CASE 8

A 65-year-old man with a history of hypertension and coronary artery disease presents to the emergency center with complaints of left-sided facial numbness and weakness. His blood pressure is normal, as is his heart rate and other vital signs. On examination, the patient has clear lungs and a normal cardiac examination. Auscultation of the carotid arteries reveals a “whooshing sound” (bruits) bilaterally. There is evidence of slurred speech and left-sided facial droop. The patient is diagnosed with a stroke. A computed tomography (CT) scan of the brain is performed. The patient is taken immediately to the intensive care unit for stabilization.

◆ What is the mechanism of the audible carotid bruit?

◆ How does one calculate the velocity of blood flow?

◆ Why is velocity of blood flow higher in arterioles than in capillaries? Why is this physiologically necessary?

◆ What is Reynolds number, and how would it apply to this case?
ANSWERS TO CASE 8: CARDIOVASCULAR HEMODYNAMICS

Summary: A 65-year-old man has new-onset facial droop and weakness along with slurred speech, consistent with a left-sided cerebral stroke. He has findings suggestive of bilateral carotid insufficiency.

◆ **Carotid bruit:** Clinical evidence of turbulence in blood flow through a narrowed carotid artery.

◆ **Velocity of blood flow:** Velocity = Q (flow) ÷ A (cross-sectional area).

◆ **Difference in velocity of blood flow in arteries and capillaries:** Capillaries have a larger combined cross-sectional area, which decreases the velocity of flow. This allows capillaries to exchange substances across the capillary wall.

◆ **Reynolds number:** Predicts whether blood flow will be laminar or turbulent (the more elevated Reynolds number, the more turbulent the flow). This number is increased with increased blood velocity, which in this case is because of narrowed vessels.

**CLINICAL CORRELATION**

This patient has a classic presentation of a stroke probably resulting from atherosclerotic disease affecting the carotid arteries. The first step, as in addressing any patient, is to examine the ABCs (airway, breathing, circulation). Reversing any ischemia, correction of severe hypertension but not overcorrection, and oxygenation are the important principles. Strokes may be caused by ischemia (decreased oxygen delivery) resulting from arterial thrombosis (clot) or embolization (clot breaks off and lodges distally) or by hemorrhage (blood collection in the brain putting pressure on the normal brain cells). The CT scan helps in assessing for hemorrhagic stroke. Some patients are candidates for thrombolytic therapy when hemorrhagic stroke is ruled out. After stabilization, carotid ultrasound studies probably will be performed, perhaps followed, if carotid insufficiency is confirmed, by carotid endarterectomy.

Calculating and understanding cardiovascular hemodynamics are of utmost importance in clinically assessing patients. Pressure in the large conducting arteries such as the carotid normally is high compared with other vessels. These vessels normally offer little resistance to blood flow. When there is narrowing of a vessel, as in this case of peripheral vascular disease, resistance increases because of the narrowing and the change in flow from laminar to turbulent. Because of the increased resistance, blood flow to the tissues that the vessel supplies decreases. Blood flow to peripheral tissues also can be compromised by a decrease in pressure in the large conducting arteries. Rapid assessment of mean arterial pressure (MAP) can determine whether a patient
is in shock and if vital organs such as the brain are perfused. As patients age, various hemodynamic changes occur, such as decreased arterial capacitance, which in turn can increase systolic blood pressure (systolic hypertension) and increase pulse pressure. Veins offer little resistance to blood flow but have the highest proportion of blood in the system. When a patient becomes hypovolemic, the adrenergic receptors are stimulated, causing constriction of the veins and thus limiting the decrease in venous return to the heart and the decrease in cardiac output.

**APPROACH TO HEMODYNAMIC PHYSIOLOGY**

**Objectives**

1. Know the components of the vascular system.
2. Know and be able to use the relationship among pressure, flow, and resistance.
3. Compare the different hemodynamic measurements between arteries and veins.
4. Be able to define systolic, diastolic, and pulse pressure.

**Definitions**

- **Cardiac output**: The volume of blood the heart pumps per minute.
- **Mean arterial pressure**: The average arterial pressure during a cardiac cycle.

**DISCUSSION**

Blood ejected by the heart (cardiac output) circulates through two vascular systems that are arranged in series: the pulmonary and the systemic systems. In this case, only the systemic system will be considered. This system is composed of a number of large conducting arteries such as the aorta and the carotids that subdivide multiple times until they give rise to the arterioles. With each subdivision, the radius of each individual vessel decreases, but the number of vessels in each subdivision increases dramatically, going from one aorta to tens of millions of arterioles. Each arteriole then feeds many capillaries. Physiologically, the focal point of this system is the billions of capillaries that function to bring each cell of the body to within a few microns of flowing blood so that exchange of substrates between the cells and the blood can take place. On the other end of the capillaries are the venules, which are about equal in number to the arterioles but are larger in diameter. The venules coalesce multiple times until they give rise to the vena cava.

The number and size of the vessels in each division markedly affect both the resistance to flow and the velocity of flow of blood in each division. The resistance to blood flow in any single vessel is inversely proportional to its radius taken to the power of 4. Thus, a halving of the radius increases
**resistance 16 times.** Conversely, the resistance offered by any division of vessels is inversely proportional to the number of vessels in that division because these vessels are arranged parallel to one another. Thus, the greater the number of vessels, the lower is the resistance. In the systemic circulation, this balance between vessel radius and vessel number is such that the small arteries, the capillaries, and, most important, the arterioles offer the greatest resistance to blood flow.

The velocity of blood flow through the vessels of any division depends on the volume of blood flow per unit of time (milliliters per second) and the combined cross-sectional area of all the vessels that constitute that division. Thus

\[
\text{Velocity} = \frac{Q \text{ (flow)}}{A \text{ (cross-sectional area)}}
\]

Because all the divisions of the systemic circulation are in series with one another, the volume of blood flow per unit time (Q) will be the same through all divisions. However, velocity of flow will differ because the combined cross-sectional area of the vessels in each division will vary. The situation in the systemic circulation is such that the peak flow velocity is highest in the large conducting arteries and lowest in the capillaries. The low flow velocity in the capillaries allows time for exchange to take place between the cells of the body and the blood. The high velocity of flow in the large arteries is normally of little consequence. However, velocity can be increased in vessels that are partially occluded (thus decreasing cross-sectional area), as in this case, to the point where flow changes from laminar to turbulent. The conditions that produce clinically audible turbulent flow are expressed in the **Reynolds equation**:

\[
R_e = \frac{D \cdot v \cdot \rho}{\eta}
\]

which solves for the **Reynolds number** (Re) when D is the diameter of the vessel, \(v\) is the velocity of flow, \(\rho\) is fluid density, and \(\eta\) is fluid viscosity. The larger the Reynolds number, the more likely there is to be turbulent flow; and so the greater the velocity, the more likely there is to be turbulence. Turbulent flow is significant because it offers more resistance and produces clinically audible sounds termed bruits. The flow of blood through a vascular bed such as the central nervous system (CNS) depends not only on the resistance to flow but also on the pressure that is driving the flow. In a normal person who is lying down (to mitigate the influence of gravity), MAP (~100 mm Hg) is much higher than the pressure in the capillaries (~20 mm Hg) and in the veins (~5 mm Hg). Although it is the MAP that is useful in considering the force that drives blood across the capillaries and into the veins, pressure in the arteries fluctuates during the cardiac cycle. Pressure rises during systole, when blood is being ejected from the heart. The peak arterial pressure during this phase of
the cycle is called systolic pressure. Pressure then falls to reach a minimum diastolic pressure as blood flows across the vascular beds during the phase of the cardiac cycle when no blood is being ejected from the heart. The arterial pressures that are estimated during the taking of blood pressure by auscultation are the systolic and diastolic pressures. The MAP can be estimated from these pressures by using the equation

\[ \text{MAP} = \text{DP} + \frac{1}{3} (\text{SP} - \text{DP}) \]

where MAP is mean arterial pressure, DP is diastolic pressure, and SP is systolic pressure.

The difference between systolic pressure and diastolic pressure is also known as the pulse pressure. Pulse pressure provides some information about stroke volume and vascular capacitance. Stroke volume can vary from moment to moment and depends on cardiac output and heart rate. Vascular capacitance, in contrast, changes over a longer time, and that change appears to be a consequence of aging. With the decrease in capacitance with aging, systolic pressure tends to increase and diastolic pressure tends to decrease.

There is a relationship among flow, pressure, and resistance that can be expressed mathematically as

\[ Q = \Delta P \div R \]

where Q is flow, \( \Delta P \) is MAP minus venous pressure (VP), and R is resistance to flow across the bed.

Unless regulatory mechanisms are impaired, mean pressure in the large conducting arteries normally is held within fairly narrow limits. Thus, blood flow to any particular vascular bed normally is regulated by changes in resistance to flow provided mainly by the arterioles. However, in pathologic states such as the one described in this case, large conducting arteries can be obstructed to the point where they offer significant resistance as a result of decreased radius and turbulent flow. This can lead to decreased blood flow to the organs they perfuse, in this case the brain.

Because there are more veins than arteries and the diameters of the veins are greater, veins contain the greatest proportion of blood. Although veins offer little resistance to blood flow, they do contain smooth muscle that by contracting and relaxing can change their diameters and/or VP. This in turn can influence cardiac output by influencing preload.
**COMPREHENSION QUESTIONS**

[8.1] If one considers a single vessel within each division of the systemic circulation in a person who is lying down, one can arrange the vessels according to the end pressure, greatest to least, within each vessel. (If the vessel exhibits a pulse pressure, one can consider the mean end pressure.) Which of the following sequences of mean end pressure is correct in this case?

A. Large artery → large vein → arteriole → venule → capillary
B. Capillary → arteriole → venule → large artery → large vein
C. Large artery → arteriole → capillary → venule → large vein
D. Large vein → venule → capillary → arteriole → large artery
E. Capillary → venule → arteriole → large vein → large artery

[8.2] A patient is suspected of having reduced flow of blood to the brain. Her blood pressure taken from the brachial artery is normal. Bruits are detected in the right carotid artery but not in the left carotid artery. A comparison of hemodynamic events in the two carotid arteries would reveal which of the following?

A. A mean pressure in the right carotid artery proximal to the site of the bruit that is lower than the mean pressure in the left carotid artery
B. Equal blood flow in both carotid arteries
C. Lower resistance to flow in the right carotid artery
D. Increased velocity of flow in the right carotid artery
E. Turbulent blood flow in both carotid arteries

[8.3] A patient suspected of suffering a myocardial infarction is being monitored in the Coronary Care Unit. The following data are obtained on this individual:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arterial systolic blood pressure</td>
<td>121 mm Hg</td>
</tr>
<tr>
<td>Arterial diastolic blood pressure</td>
<td>82 mm Hg</td>
</tr>
<tr>
<td>Venous blood pressure</td>
<td>2 mm Hg</td>
</tr>
<tr>
<td>Cardiac output</td>
<td>4185 mL/min</td>
</tr>
<tr>
<td>Radius of the aorta</td>
<td>1.2 cm</td>
</tr>
</tbody>
</table>

Which of the following can be concluded from the monitored data?

A. The patient’s MAP is 95 mm Hg
B. The pulse pressure is 80 mm Hg
C. Total resistance to flow is approximately 45 resistance units
D. The patient’s blood flow in the carotid artery must be turbulent
E. The velocity of blood flow through the aorta is 3487 cm/s
**Answers**

[8.1] **C.** In a supine person, the effect of gravity is essentially nil and intravascular pressures are caused by contractions of the heart. Because fluid flows from regions of higher pressure to regions of lower pressure, pressures must be higher in the large arteries than in the arterioles, than in the capillaries, than in the venules, than in the large veins.

[8.2] **D.** The velocity of blood flow must be increased in the right carotid artery to produce the turbulence that is detected as bruits. Flow in the left carotid artery must be laminar because of the absence of bruits. The turbulent flow in the right carotid artery increases the resistance to flow in that artery, thus reducing blood flow, making it less than it is through the left carotid artery. Pressure in the right carotid artery distal to the site of the bruits will be decreased, but pressure proximal to the site of the bruits will be the same as the pressure in the left carotid artery.

[8.3] **A.** The MAP can be estimated by using the equation $\text{MAP} = \text{DP} + 1/3 (\text{SP} − \text{DP})$. The pulse pressure ($\text{SP} − \text{DP}$) is 39 mm Hg. ($93 = 82 + 13$). The resistance to flow can be calculated by using the equation $Q = \Delta P ÷ R$ rearranged to solve for $R$. Thus, $R = (93 − 2) [\text{MAP} − \text{VP}] ÷ 4185$, or approximately 0.022 resistance unit. From the data given, there is no reason to suspect turbulent flow anywhere in the vasculature. In the aorta, the velocity of flow can be calculated by using the equation $v = Q ÷ A$. Thus, $v = 4185 \text{ cm}^3/60 \text{ s} ÷ 4.52 \text{ cm}^2$, or approximately 15.4 cm/s.
PHYSIOLOGY PEARLS

❖ Transfer of material in and out of the blood, mainly by diffusion, takes place across capillary walls.
❖ In a healthy person, variations in blood flow through an organ come about through dilation and constriction of an organ’s arterioles, thus changing resistance, rather than through changes in systemic arterial pressure.
❖ Arterial pressure and blood flow can be measured by using one of several techniques. Resistance, however, is calculated by using the equation

\[ Q = \Delta P/R \]

where Q is flow, \( \Delta P \) is MAP minus VP, and R is resistance to flow across the bed.
❖ The velocity of blood flow is highest in the large arteries, slowest in the capillaries, and intermediate in the veins because of variations in the total cross-sectional areas of these vascular beds.
❖ Blood flow in all regions of the vasculature normally is nonturbulent (laminar); however, it can become turbulent in diseased arteries as a result of the high velocity of flow.
❖ The pressure that causes flow is highest in the large arteries and lowest in the large veins. Pressure falls dramatically as blood flows through the small arteries and arterioles because of the high resistance to flow provided by these vessels.
❖ The difference between systolic and diastolic pressures is the pulse pressure. The amplitude of the pulse pressure is influenced mainly by stroke volume and the capacitance (stiffness) of the large arteries.

REFERENCES