Vascular Hemodynamics

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Learning objectives

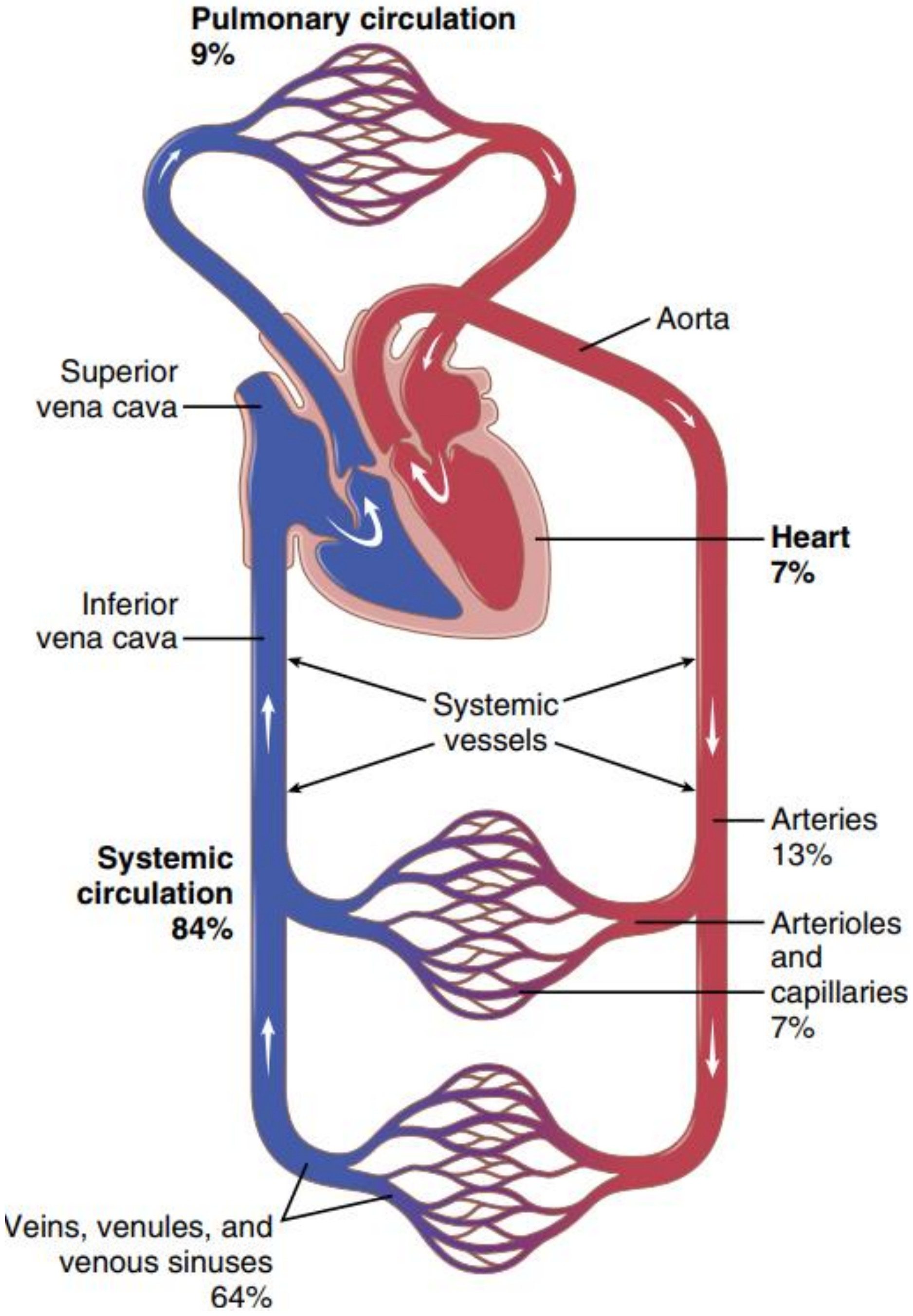
- To understand the relationship between blood flow, blood pressure gradient, and blood flow rate.
- To recognize the relationship between vascular cross sectional area and velocity of blood flow.
- To differentiate between laminar flow and turbulent flow of blood, and the factors that affect the type of flow.
- To differentiate between resistance and conductance, and the factors affecting them.
- To recognize the relationship between total vascular resistance and the individual resistances in the vasculature that are arranged as series vs parallel ones.

What is/are the function/s of the cardiovascular system?

- Transport nutrients to the tissues.
- Transport waste products away.
- Transport hormones from one part of the body to another.
- Thermoregulation.
- Maintain an appropriate environment in all the tissue fluids for survival and optimal function of the cells.

Hemodynamics

- The governing principles of blood flow and its behavior in the blood vessels.



Pulmonary circulation
9%
Aorta
Superior
vena cava
Heart
7%
Inferior
vena cava
Systemic
vessels
Arteries
13%
Systemic
circulation
84%
Arterioles
and
capillaries
7%
Veins, venules, and
venous sinuses
64%

Blood flow

- Blood flow rate means the quantity of blood that passes a given point in the circulation in a given period of time.

- The overall blood flow in the total circulation of an adult person at rest is about 5000 ml/min. This is called the **cardiac output** because it is the amount of blood pumped into the aorta by the heart each minute.

- Blood flow through a blood vessel is determined by two factors:
- (1) pressure difference of the blood between the two ends of the vessel, also sometimes called the pressure gradient along the vessel, which pushes the blood through the vessel.
- (2) the impediment to blood flow through the vessel, which is called vascular resistance.

Q (or F) = $\Delta P/R$

- Physiologically, this means that blood flow is equal to the change in pressure divided by systemic resistance. In other words, to increase blood flow, one could either increase the pressure difference (e.g., increased cardiac force) or decrease the systemic vascular resistance (e.g., dilate blood vessels).

- It is the difference in pressure between the two ends of the vessel, not the absolute pressure in the vessel, that determines flow rate.

- The direction of blood flow is determined by the direction of the pressure gradient and always is from high to low pressure.

- The major mechanism for changing blood flow in the cardiovascular system is by changing the resistance of blood vessels, particularly the arterioles.

- The resistance of the entire systemic vasculature is called the total peripheral resistance (TPR) or the systemic vascular resistance (SVR).

- Blood vessel **resistance** can be thought of as how difficult it is to pass blood through a given set of vessels. Intuitively, the size and shape of the blood vessel can alter the ease of blood flow.

Problem Solving Q

- Renal blood flow is measured by placing a flow meter on a woman's left renal artery. Simultaneously, pressure probes are inserted in her left renal artery and left renal vein to measure pressure. Renal blood flow measured by the flow meter is 500 mL/min. The pressure probes measure renal arterial pressure as 100 mm Hg and renal venous pressure as 10 mm Hg. What is the vascular resistance of the left kidney in this woman?

Solution

$$Q = \Delta P/R$$

Rearranging and solving for R,

$$R = \Delta P/Q$$
$$= (\text{Pressure in renal artery} - \text{Pressure in renal vein})/\text{Renal blood flow}$$

$$R = (100 \text{ mm Hg} - 10 \text{ mm Hg})/500 \text{ mL per min}$$
$$= 90 \text{ mm Hg}/500 \text{ mL per min}$$
$$= 0.18 \text{ mm Hg/mL per min}$$

Velocity of blood flow

- The rate of displacement of blood per unit time.

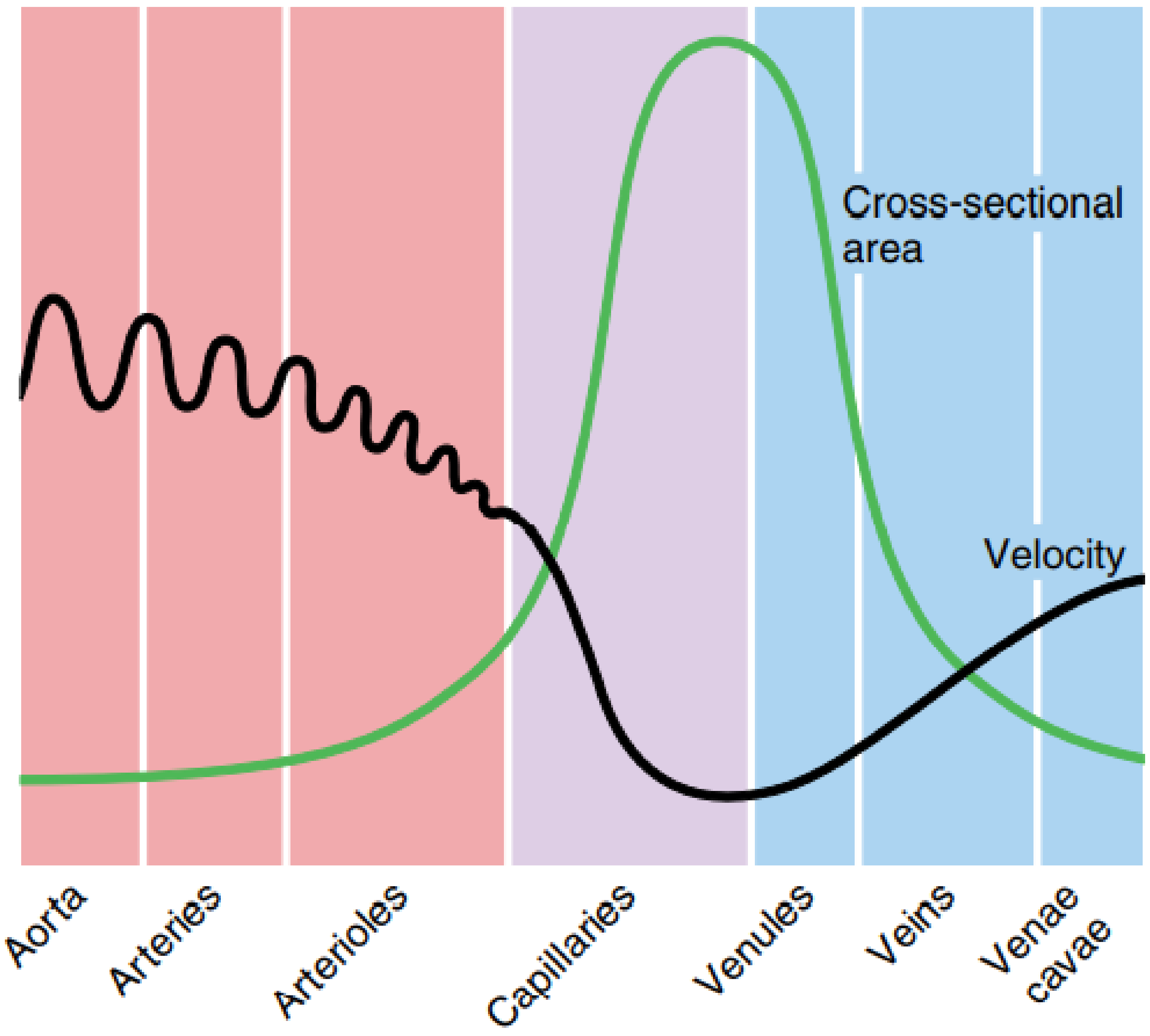
- **V=Q/A**

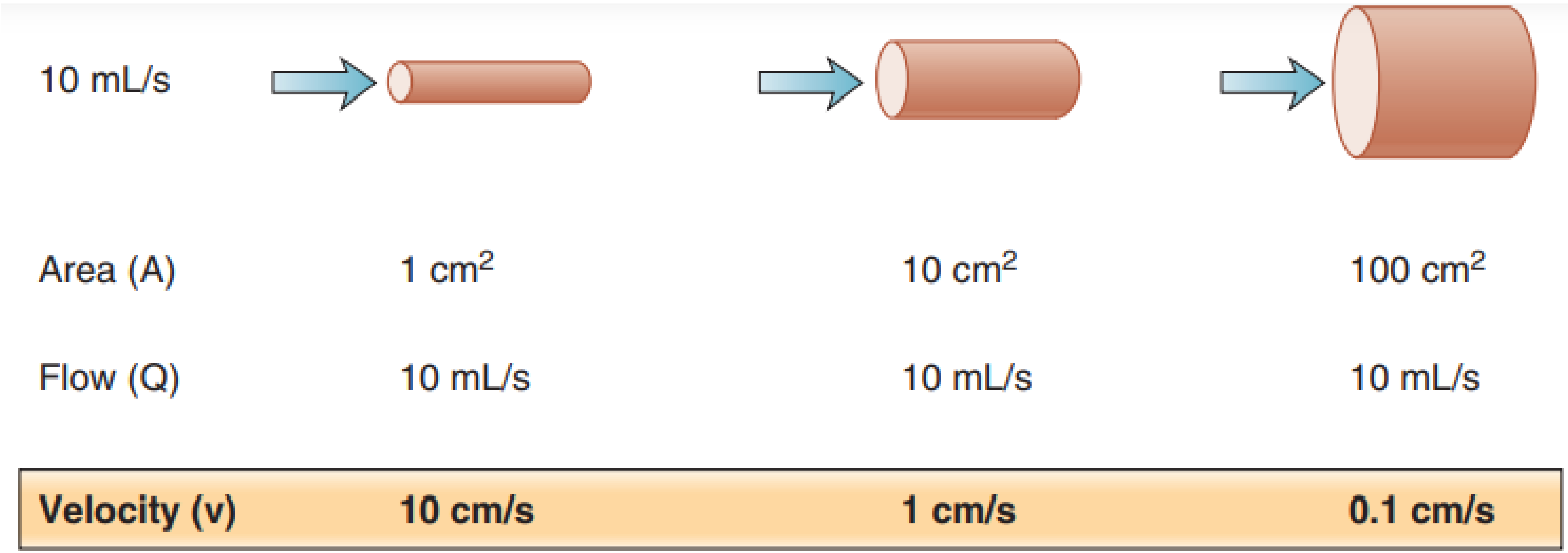
where

- v =Velocity of blood flow (cm/s)
- Q =Flow (mL/s)
- A =Cross-sectional area (cm2)

Vessels Cross-Sectional Area (cm2)

Aorta	2.5
Small arteries	20
Arterioles	40
Capillaries	2500
Venules	250
Small veins	80
Venae cavae	8


Cross-sectional area
Velocity
Aorta
Arteries
Arterioles
Capillaries
Venules
Veins
Venae cavae



10 mL/s
Area (A)
1 cm2
10 cm2
100 cm2
Flow (Q)
10 mL/s
10 mL/s
10 mL/s
Velocity (v)
10 cm/s
1 cm/s
0.1 cm/s

Problem Solving Q

- A man has a cardiac output of 5.5 L/min. The diameter of his aorta is estimated to be 20 mm, and the total cross-sectional area of his systemic capillaries is estimated to be 2500 cm2 . What is the velocity of blood flow in the aorta relative to the velocity of blood flow in the capillaries?

Solution

$$
\begin{aligned}
V_{capillaries} &= Q/A \\
&= \frac{5.5\ \text{L/min}}{2500\ \text{cm}^2} \\
&= \frac{5500\ \text{mL/min}}{2500\ \text{cm}^2} \\
&= \frac{5500\ \text{cm}^3/\text{min}}{2500\ \text{cm}^2} \\
&= 2.2\ \text{cm/min} \\
V_{aorta} &= Q/A \\
&= \frac{5500\ \text{cm}^3/\text{min}}{3.14\ \text{cm}^2} \\
&= 1752\ \text{cm/min}
\end{aligned}
$$

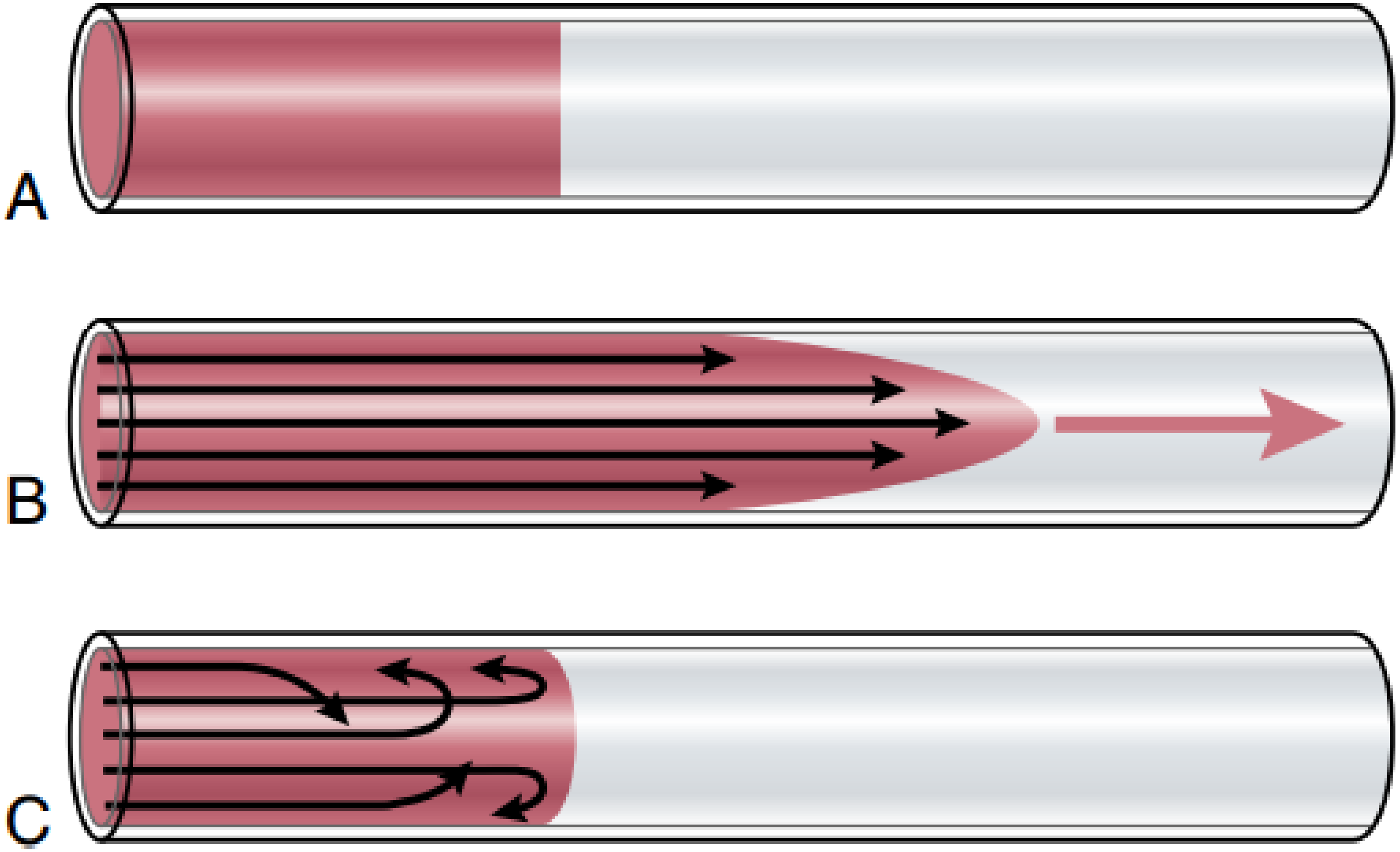
Hence, velocity in the aorta is 800-fold that in the capillaries (1752 cm/min in the aorta compared with 2.2 cm/min in the capillaries).

Laminar flow

- Ideally, blood flow in the cardiovascular system is laminar or streamlined.
- In laminar flow, there is a smooth **parabolic profile of velocity** within a blood vessel, with the velocity of blood flow highest in the center of the vessel and lowest toward the vessel walls.

- The reason for these differences in blood flow velocity is wall stress (a type of shear stress). When blood flows through a vessel, friction exists between the fluid and the wall of the vessel. This friction decreases the velocity of the blood closest to the wall.

Laminar Blood Flow in Vessels



Turbulent flow

- In turbulent flow, the fluid streams do not remain in the parabolic profile; instead, the streams mix radially and axially.

- Because kinetic energy is wasted in propelling blood radially and axially, more energy (pressure) is required to drive turbulent blood flow than laminar blood flow.

- Laminar flow is silent, while turbulent flow is audible.
- For example, the Korotkoff sounds used in the auscultatory measurement of blood pressure are caused by turbulent flow.
- Blood vessel stenosis (narrowing) and cardiac valve disease can cause turbulent flow and often are accompanied by audible vibrations called murmurs.

Reynolds' number

- The **Reynolds number** is a dimensionless number that is used to predict whether blood flow will be laminar or turbulent. (The measure of the tendency for turbulence to occur.)
- It considers a number of factors:
- Re= ρVD/μ
- Re is the Reynolds number, ρ is the **density**, V is **velocity**, D is the **diameter** of the cylinder, and μ is the **viscosity**.
- Turbulence is more likely to develop at a high Re number.

- when Reynolds’ number rises above approximately 2000, turbulence will usually occur, even in a straight, smooth vessel.

- Reynolds’ number for flow in the vascular system normally rises to 200 to 400, even in large arteries. As a result, there is almost always some flow turbulence at the branches of these vessels. In the proximal portions of the aorta and pulmonary artery, Reynolds’ number can rise to several thousand during the rapid phase of ejection by the ventricles, which causes considerable turbulence.

Anemia

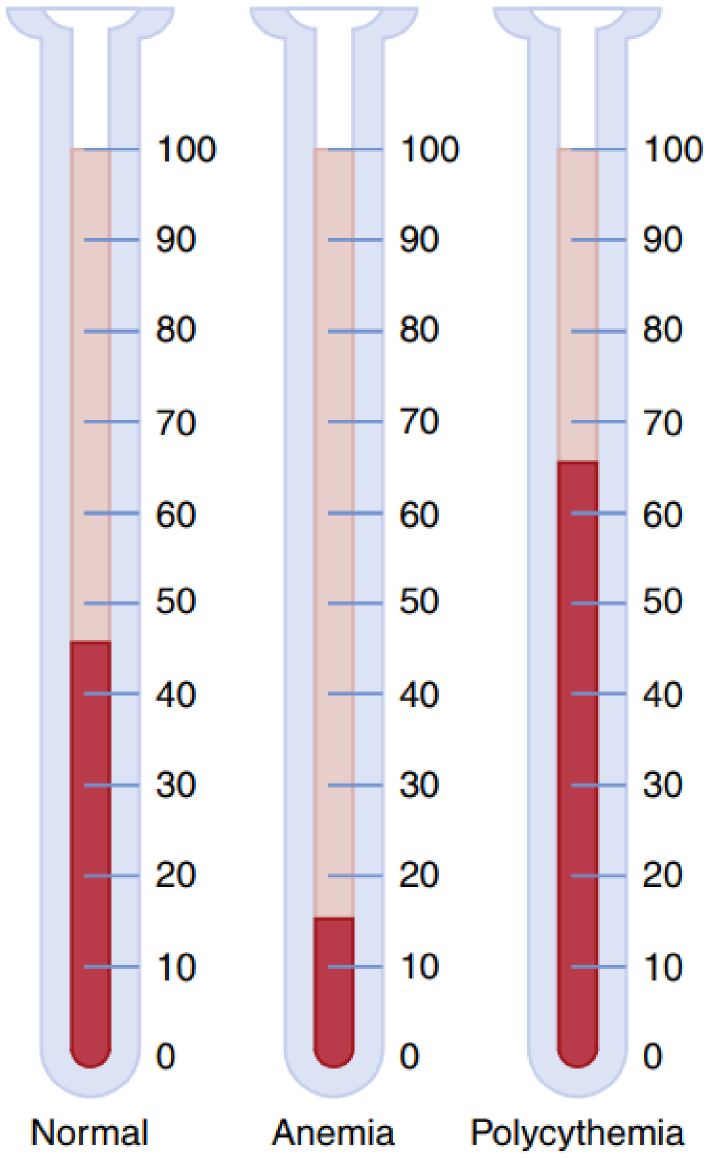
- Two common clinical situations, anemia and thrombi, illustrate the application of Reynolds number in predicting turbulence.

- Anemia is associated with a **decreased hematocrit** and, because of turbulent blood flow, causes functional murmurs. Reynolds number, the predictor of turbulence, is increased in anemia due to **decreased blood viscosity**. A second cause of increased Reynolds number in patients with anemia is a high cardiac output, which causes an **increase in the velocity of blood flow** ($v = Q/A$).

Hematocrit

Hematocrit—the Proportion of Blood That Is Red Blood Cells.

If a person has a hematocrit of 40, this means that 40% of the blood volume is cells, and the remainder is plasma.



Thrombi

- Thrombi are blood clots in the lumen of a vessel.

- Thrombi narrow the **diameter** of the blood vessel, which causes an increase in blood **velocity** at the site of the thrombus, thereby increasing Reynolds number and producing turbulence.

Vascular hemodynamics-2

P=Q.R

- Q=P/R
- P=Q*R
- MAP= CO*TPR

- R unit is PRU: peripheral resistance unit.

Resistance

- Resistance occurs as a result of friction between the flowing blood and the intravascular endothelium all along the inside of the vessel.

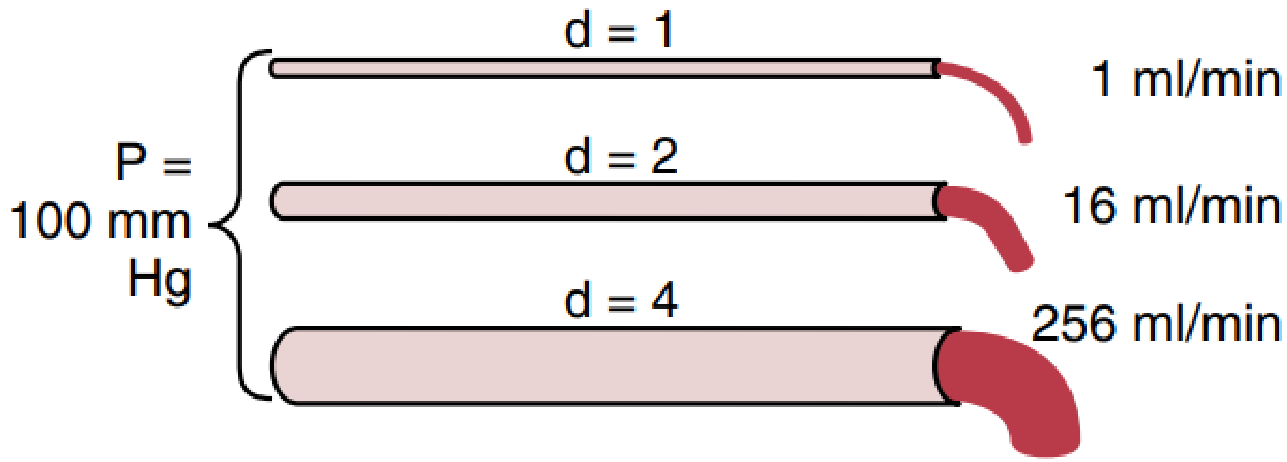
- Resistance is the impediment to blood flow in a vessel, but it cannot be measured by any direct means. Instead, resistance must be calculated from measurements of blood flow and pressure difference between two points in the vessel.

Conductance

- Conductance is a measure of the blood flow through a vessel for a given pressure difference.

- Conductance is the exact reciprocal of resistance:
- Conductance =1 / Resistance

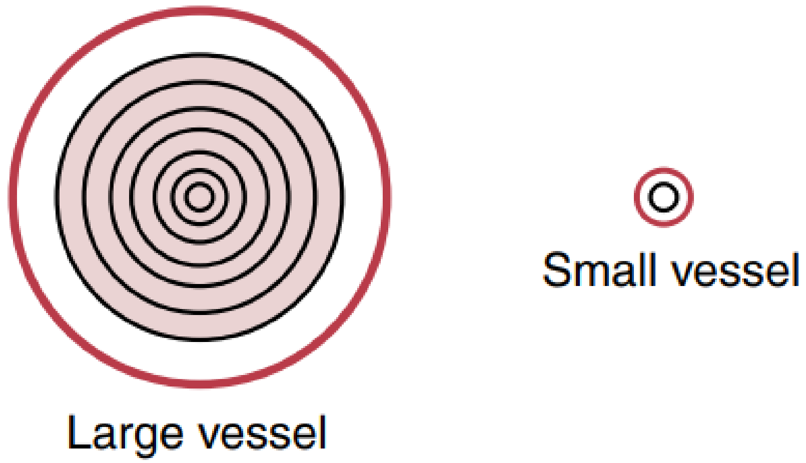
- The conductance of the vessel increases in proportion to the fourth power of the diameter, in accordance with the following formula:
- Conductance ∝ Diameter 4



Poiseuille’s Law

- In the small vessel, essentially all the blood is near the wall, so the extremely rapidly flowing central stream of blood simply does not exist.
- By integrating the velocities of all the concentric rings of flowing blood and multiplying them by the areas of the rings, one can derive the following formula, known as Poiseuille’s law:

- **$F = \pi\ \Delta Pr4/\ 8\eta l$**



- F is the rate of blood flow, ΔP is the pressure difference between the ends of the vessel, r is the radius of the vessel, l is length of the vessel, and η is viscosity of the blood.

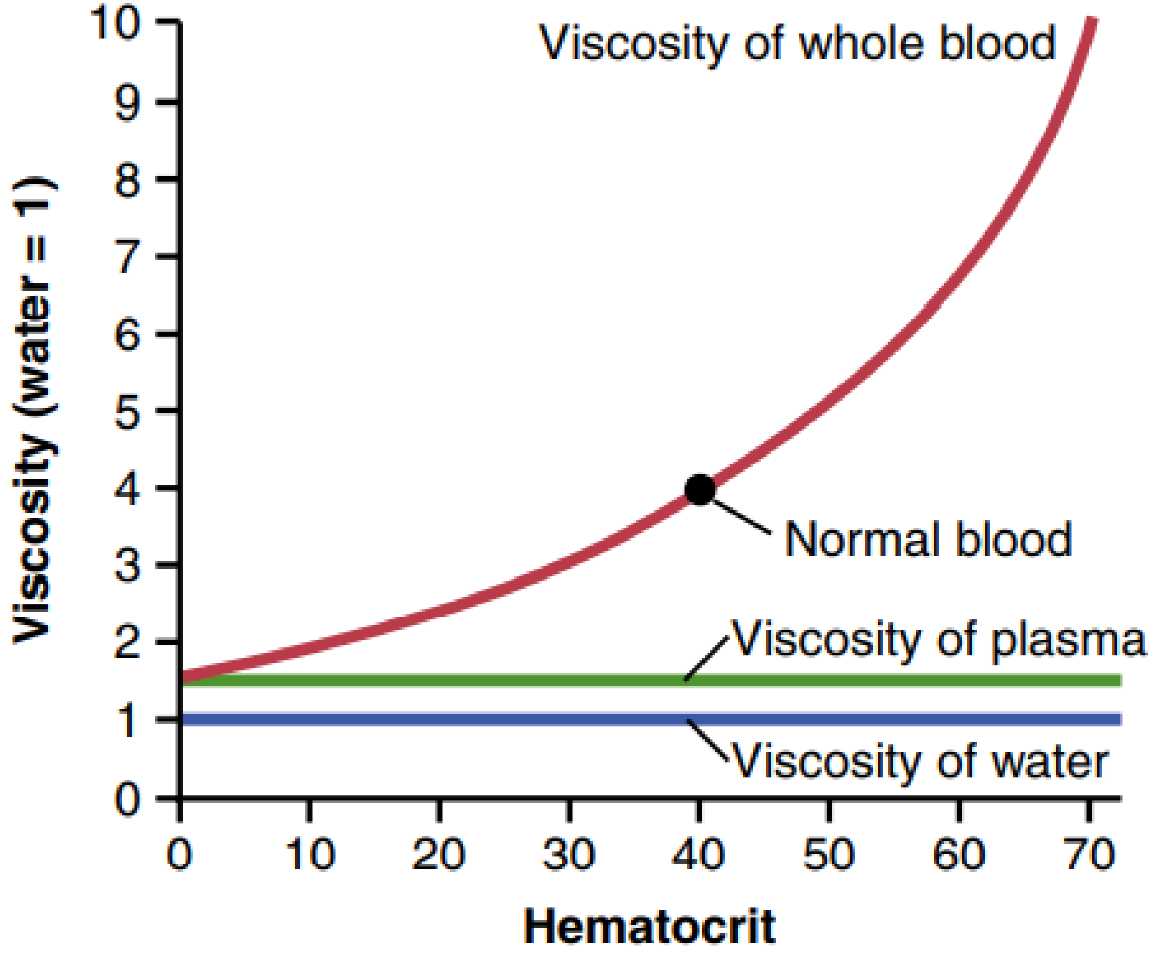
- The rate of blood flow is directly proportional to the fourth power of the radius of the vessel, which demonstrates once again that the diameter of a blood vessel plays the greatest role of all factors in determining the rate of blood flow through a vessel.

Resistance

- The blood vessels and the blood itself constitute resistance to blood flow.
- The relationship between resistance, blood vessel diameter (or radius), and blood viscosity is described by the Poiseuille equation.

Blood viscosity

- The viscosity of whole blood at a normal hematocrit is about 3 to 4, which means that three to four times as much pressure is required to force whole blood as to force water through the same blood vessel.
- When the hematocrit rises to 60 or 70, which it often does in persons with polycythemia, the blood viscosity can become as great as 10 times that of water, and its flow through blood vessels is greatly retarded.
- Other factors that affect blood viscosity are the plasma protein concentration and types of proteins in the plasma, but these effects are so much less than the effect.


Viscosity of whole blood
Normal blood
Viscosity of plasma
Viscosity of water
Viscosity (water = 1)
Hematocrit
0
1
2
3
4
5
6
7
8
9
10
0
10
20
30
40
50
60
70

Problem Solving Q

- A man suffers a stroke caused by partial occlusion of his left internal carotid artery. An evaluation of the carotid artery using magnetic resonance imaging (MRI) shows a 75% reduction in its radius. Assuming that blood flow through the left internal carotid artery was 400 mL/min prior to the occlusion, what is blood flow through the artery after the occlusion?

Answer

The first question is ***How much would resistance increase with 75% occlusion of the artery?*** The answer is found in the Poiseuille equation. After the occlusion, the radius of the artery is one-fourth its original radius; thus resistance has increased by $1/(1/4)^4$, or 256-fold.

The second question is ***What would the flow be if resistance were to increase by 256-fold?*** The answer is found in the flow, pressure, resistance relationship ($Q = \Delta P/R$). Because resistance increased by 256-fold, flow decreased to 1/256, or 0.0039, or 0.39% of the original value. The flow is 0.39% of 400 mL/min, or 1.56 mL/min. Clearly, this is a dramatic decrease in blood flow to the brain, all based on the fourth-power relationship between resistance and vessel radius.

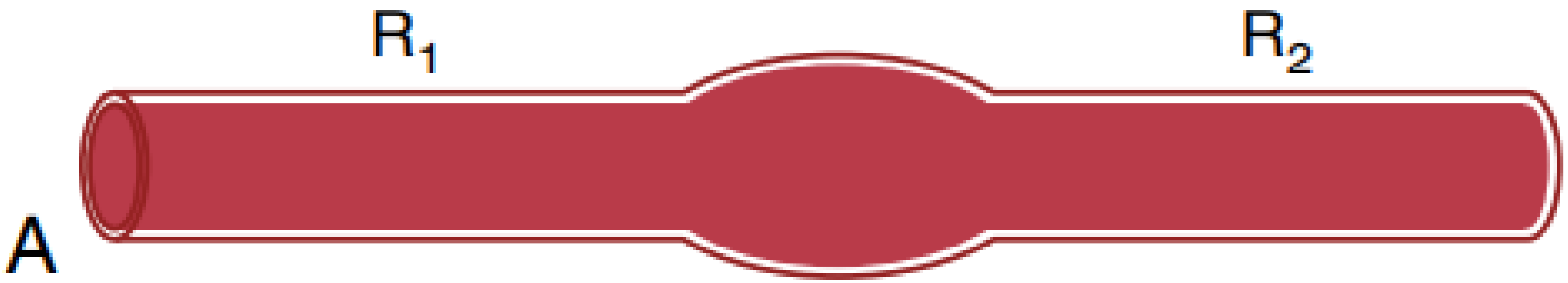
Total vascular resistance

- The total resistance offered by a set of blood vessels also depends on whether the vessels are arranged in series (i.e., blood flows sequentially from one vessel to the next) or in parallel (i.e., the total blood flow is distributed simultaneously among parallel vessels).

Resistance

- The arteries, arterioles, capillaries, venules, and veins are collectively arranged in series.

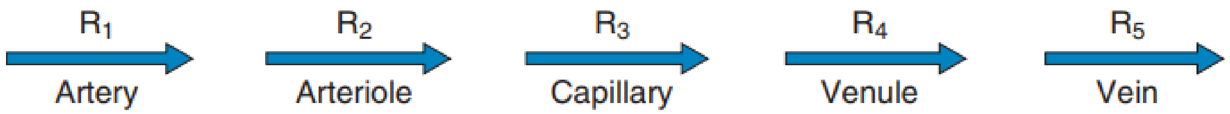
- The total peripheral vascular resistance is therefore equal to the sum of resistances of the arteries, arterioles, capillaries, venules, and veins.



$$R_{total} = R_1 + R_2 + R_3 + R_4 \ldots$$

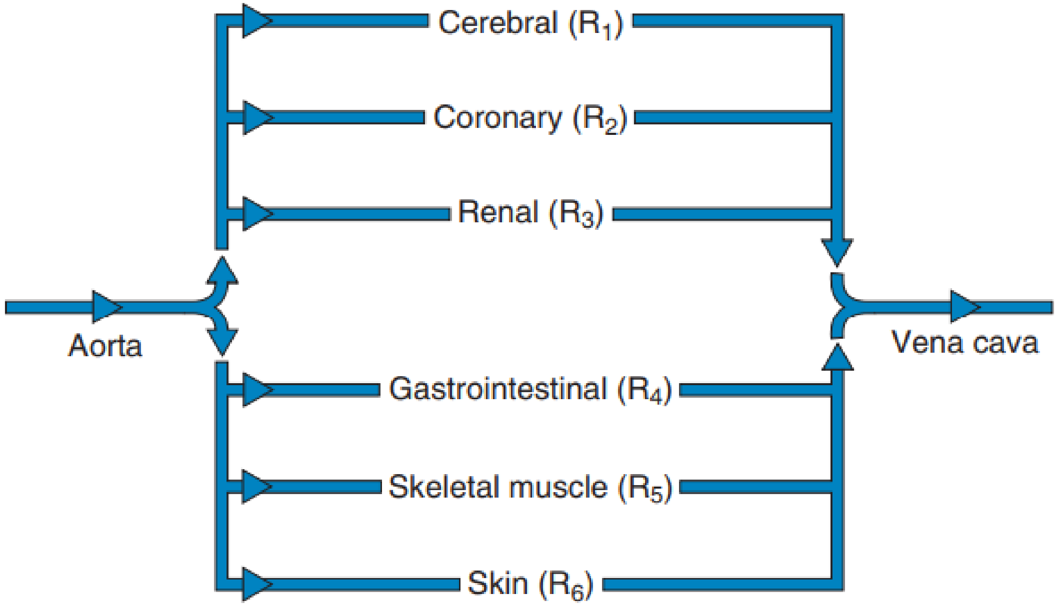
SERIES RESISTANCES

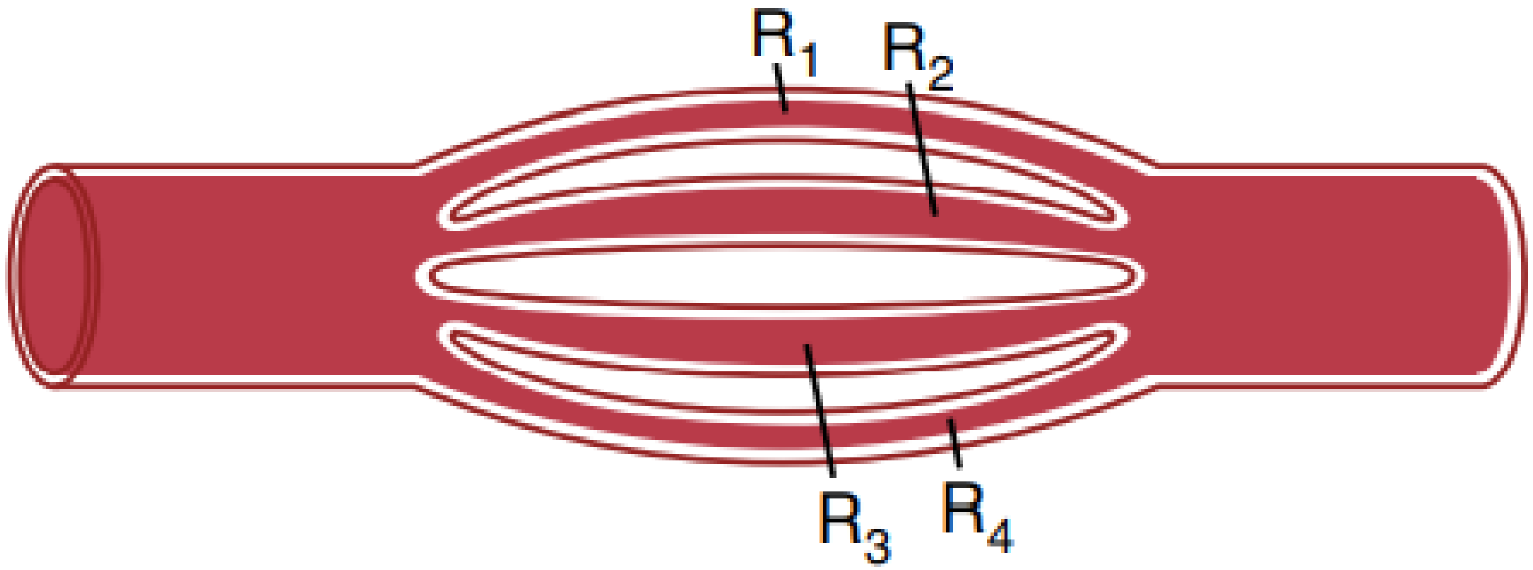
$$R_{total} = R_1 + R_2 + R_3 + R_4 + R_5$$



PARALLEL RESISTANCES

$$\frac{1}{R_{total}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \frac{1}{R_4} + \frac{1}{R_5} + \frac{1}{R_6}$$





B

$$\frac{1}{R_{total}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \frac{1}{R_4} \cdots$$

- Blood vessels branch extensively to form parallel circuits that supply blood to the many organs and tissues of the body. This parallel arrangement permits each tissue to regulate its own blood flow, to a great extent, independently of flow to other tissues.
- for a given pressure gradient, far greater amounts of blood will flow through this parallel system than through any of the individual blood vessels.
- Therefore, the total resistance is far less than the resistance of any single blood vessel. Flow through each of the parallel vessels is determined by the pressure gradient and its own resistance, not the resistance of the other parallel blood vessels. However, increasing the resistance of any of the blood vessels increases the total vascular resistance.

- For example, brain, kidney, muscle, gastrointestinal, skin, and coronary circulations are arranged in parallel, and each tissue contributes to the overall conductance of the systemic circulation.
- Blood flow through each tissue is a fraction of the total blood flow (cardiac output) and is determined by the resistance (the reciprocal of conductance) for blood flow in the tissue, as well as the pressure gradient.
- Therefore, amputation of a limb or surgical removal of a kidney also removes a parallel circuit and reduces the total vascular conductance and total blood flow (i.e., cardiac output) while increasing the total peripheral vascular resistance.

Arterioles

- In the systemic circulation, about two thirds of the total systemic resistance to blood flow is resistance in the small arterioles.
- The internal diameters of the arterioles range from as little as 4 micrometers to as much as 25 micrometers.
- fourth power law makes it possible for the arterioles, responding with only small changes in diameter to nervous signals or local tissue chemical signals, either to turn off the blood flow to the tissue almost completely or, at the other extreme, to cause a vast increase in flow.

References

- Guyton and Hall, Textbook of Medical Physiology, 14th edition.
- Costanzo, Physiology Textbook, 6th edition.
- Tortora and Derrickson, Principles of Anatomy and Physiology Textbook, 14th edition.
- Pollock JD, Murray I, Bordes SJ, et al. Physiology, Cardiovascular Hemodynamics. [Updated 2022 Mar 18]. In: StatPearls [Internet]. Treasure Island (FL): StatPearls Publishing; 2022 Jan-. Available from: https://www.ncbi.nlm.nih.gov/books/NBK470310/

Thank you

Kindly, support your colleagues and fill up this questionnaire about the knowledge and prevalence of Neurostimulants use among medical students in Jordan.

https://docs.google.com/forms/d/e/1FAIpQLScpQ_zEt0Nt7_c6yAJu2bJ8X99s3iyWIO_is8Oq4MeZ4bv42A/viewform