Case 10

Essential Cardiovascular Calculations

This case is designed to take you through important basic calculations involving the cardiovascular system. Use the information provided in Table 2-1 to answer the questions. Part of the challenge in answering these questions will be in deciding which information you need in order to perform each calculation. Good luck!

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Systolic pressure (aorta)</td>
<td>124 mm Hg</td>
</tr>
<tr>
<td>Diastolic pressure (aorta)</td>
<td>82 mm Hg</td>
</tr>
<tr>
<td>R-R interval</td>
<td>800 msec</td>
</tr>
<tr>
<td>Left ventricular end-diastolic volume</td>
<td>140 mL</td>
</tr>
<tr>
<td>Left ventricular end-systolic volume</td>
<td>70 mL</td>
</tr>
<tr>
<td>Mean pulmonary artery pressure</td>
<td>15 mm Hg</td>
</tr>
<tr>
<td>Right atrial pressure</td>
<td>2 mm Hg</td>
</tr>
<tr>
<td>Left atrial pressure</td>
<td>5 mm Hg</td>
</tr>
<tr>
<td>O$_2$ consumption (whole body)</td>
<td>250 mL/min</td>
</tr>
<tr>
<td>O$_2$ content of systemic arterial blood</td>
<td>0.20 mL O$_2$/mL blood</td>
</tr>
<tr>
<td>O$_2$ content of pulmonary arterial blood</td>
<td>0.152 mL O$_2$/mL blood</td>
</tr>
</tbody>
</table>

*R-R interval,* time between R waves on the electrocardiogram.

**QUESTIONS**

1. Mean arterial pressure is not the simple average of systolic and diastolic pressures. Why not? How is mean arterial pressure estimated? From the information given in Table 2-1, calculate the mean arterial pressure in this case.

2. Calculate the stroke volume, cardiac output, and ejection fraction of the left ventricle.

3. Calculate cardiac output using the Fick principle.

4. What is the definition of total peripheral resistance (TPR)? What equation describes the relationship between TPR, arterial pressure, and cardiac output? What is the value of TPR in this case?

5. How is pulmonary vascular resistance calculated? What is the value of pulmonary vascular resistance in this case? Compare the calculated values for pulmonary vascular resistance and TPR, and explain any difference in the two values.

6. What is total blood flow (in mL/min) through all of the pulmonary capillaries?

7. What is total blood flow (in mL/min) through all of the systemic arteries?

8. What information, in addition to that provided in Table 2-1, is needed to calculate the resistance of the renal vasculature?
9. If the diameter of the aorta is 20 mm, what is the velocity of aortic blood flow? Would you expect the velocity of blood flow in systemic capillaries to be higher, lower, or the same as the velocity of blood flow in the aorta?
ANSWERS AND EXPLANATIONS

1. Systemic arterial pressure is not a single value because arterial pressure varies over the course of each cardiac cycle. Its highest value is systolic pressure, which is measured just after blood is ejected from the left ventricle into the aorta (i.e., systole). Its lowest value is diastolic pressure, which is measured as blood flows from the arteries into the veins and back to the heart (i.e., diastole).

Mean arterial pressure cannot be calculated as the simple average of systolic and diastolic pressures because averaging does not take into account the fact that a greater fraction of each cardiac cycle is spent in diastole (approximately two-thirds) than in systole (approximately one-third). Thus, mean arterial pressure is closer to diastolic pressure than to systolic pressure. Figure 2-1 shows an arterial pressure tracing over a single cardiac cycle. The difference between systolic pressure and diastolic pressure is called pulse pressure.

![Arterial Pressure Tracing](image)

Although this approach is impractical, mean arterial pressure can be determined by measuring the area under the arterial pressure curve. Alternatively, mean arterial pressure can be estimated as follows:

\[
\text{Mean arterial pressure} = \text{diastolic pressure} + \frac{1}{3} \text{pulse pressure}
\]

\[
= \text{diastolic pressure} + \frac{1}{3} (\text{systolic pressure} - \text{diastolic pressure})
\]

where

- Diastolic pressure = lowest value for arterial pressure in a cardiac cycle
- Systolic pressure = highest value for arterial pressure in a cardiac cycle
- Pulse pressure = systolic pressure - diastolic pressure

Therefore, in this case:

\[
\text{Mean arterial pressure} = 82 \text{ mm Hg} + \frac{1}{3} (124 \text{ mm Hg} - 82 \text{ mm Hg})
\]

\[
= 82 \text{ mm Hg} + \frac{1}{3} (42 \text{ mm Hg})
\]

\[
= 82 \text{ mm Hg} + 14 \text{ mm Hg}
\]

\[
= 96 \text{ mm Hg}
\]
These calculations concern the cardiac output of the left ventricle. The basic relationships are as follows:

**Stroke volume** = end-diastolic volume − end-systolic volume

*where*

Stroke volume = volume ejected by the ventricle during systole (mL)
End-diastolic volume = volume in the ventricle before ejection (mL)
End-systolic volume = volume in the ventricle after ejection (mL)

**Cardiac output** = stroke volume × heart rate

*where*

Cardiac output = volume ejected by the ventricle per minute (mL/min)
Stroke volume = volume ejected by the ventricle (mL)
Heart rate = beats/min

**Ejection fraction** = stroke volume/end-diastolic volume

*where*

Ejection fraction = fraction of the end-diastolic volume ejected in one stroke

Now we can use these basic equations to calculate stroke volume, cardiac output, and ejection fraction in this case.

Stroke volume = left ventricular end-diastolic volume - left ventricular end-systolic volume
= 140 mL − 70 mL
= 70 mL

Cardiac output is the volume ejected by the left ventricle per minute. It is calculated as the product of stroke volume (determined to be 70 mL) and heart rate. Heart rate is not given in Table 2-1, but it can be calculated from the R-R interval. "R" is the R wave on the electrocardiogram and represents electrical activation of the ventricles. The R-R interval is the time elapsed from one R wave to the next (Figure 2-2). It is also called cycle length (i.e., time elapsed in one cardiac cycle).

![Electrocardiogram measured from lead II. The interval between R waves is the cycle length.](image-url)
Cycle length can be used to calculate heart rate as follows:

\[
\text{Heart rate} = \frac{1}{\text{cycle length}} \\
= \frac{1}{800 \text{ msec}} \\
= \frac{1}{0.8 \text{ sec}} \\
= 1.25 \text{ beats/sec} \\
= 75 \text{ beats/min}
\]

Cardiac output = stroke volume \times \text{heart rate} \\
= 70 \text{ mL} \times 75 \text{ beats/min} \\
= 5250 \text{ mL/min}

Ejection fraction = \frac{\text{stroke volume}}{\text{end-diastolic volume}} \\
= \frac{70 \text{ mL}}{140 \text{ mL}} \\
= 0.5, \text{ or } 50\%

3. As shown in Question 2, we calculate cardiac output as the product of stroke volume and heart rate. However, we measure cardiac output by the Fick principle of conservation of mass. The Fick principle for measuring cardiac output employs two basic assumptions: (1) Pulmonary blood flow (the cardiac output of the right ventricle) equals systemic blood flow (the cardiac output of the left ventricle) in the steady state. (2) The rate of O₂ utilization by the body is equal to the difference between the amount of O₂ leaving the lungs in pulmonary venous blood and the amount of O₂ returning to the lungs in pulmonary arterial blood. This relationship can be stated mathematically as follows:

\[
\text{O₂ consumption} = \text{cardiac output} \times [\text{O₂}]_{\text{pulmonary vein}} - \text{cardiac output} \times [\text{O₂}]_{\text{pulmonary artery}}
\]

Rearranging to solve for cardiac output:

\[
\text{Cardiac output} = \frac{\text{O₂ consumption}}{[\text{O₂}]_{\text{pulmonary vein}} - [\text{O₂}]_{\text{pulmonary artery}}}
\]

where

Cardiac output = cardiac output (mL/min) \\
O₂ consumption = O₂ consumption by the body (mL O₂/min) \\
[O₂]_{\text{pulmonary vein}} = O₂ content of pulmonary venous blood (mL O₂/mL blood) \\
[O₂]_{\text{pulmonary artery}} = O₂ content of pulmonary arterial blood (mL O₂/mL blood)

In this case, cardiac output can be calculated by substituting values from Table 2–1. To find the appropriate values in the table, recall that systemic arterial blood is equivalent to pulmonary venous blood.

\[
\text{Cardiac output} = \frac{250 \text{ (mL/min)}}{0.20 \text{ mL O₂/mL blood} - 0.152 \text{ mL O₂/mL blood}}
\]

\[
= \frac{250 \text{ mL/min}}{0.048 \text{ mL O₂/mL blood}} \\
= 5208 \text{ mL/min}
\]

Thus, the value for cardiac output measured by the Fick principle (5208 mL/min) is very close to the value of 5250 mL/min calculated as the product of stroke volume and heart rate in Question 2.
4. TPR is the collective resistance to blood flow that is provided by all of the blood vessels on the systemic side of the circulation. These blood vessels include the aorta, large and small arteries, arterioles, capillaries, venules, veins, and vena cava. Most of this resistance resides in the arterioles.

The fundamental equation of the cardiovascular system relates blood flow, blood pressure, and resistance. The relationship is analogous to the one that relates current (I), voltage (V), and resistance (R) in electrical circuits as expressed by Ohm's law \( I = \frac{\Delta V}{R} \). Blood flow is analogous to current flow, blood pressure is analogous to voltage, and hemodynamic resistance is analogous to electrical resistance. Thus, the equation for blood flow is:

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

or, rearranging and solving for \( R \),

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

where

- \( Q \) = blood flow (mL/min)
- \( \Delta P \) = pressure difference (mm Hg)
- \( R \) = resistance (mm Hg/mL per min)

Therefore, to calculate total peripheral resistance (TPR), it is necessary to know the total blood flow through the systemic circulation (i.e., cardiac output of the left ventricle) and the pressure difference across the entire systemic circulation. In solving this problem, it may be helpful to visualize the organization and circuitry of the cardiovascular system (Figure 2-3).

![Circuity of the cardiovascular system](image-url)
Cardiac output was calculated by different methods in Questions 2 and 3 as 5250 mL/min and 5208 mL/min, respectively. These values are similar, and we can (arbitrarily) take the average value (5229 mL/min) to represent cardiac output. The pressure difference across the systemic circulation (ΔP) is the difference in pressure at the inflow and outflow points. Inflow pressure is aortic pressure, and outflow pressure is right atrial pressure. In Question 1, mean aortic pressure was calculated as 96 mm Hg. Right atrial pressure is given in Table 2-1 as 2 mm Hg. Thus, ΔP across the systemic circulation is 96 mm Hg – 2 mm Hg, or 94 mm Hg. Resistance (R), which represents TPR, is:

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

or

\[ \text{TPR} = \frac{\text{mean arterial pressure} - \text{right atrial pressure}}{\text{cardiac output}} \]

\[ = \frac{94 \text{ mm Hg}}{5229 \text{ mL/min}} \]

\[ = 0.018 \text{ mm Hg/mL per min} \]

5. Pulmonary vascular resistance is calculated in the same way that TPR was calculated in Question 4. We need to know the values for pulmonary blood flow (cardiac output of the right ventricle) and the pressure difference across the pulmonary circulation. To determine pulmonary blood flow, it is necessary to understand that the left and right sides of the heart operate in series (i.e., blood flows sequentially from the left heart to the right heart and back to the left heart). Thus, in the steady state, the cardiac output of the right ventricle (pulmonary blood flow) equals the cardiac output of the left ventricle, or 5229 mL/min. The pressure difference across the pulmonary circulation is inflow pressure minus outflow pressure. The inflow pressure is mean pulmonary artery pressure (15 mm Hg), and the outflow pressure is left atrial pressure (5 mm Hg). Thus, pulmonary vascular resistance is:

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

\[ = \frac{\text{mean pulmonary artery pressure} - \text{left atrial pressure}}{\text{cardiac output}} \]

\[ = \frac{10 \text{ mm Hg}}{5229 \text{ mL/min}} \]

\[ = 0.0019 \text{ mm Hg/mL per min} \]

Although pulmonary blood flow is equal to systemic blood flow, pulmonary vascular resistance is only one-tenth the value of systemic vascular resistances. How is this possible? Since pulmonary resistance is lower than systemic resistance, shouldn’t pulmonary blood flow be higher than systemic blood flow? No, because pulmonary pressures are also much lower than systemic pressures. Thus, pulmonary blood flow can be exactly equal to systemic blood flow because pulmonary vascular resistance and pressures are proportionately lower than systemic vascular resistance and pressures.

6. Because of the serial arrangement of blood vessels within the lungs (i.e., blood flows from the pulmonary artery to smaller arteries to arterioles to capillaries to veins), the total blood flow at any level of the pulmonary vasculature (e.g., at the level of all of the pulmonary capillaries) is the same. Thus, total blood flow through all of the pulmonary capillaries equals total blood flow through the pulmonary artery, which is the cardiac output of the right ventricle, or 5229 mL/min.

7. This question addresses the same issue as Question 6, but in terms of the systemic circulation. Because of the serial arrangement of blood vessels in the systemic circulation (i.e., blood
flows from the aorta to smaller arteries to arterioles, and so forth), the total blood flow at any level of the systemic vasculature (e.g., at the level of all of the arteries) is the same. Thus, total blood flow through all of the systemic arteries equals the cardiac output of the left ventricle, or 5229 mL/min.

8. The principles that were used to determine TPR (or to determine pulmonary vascular resistance) can also be used to calculate the vascular resistance of individual organs (e.g., kidney). Recall how the pressure, flow, resistance relationship was rearranged to solve for resistance: \( R = \frac{\Delta P}{Q} \). R can also represent the resistance of the blood vessels in an individual organ (e.g., kidney), \( \Delta P \) can represent the pressure difference across the organ’s vasculature (e.g., for the kidney, the pressure in the renal artery minus the pressure in the renal vein), and Q can represent the organ’s blood flow (e.g., renal blood flow).

Actually, none of the exact information needed to calculate renal vascular resistance is available in Table 2-1 or from the previous calculations. Renal arterial pressure is close, but not exactly equal, to mean arterial pressure that was calculated for the aorta in Question 1. The mean pressure in large “downstream” arteries is slightly lower than the pressure in the aorta. (It must be lower in order for blood to flow in the right direction, i.e., from the aorta to the distal arteries.) Like the pressure in any large vein, renal venous pressure must be slightly higher than right atrial pressure. Because of the parallel arrangement of arteries off the aorta, renal blood flow is only a fraction of total systemic blood flow.

9. The velocity of blood flow is the rate of linear displacement of blood per unit time:

\[ v = \frac{Q}{A} \]

where

- \( v \) = linear velocity of blood (cm/min)
- \( Q \) = blood flow (mL/min)
- \( A \) = cross-sectional area of a blood vessel (cm²)

In words, velocity is proportional to blood flow and is inversely proportional to the cross-sectional area of the blood vessel. Blood flow through the aorta is total systemic blood flow, or cardiac output, which is 5229 mL/min. The cross-sectional area can be calculated from the diameter of the aorta, which is 20 mm (radius, 10 mm).

\[ v = \frac{Q}{\pi r^2} \]
\[ = \frac{5229 \text{ mL/min}}{3.14 \times (10 \text{ mm})^2} \]
\[ = \frac{5229 \text{ mL/min}}{3.14 \times 1 \text{ cm}^2} \]
\[ = \frac{5229 \text{ cm}^3/\text{min}}{3.14 \text{ cm}^2} \]
\[ = 1665 \text{ cm/min} \]

Based on the inverse relationship between velocity and radius of blood vessels, the velocity of blood flow should be lower in all of the capillaries than in the aorta. (Of course, a single capillary has a smaller radius than the aorta, but all of the capillaries have a larger collective radius and cross-sectional area than the aorta.)
Key topics

| Cardiac output |
| Cycle length |
| Diastolic pressure |
| Ejection fraction |
| Electrocardiogram (ECG) |
| Fick principle of conservation of mass |
| Heart rate |
| Mean arterial pressure |
| Pressure, blood flow, resistance relationship |
| Pulmonary vascular resistance |
| Pulse pressure |
| R-R interval |
| Stroke volume |
| Systolic pressure |
| Total peripheral resistance (TPR) or systemic vascular resistance |
| Velocity of blood flow |