20. Cardiovascular System: Vessels and Circulation

In this chapter we examine blood vessels and properties of flow through these vessels. Each blood vessel falls into one of three major categories: (1) **arteries** carry blood away from the heart, (2) **veins** carry blood toward the heart, and (3) **capillaries** allow diffusion between the blood and surrounding tissues. An adult human has more than ten billion capillaries.

I. Structure and Function of Blood Vessels

General structure of vessels
Arteries and veins are made of three layers of tissue, which surround a cavity called the lumen (Fig. 20.1). These tissue layers provide strength and flexibility, but they are too thick to allow significant exchange of gases between the blood and surrounding tissues.

A. The **tunica intima** is the innermost layer. It consists of endothelial tissue that lines the blood vessel and an underlying layer of areolar connective tissue with lots of elastic fibers. The endothelial tissue provides a slick surface to minimize friction with the flowing blood.

B. The **tunica media** is the middle layer. It is made of concentric rings of smooth muscle in a framework of loose connective tissue. Collagen fibers bind this layer with the inner and outer layers. This is the thickest layer in arteries.

C. The **tunica externa** is the outermost layer. It is a layer of fibrous connective tissue, which adds strength and support to the vessel. This is generally the thickest layer in veins. Connective tissue fibers of this layer blend into surrounding tissue to anchor the vessels.

Arteries
Elastic fibers and thick muscular walls give the arteries both **elasticity** and **contractility**.
Elasticity allows these vessels to respond to and dampen changes in blood pressure generated by pumping of the heart. Contractility allows **vasoconstriction** and **vasodilation** in response to signals from the nervous system. Refer back to Chapter 15 and note the general effects of the parasympathetic and sympathetic nervous systems on blood vessels.

In traveling from the heart to the capillaries, blood flows through three types of arteries with somewhat different properties (Table 19.1):

A. **Elastic arteries** are large vessels designed to transport large volumes of blood to major regions of the body. The tunica media of these vessels contains large proportions of elastic fibers, and a smaller proportion of smooth muscle. In response to ventricular systole, these vessels expand to accommodate blood from the heart and dampen the increase in pressure. As blood moves through the vessels and the ventricles enter diastole, these vessels contract and dampen the drop in pressure.

B. **Muscular arteries** distribute blood throughout the muscles and organs. These vessels contain a higher proportion of muscle than the elastic arteries.

C. **Arterioles** are the smallest of the arteries; some contain just one layer of smooth muscle cells. Arterioles are largely responsible for regulating the amount of blood that flows to a particular set of capillaries. They do this by either contracting or relaxing to either restrict or increase the amount of blood flowing through them. Contraction or relaxation changes the **resistance** to flow through the vessel.
Capillaries
Capillaries have very thin walls (one cell layer thick) in order to allow efficient gas exchange between the blood and surrounding tissues. Neither a tunica media nor a tunica externa is present.

Within the body are three slightly different types of capillaries (Table 20.2):

A. **Continuous capillaries** are the most common capillaries. They are particularly abundant in the skin and muscles. As their name suggests, the endothelial cells of these capillaries form a continuous lining. The endothelial cells are held together with tight junctions, but there are some gaps (**intercellular clefts**) that allow small amounts of fluid to pass between cells. An exception to this is found in the capillaries of the brain, in which tight junctions form a complete barrier to the movement of fluids between cells. Recall the blood-brain barrier discussed in BIO 205.

B. **Fenestrated capillaries** contain endothelial cells that have pores. These pores make the fenestrated capillaries considerably more permeable to fluids than the continuous capillaries. The fenestrated capillaries are typically found where active absorption of materials into the blood is required, such as in the small intestine and endocrine organs. They are also found in the kidneys where filtration occurs.

C. **Sinusoids** have large lumens, very few tight junctions between the endothelial cells, and fenestrations. Thus, they tend to be especially leaky, allowing even large molecules and cells to pass between the blood and surrounding tissues. These capillaries are often used by formed elements to move in and out of the blood vessels. Sinusoidal capillaries are found primarily in the liver, bone marrow, spleen, and other lymphoid organs.

Capillaries function as parts of interconnected networks referred to as **capillary beds** (Fig. 20.5). **Precapillary sphincters** regulate the flow of blood through various capillaries. **Thoroughfare channels** are direct connections between arterioles and venules that allow blood to bypass most of the capillaries in a capillary bed. Blood flow must be carefully regulated to the parts of the body that need it. A human does not have enough blood in his or her body to fill up all of the capillaries at once.

Veins
Veins collect blood from the tissues and return it to the heart. Their walls are thinner than those of arteries because of lower blood pressures. **Venules** are the smallest veins, and the tunica media is generally absent in all but the largest venules.

The blood pressure in veins may be sufficiently low that it cannot overcome the force of gravity. Therefore, most veins contain valves to help prevent the back-flow of blood (Fig. 20.3). How does contraction of certain skeletal muscles (e.g., in the legs) work with valves to enhance **venous return**?
II. Capillary Exchange

Diffusion and vesicular transport
One of the major functions of capillaries is diffusive exchange of respiratory gases, oxygen and carbon dioxide. We will study this in detail when we examine the respiratory system.

Bulk flow
Bulk flow is the movement of a fluid and any dissolved substances in the fluid down a pressure gradient. When considering bulk flow of blood and other fluids in the body, two types of pressure should be considered:

1. **Hydrostatic pressure** is the physical pressure exerted by a fluid on its surroundings. As we examine exchange between the blood in a capillary and the interstitial fluid surrounding the capillary, we will consider blood hydrostatic pressure (HP_b) and interstitial fluid hydrostatic pressure (HP_if). The HP_if is generally so low that we can consider it to be zero.

2. **Colloid osmotic pressure** is created by the presence of large molecules (mainly proteins) that cannot diffuse across the capillary wall. These molecules attract water and create osmotic pressure. We will consider blood colloid osmotic pressure (COP_b) and interstitial fluid colloid osmotic pressure (COP_if).

Net filtration pressure
Hydrostatic pressure is higher in arteries than in veins. Thus, hydrostatic pressure is greater at the arterial end of a capillary than at the venous end. Along the entire length of the capillary, HP_b is generally greater than HP_if, which is approximately zero. This means that hydrostatic pressure tends to drive fluid out of the capillaries, especially at the arterial end.

The concentration of molecules that create colloid osmotic pressure tends to be greater in the blood than in the interstitial spaces. Thus COP_b is generally greater than COP_if. This means that colloid osmotic pressure tends to draw fluid into the capillaries.

At the arterial end of a capillary bed, the net HP typically exceeds the net COP, and there is net loss of fluid from the capillaries at the arterial end. At the venous end of a capillary bed, the net COP typically exceeds the net HP, and there is a net gain of fluid into the capillaries at the venous end.

Overall, there tends to be a net loss of fluid from the capillaries. We will see later that this fluid is absorbed into the lymphatic system.
III. Blood Pressure, Resistance, and Total Blood Flow

Blood pressure
Define the term “blood pressure.”

Figure 20.10 shows the approximate blood pressure as blood flows through the circulatory system. Pressure is highest at the aorta and lowest at the venae cavae. Thus, blood expelled by the left ventricle flows down its pressure gradient until it reaches the right atrium.

Pressure varies significantly with the beating of the heart until blood reaches the arterioles. Pressure is highest in the arteries after the ventricles contract and expel blood into the arteries. This peak in pressure is what we call the systolic blood pressure (approximately 120 mm Hg in healthy adults). Elastic arteries expand to absorb some of the pressure. As the ventricles enter diastole, the pressure drops to what we call the diastolic blood pressure (approximately 70 to 80 mm Hg in healthy adults). Elastic arteries contract to keep the pressure from dropping too low.

The difference between systolic pressure and diastolic pressure is called the pulse pressure, and this difference is what is felt when someone measures a pulse. Be aware of the difference between “pulse pressure” and “pulse”! The former is a measurement of pressure; the latter is a measure of heart rate. Look at Fig. 20.10 and explain why the pulse cannot be felt in a vein.

Resistance
Define the term “resistance” as it applies to the flow of a fluid.

Resistance to the flow of blood through a blood vessel is determined by three factors: (1) the viscosity of the blood, (2) the length of the blood vessel, and (3) the diameter of the blood vessel. Understand how a change in each of these factors increases or decreases the resistance. In the space below, give at least one example of how these factors may change naturally in the human body.

Viscosity–
Vessel length–
Vessel diameter–

When considering vessel diameter, be aware that resistance within a vessel is inversely proportional to the fourth power of the radius (\( R \propto 1/r^4 \)). What effect does decreasing the radius by a factor of two have on resistance?

How does this relate to atherosclerosis?
The relationship of blood flow to blood pressure gradients and resistance

A fluid (like blood) will flow through a tube (like a blood vessel) as a result of differences in pressure at different points in the tube. The fluid always flows in the direction from high pressure to low pressure (i.e., down a pressure gradient). The relationship between flow (F) through a tube and the pressure gradient (ΔP) is given by the following equation:

\[ F = \frac{\Delta P}{R} \]

where R is the resistance to flow.

When studying the circulatory system, we can say that flow through the entire system is equivalent to cardiac output (CO); the difference in pressure is approximately equal to the mean blood pressure (BP); and resistance comes primarily from friction in the small vessels of the periphery (total peripheral resistance, TPR). Thus, the equation given above becomes the following equation:

\[ CO = \frac{BP}{TPR} \]

IV. Regulation of Blood Pressure and Blood Flow

Because flow depends upon blood pressure, it is important to keep blood pressure high enough to maintain sufficient transport of gases and nutrients. However, a blood pressure that is too high may result in hemorrhaging or aneurysms. The body has both short- and long-term mechanisms to regulate blood pressure. By rearranging the equation given above, you can see that blood pressure can be altered via changes in cardiac output and total peripheral resistance:

\[ BP = CO \times TPR \]

Neural regulation of blood pressure

Short-term regulation of blood pressure is mediated primarily by the nervous system. Neural control generally is accomplished via reflex arcs that involve baroreceptors or chemoreceptors, the vasomotor center of the medulla, and sympathetic efferent pathways. The effectors of these reflex arcs are vascular smooth muscles, primarily of the arterioles.

The vasomotor center is constantly sending some stimulation along these sympathetic pathways, leading to some constant level of constriction, called vasomotor tone. Baroreceptors sense increased pressure in the blood vessels as the vessels are stretched. They are located in the carotid arteries, the aortic arch, and in most other larger arteries of the neck and thorax. Stimulation of the baroreceptors sends afferent signals along the glosopharyngeal nerves that inhibit the vasomotor center. What effect does this have on the blood vessels and blood pressure?
Afferent impulses from the baroreceptors also inhibit the cardioacceleratory center and stimulate parasympathetic activity. The baroreceptor system functions to protect against harmful short-term changes in blood pressure, but it is rather ineffective in protecting against long-term changes. Which cranial nerve will carry parasympathetic signals to the heart?

**Chemoreceptors** in the aortic arch and large arteries of the neck monitor the concentration of CO$_2$ in the blood. As the level of CO$_2$ rises, the chemoreceptors stimulate the cardioacceleratory and vasomotor centers. You should be able to figure out the effect on blood pressure and how it relates to the change in CO$_2$. A similar effect is caused by decreasing levels of oxygen in the blood.

Baroreceptors and chemoreceptors work via reflex pathways. Higher brain centers can also affect blood pressure. For example, the hypothalamus can cause a strong rise in blood pressure during the fight-or-flight response. The cerebrum can also affect blood pressure. Start thinking about taking one of my exams, and your blood pressure may rise!

**Hormonal regulation of blood pressure**
Long-term regulation is accomplished primarily by the kidneys, and it involves changes in blood volume. The kidneys act to regulate blood volume both directly and indirectly.

The **direct renal mechanism** of blood pressure regulation is fairly simple and intuitive: When blood pressure is high, the amount of filtration of fluid into the kidneys naturally increases, and more urine is formed. Blood volume decreases and blood pressure decreases. When blood pressure is low, less fluid is filtered into the kidneys and fluids are conserved. Combined with intake of fluids, this results in an increase in blood volume and blood pressure. (Note that this is not the result of hormones.)

Here come the hormones . . .

The **indirect renal mechanism** of blood pressure regulation involves various chemicals that act to elevate blood pressure in response to a decline in blood pressure. A drop in blood pressure causes the kidneys to release the enzyme, renin, into the blood. Renin leads to the production of the chemical, angiotensin II, which is a strong vasoconstrictor. What effect does systemic vasoconstriction have on total peripheral resistance and blood pressure?

Angiotensin II also stimulates the release of the hormone, aldosterone, from the adrenal cortex. Aldosterone promotes the retention of sodium by the kidneys, and the release of ADH by the pituitary gland. What effect does sodium retention have on water retention?

What is the effect of ADH?

What is the effect of aldosterone on blood pressure?
Autoregulation
We have just discussed how the nervous and endocrine systems can generally affect cardiac output and systemic blood pressure. It is also important that the body be able to specifically regulate blood flow to individual organs based on their changing demands for blood. To some extent, this is accomplished by autoregulation, in which local conditions affect flow to a particular organ.

Declining nutrient levels in an organ stimulate vasodilation of nearby arterioles and relaxation of precapillary sphincters. This, obviously, allows more blood and more nutrients into the organ. Is this an example of positive or negative feedback?

Arterioles are generally able to respond automatically to changes in blood pressure. Stretch of vascular smooth muscle tends to cause vasoconstriction. How can this protect an organ?

Reductions in stretch cause increased tone and vasodilation. How can this help maintain homeostasis?

V. Velocity of Blood Flow

Blood flow through tissues is called perfusion. Each organ in the body typically has a small number of arteries bringing blood to it. Once these arteries enter the organ they rapidly branch into arterioles and capillaries. Proper delivery of oxygen and other nutrients to the organ depends on properly matching the demand for blood by the organ to the supply of blood to the organ.

Figure 20.16 shows that as blood travels through the body, the velocity of blood flow is inversely proportional to the cross-sectional area of blood vessels being filled. Although capillaries are smaller than arteries and veins, the immense number of capillaries means that as blood flows from arteries to arterioles and then to capillaries, the total cross-sectional area increases (and velocity decreases). This is beneficial in that slow movement of blood through capillaries allows adequate time for exchange to occur. As capillaries merge to form venules and veins, the cross-sectional area decreases and flow increases as blood returns to the heart.