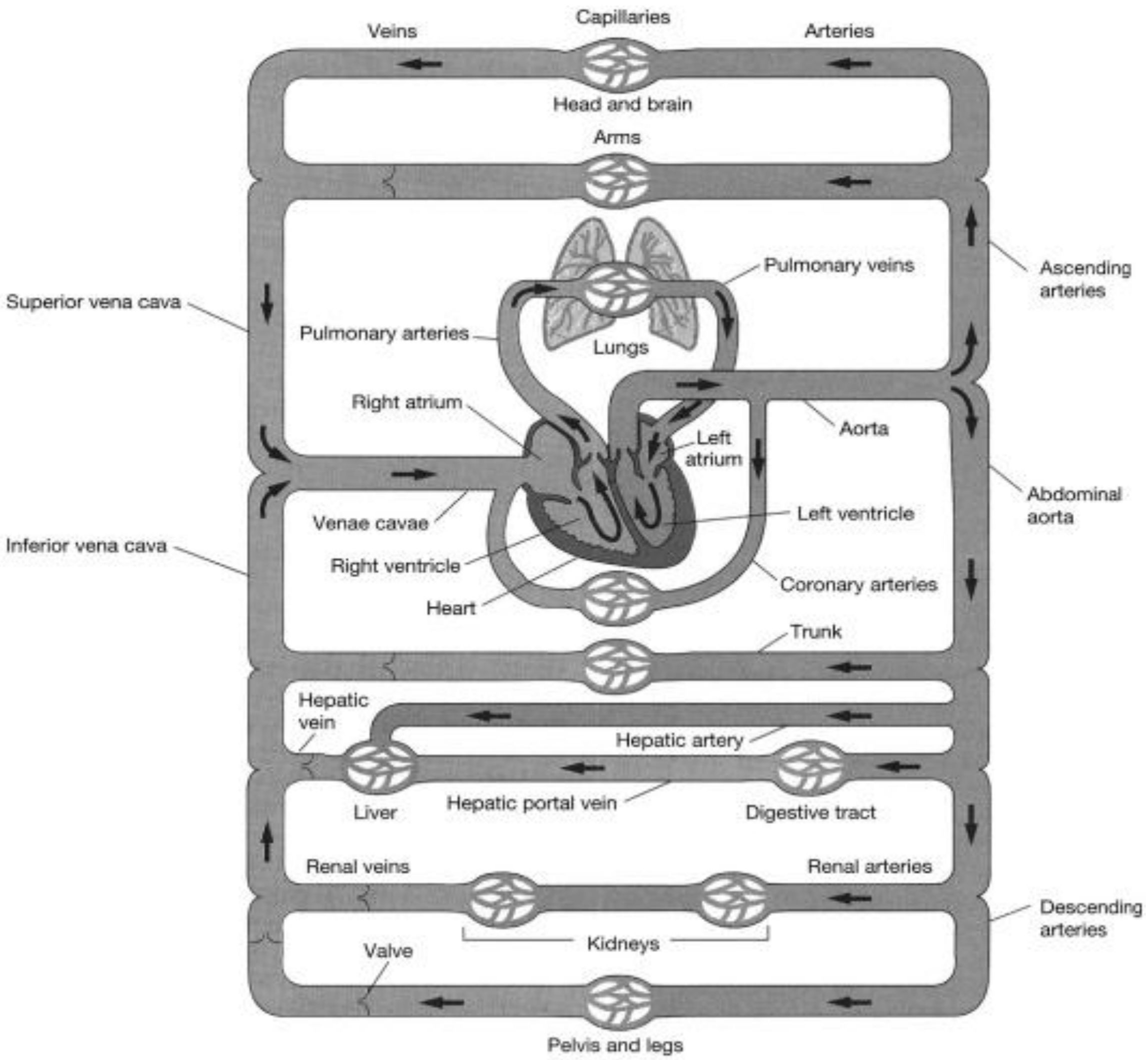

Figure 1 A diagram depicting the flow of blood through the systemic and pulmonary circulatory systems, highlighting the major branches. This passage was used with the author's permission from silver thorn, D.U. (2001). Prentice Hall, Upper Saddle River, New Jersey, published the second edition of Human Physiology: An Integrated Approach.

the arterioles. These, in turn, are responsible for transporting blood to the capillaries that may be found in the tissues of a variety of organs. Diffusion is the process that allows oxygen and nutrients to go to the tissues from the capillaries via the walls of the capillaries. Carbon dioxide and other byproducts (waste) are produced because of cellular metabolism in the tissues. Carbon dioxide may be dissolved in the blood, and the circulation is responsible for transporting waste products. Venules and veins are where the blood ultimately drains to. These blood arteries finally discharge their contents into two big veins known as the superior vena cava (SVC) and the inferior vena cava (IVC). These veins are responsible for transporting blood that is high in carbon dioxide back to the right atrium. The systemic circulation's mean blood pressure can reach a high of 93 millimeters of mercury, but it seldom does.

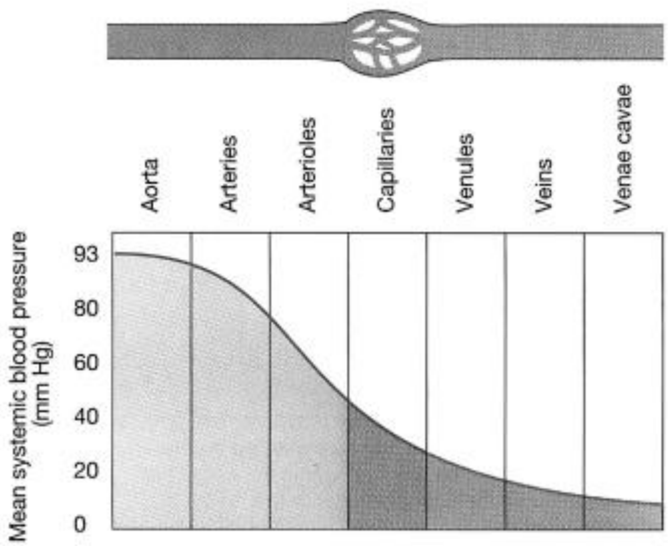

FIGURE 2 The difference in pressure across the blood vessels. The aorta, which carries blood that is rich in oxygen out from the heart, has some of the greatest pressures observed in the body. The biggest veins, which carry oxygen-depleted blood towards the heart, have the lowest pressures of all the veins in the body. This article has been reproduced with the author's kind permission from silver thorn, D. U. (2001). Prentice Hall, Upper Saddle River, New Jersey, published the second edition of Human Physiology: An Integrated Approach.

mm Hg to a low of a few mm Hg in the venae cave. mm Hg in the arteries to a low of few mm Hg in the venae cave. As can be seen in Figure 2, blood pressure steadily drops the further it is removed from the heart. The aorta and the systemic arteries have the highest pressure in the vessels of the circulatory system, while the venae cave have the lowest pressure. This is because the aorta and the systemic arteries carry the most blood. When the right atrium contracts, blood that is high in carbon dioxide is forced through the tricuspid valve and into the right ventricle. This process occurs in the pulmonary circulation. When the right ventricle contracts, blood is pumped into the pulmonary arteries through the pulmonic valve, which is also referred to as the semilunar valve. These arteries branch out and carry blood into the intricate network of pulmonary capillaries in the lungs, which is known as the pulmonary circulation. These capillaries are in and around the alveoli walls as well as in between them. When a person takes a breath in, the amount of oxygen in the air that is taken in by the alveolar region's air sacs is higher than the amount of oxygen that is taken in by the capillary blood. Oxygen enters the bloodstream by penetrating the capillary walls and diffusing into the circulation. At the same time, there is a larger concentration of carbon dioxide in the blood than there is in the air, and carbon dioxide can diffuse from the blood into the alveoli. Carbon dioxide is expelled from the body through the mouth and the nose. Blood that has been oxygenated exits the lungs via the pulmonary veins and travels to the left atrium of the heart. Blood is pumped into the left ventricle from the left atrium when the left atrial contracts. This happens through the bicuspid (mitral) valve. Figures 3 and 4 each give an overview of the external and cellular respiration processes, as well as the branching of the airways. Under typical circumstances, the systemic and pulmonary circulations work together to move blood through the body at a pace of around 5.2 liters per minute. One complete cardiac cycle consists of the systemic circulation, the pulmonary circulation, and everything in between. The term "cardiac cycle" refers to any one of these events linked to the flow of blood that occur between the beginning of one heartbeat and the beginning of the following heartbeat. The term can also refer to all these events taken together. During each phase of the cardiac cycle, the blood pressure rises and then falls.

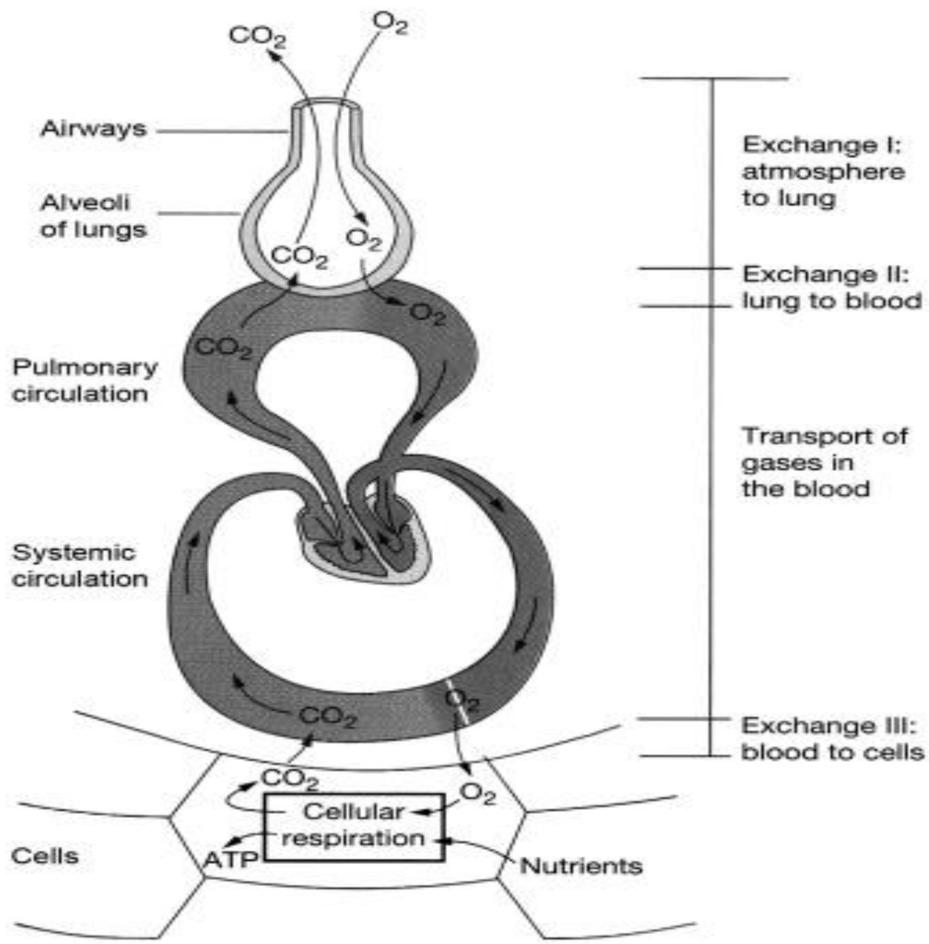

Figure 3 An outline of both the cellular and the external respiration processes. Cells get their oxygen and nutrition from the circulation, and they release their waste products, including carbon dioxide, into the bloodstream. This article has been reproduced with the author's kind permission from silver thorn, D. U. (2001). Prentice Hall, Upper Saddle River, New Jersey, published the second edition of Human Physiology: An Integrated Approach.

reduces in size. The term "heart rate" refers to the frequency of the cardiac cycle. A section of the autonomic nervous system (the element of the nervous system that does not require the involvement of the brain to operate) is responsible for controlling the heartbeat cycle. This piece of the autonomic nervous system also controls blood pressure. Blood is delivered to and taken away from the heart muscle itself when there is coronary circulation. Because the myocardial, which is the muscular tissue of the heart, is dense, the coronary blood arteries are essential for delivering blood to the innermost layers of the myocardium. Coronary arteries are the blood

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vessels that deliver oxygen-rich blood to the myocardium, often known as the muscle tissue, that makes up the heart. The root of the aorta is the origin of the major coronary artery, which then divides into the coronary arteries of the left and right sides of the heart. The right coronary artery receives the remaining twenty to thirty percent of the coronary blood flow, whereas the left coronary artery receives up to around seventy-five percent of the coronary blood supply. The deoxygenated blood leaves the heart via the cardiac veins, which are fed by the blood that travels through the capillaries of the heart and returns through the cardiac veins.

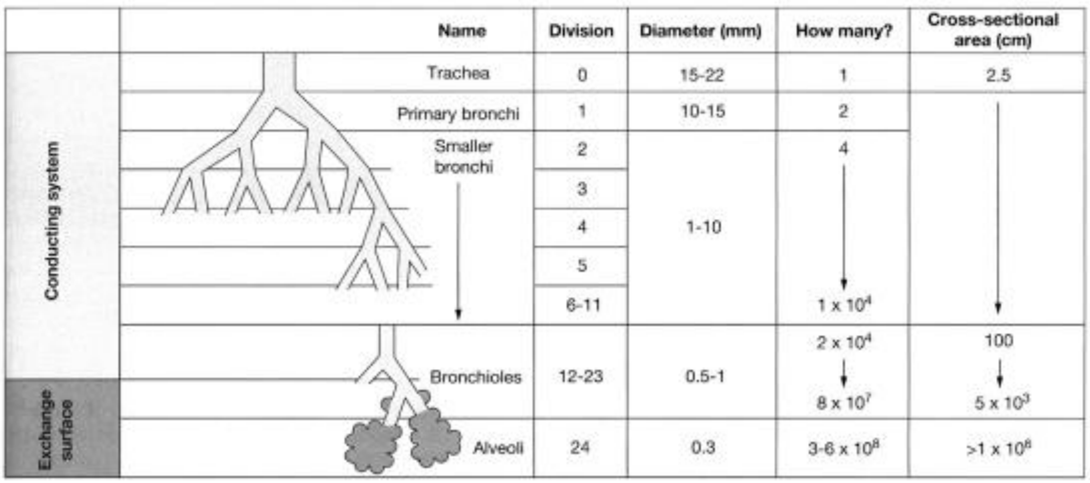

Figure 4 The human lungs have several branches of the airways. Areas are measured using the cm2 unit. This article has been reproduced with the author's kind permission from silver thorn, D. U. (2001). Prentice Hall, Upper Saddle River, New Jersey, published the second edition of Human Physiology: An Integrated Approach.

the muscle. The coronary arteries are relatively thin veins that run along the surface of the heart. These coronary arteries are frequently damaged by atherosclerosis and have the potential to become clogged, which can lead to angina or a heart attack. The coronary arteries are considered end circulation since they provide the only source of blood flow to the myocardium. This makes them a vital component of the cardiovascular system.

The Heart as a Pump

Two atria (located in the chest) and two ventricles (located in the abdomen) work together to pump blood throughout the body. A muscle known as the septum separates the left side of the heart from the right side of the heart, which maintains the distinct blood volume levels in each side of the heart. By way of the heart valves, the higher chambers of the heart communicate with the lower chambers. Because it has four valves, the heart can control the flow of blood to guarantee that it only goes in the proper direction. The tricuspid valve, which has three flaps, is located between the right atrium and the right ventricle. The bicuspid valve, which has two flaps and is also known as the mitral valve, is located between the left atrium and the left ventricle. Together, these two valves make up the atrio-ventricular (AV) valves. Between the right ventricle and the pulmonary artery is where you'll find the pulmonary valve, and between the left ventricle and the aorta is where you'll find the aortic valve. Semilunar valves are the name given to both the pulmonary and the aortic valves because they each contain three cusps that are shaped like a half-moon and are symmetrical. The four chambers that make up the heart's structure work together to accomplish the task of pumping blood via the pulmonary and systemic circulations. The veins supply blood to the atria; the right atrium receives blood rich in carbon dioxide from the superior vena cava and the inferior vena cava (SVC and IVC), while the left atrial receives blood high in oxygen from the pulmonary veins. Each side of the heart beats in time with the other because it is regulated by a single electrical impulse that travels across the entire heart. The contraction of the chambers of the heart is caused by the activation of the heart muscle, also known as the myocardium, by electrical activity. After this, there is an instantaneous transition to the mechanical contraction of the heart. Contraction occurs in both atriums at the same time. When the atriums contract, blood is pushed down through the valves and into the ventricles from the upper chambers of the heart. The muscles of the ventricles and the atria are electrically distinct from one another, except for a single channel that allows an electrical impulse to go from the atria to the ventricles. During the time that the impulse is travelling down the route, it has a delay of around 110 milliseconds before it reaches the ventricles. Because of this delay, the ventricles can fill up before they begin to constrict. The right ventricle is a low-pressure pump that feeds pulmonary circulation, whereas the left ventricle is a high-pressure pump that supplies systemic circulation. This is because the lungs present far less resistance to flow than the organs that are part of the system.

The previous talks have shown that the pumping activity of the heart may be thought of as a two-part process, with the first stage being a contraction known as systole and the second phase being a filling or relaxation known as diastole. This period of the heartbeat is referred to as systole, and it is during this time that the muscle of the heart contracts and blood is pushed out of the body. The atrial systole, the ventricular systole, and the full cardiac diastole are the three stages that occur during a single beat of the heart. During the 0.1 seconds that make up atrial systole, the left and right atriums of the heart undergo a muscular contraction that is referred to as atrial systole. When the atria contract, the blood pressure in each atrium increases. This raises the blood pressure in each atrial, which in turn drives the mitral and tricuspid valves to open, allowing blood to flow into the ventricles. During the contraction of the atrium (atrial systole), the AV valves do not close. The contraction of the muscles that make up the left and right ventricles takes place during the 0.3 seconds that follow the atrial systole of the heart. This is known as ventricular systole. The systolic contraction of the ventricle produces enough pressure to close the AV valves, while at the same time forcing the aortic and pulmonic valves to open. (The aortic and pulmonic valves are always closed, except for a brief time during ventricular systole in which the pressure in the ventricle rises higher than the pressure in the aorta for the left ventricle and higher than the pressure in the pulmonary artery for the right ventricle.) The normal pressures in the aorta and the pulmonary artery both increase to 120 mm Hg and 24 mm Hg, respectively, during the systolic phase of the heartbeat (1 mm Hg equals 133 Pa). The passage of blood through the aortic valve in adults with normal hearts begins at the beginning of ventricular systole and quickly increases to a peak value of around 1.35 meters per second during the first one-third of systole. After then, there is a gradual slowing down of the blood flow. Pulmonic valve peak velocities are lower, and they are around 0.75 meters per second in typical individuals. During systole, the contraction of the ventricles causes approximately two-thirds of the blood in these chambers to be expelled. When the left ventricle is no longer filling with blood, its pressure drops below that of the aorta, which causes the aortic valve to collapse. In a similar manner, the pulmonic valve will close once the pressure in the right ventricle drops to a level that is lower than the pressure in the pulmonary artery. In this way, the aorta, and pulmonic valves both shut near the conclusion of the ventricular systole, with the aortic valve closing a little bit earlier than the pulmonic valve. During the period of the heartbeat known as diastole, the chambers of the heart are allowed to refill with blood. After each contraction, the heart goes through a period of relaxation known as diastole, during which it prepares to be refilled with blood that is flowing throughout the body. Refilling of the ventricles, also known as ventricular diastole, takes place while the atrium contracts. After the ventricle has been filled with blood and ventricular systole has begun, the atria will begin to refill with blood, which is referred to as atrial diastole. This will cause the AV valves to collapse. Both the atria and the ventricles begin refilling about 0.4 seconds after the ventricular systole, at which point both chambers are in the diastolic phase of the cardiac cycle. During this time, both AV valves will be closed, but the aortic and pulmonic valves will be open. The diastolic pressure in the aorta is typically 80 mm Hg, whereas the diastolic pressure in the pulmonary artery is just 8 mm Hg. Therefore, the normal ratios of systolic pressure to diastolic pressure for the aorta are 120/80 mm Hg, whereas the ratios for the pulmonary artery are 24/8 mm Hg. The pressure pulse is calculated by subtracting the systolic pressure from the diastolic pressure. This value, in the case of the aorta (left ventricle), is 40 mm Hg. The pulse pressure may be thought of as a measurement of the pressure wave's overall strength. It rises when there is a greater volume of strokes, such as when there is more activity or exercise. The pressure waves that are generated because of the ventricular contraction have an amplitude that decreases the more away, they are from the heart, and these waves are not detectable in the capillaries. The pressure that is present throughout the systemic circulation is seen in figure 5.

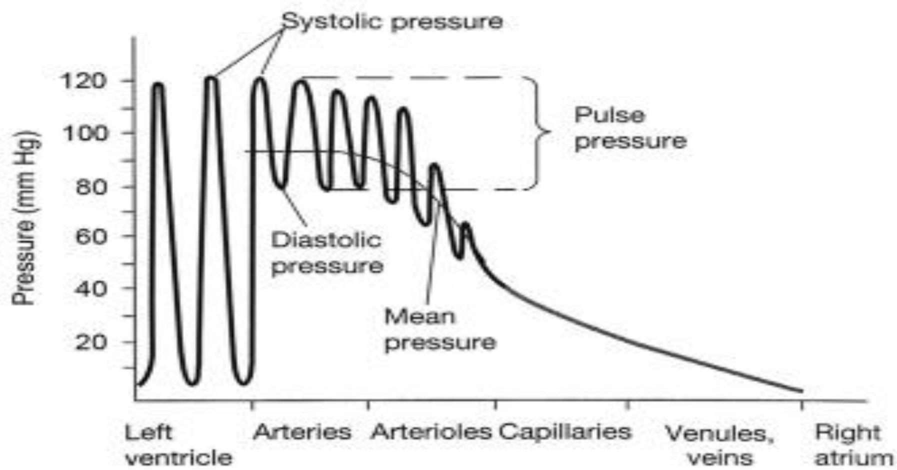

Figure 5 Changes in pressure across the whole of the systemic circulation. The left ventricle is home to some of the heart's most dramatic shifts in pressure. The elasticity of the arteries, the viscosity of the blood, and the fact that the system is branching all work together to progressively dampen these effects. This article has been reproduced with the author's kind permission from silver thorn, D. U. (2001). Prentice Hall, Upper Saddle River, New Jersey, published the second edition of Human Physiology: An Integrated Approach.

Conclusion

The purpose of this article is to provide an overview of the field of biofluid dynamics and to discuss the significance of this field about the problem-solving processes of the cardiovascular and respiratory systems. This chapter not only offered an overview of the significance of the subject matter, but it also gave the reader information on the anatomy and physiology of the cardiovascular and respiratory systems. In addition to this, a comprehensive analysis of several cardiovascular and respiratory disorders is presented. For anyone interested in learning more about the subject at hand, a list of resources may be found lower down on this page.

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