BME 5742 Bio-Systems Modeling and Control

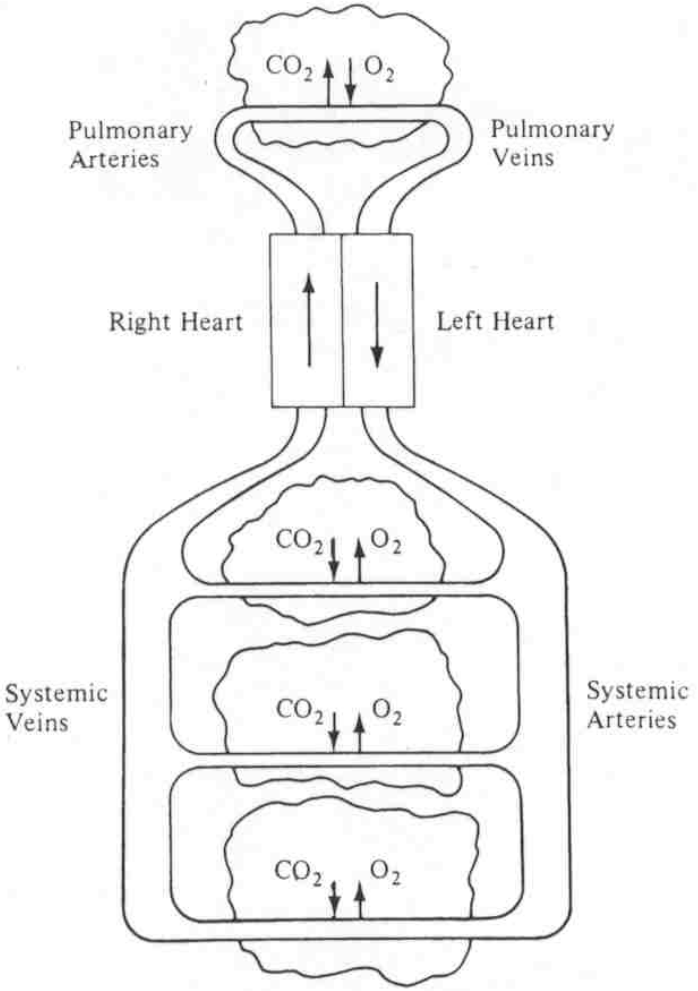
Lecture 39
Heart & Blood Circulation
Basic Definitions

References

- Our main reference is the book: F.C. Hoppensteadt and C.S. Peskin “Modeling and Simulation in Medicine and the Life Sciences”
- Here and there, lectures are supplemented from the books of Guyton and Hall’s “Medical Physiology”, “Eckert’s Animal Physiology”, Scanlon & Sanders “Anatomy and Physiology” and Keener & Sneyd’s “Mathematical Physiology”.

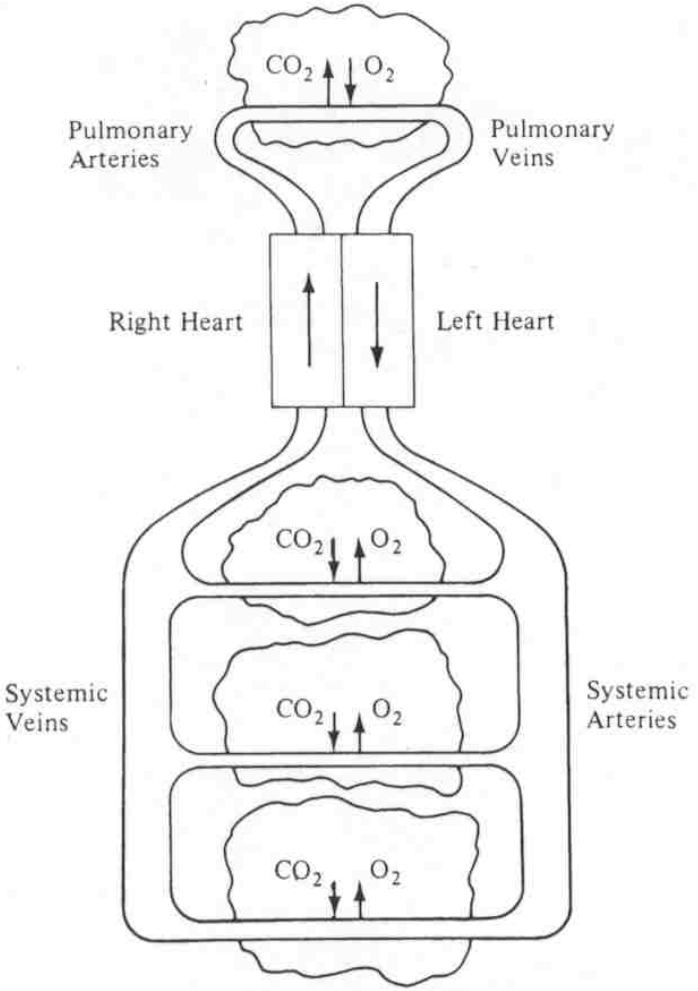
Function of the Heart

- Heart's function is to pump blood.
- Blood carries oxygen (O_2) from the lungs to every tissue in the body, and it carries carbon dioxide (CO_2) from these tissues back to the lungs.



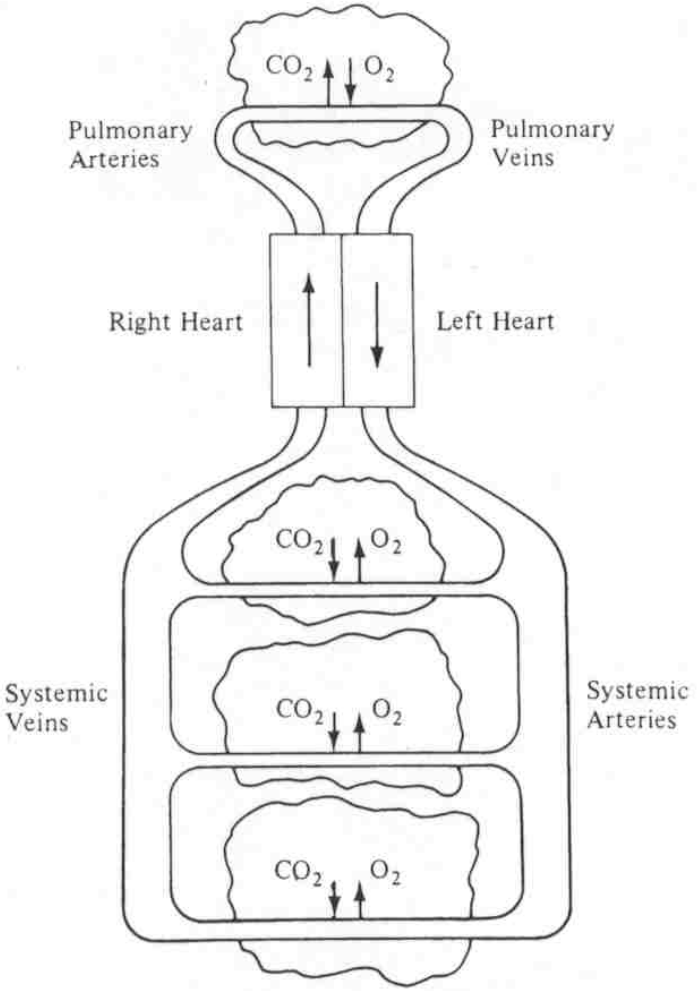
Function of the Two Heart Sides

- The left side of the heart receives blood that is rich in O_2 and pumps this blood into the systemic arteries.
- The right side of the heart receives blood that is rich in CO_2 and pumps this blood into the pulmonary arteries.



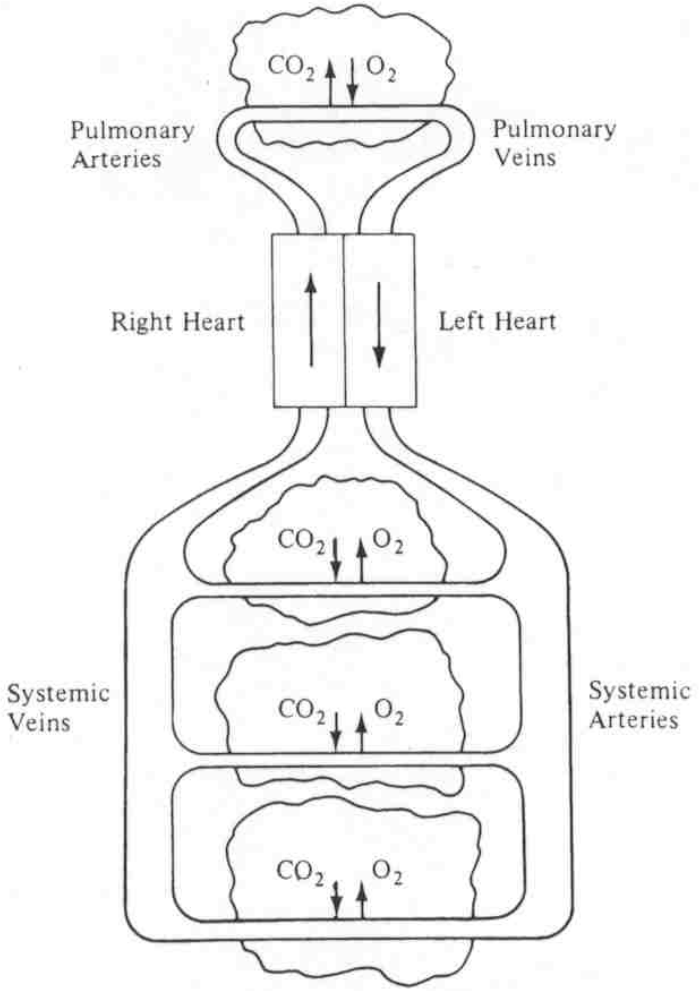
The Arteries System

The systemic arteries form a tree of progressively smaller blood vessels that supply fully oxygenated blood to all organs and tissues.



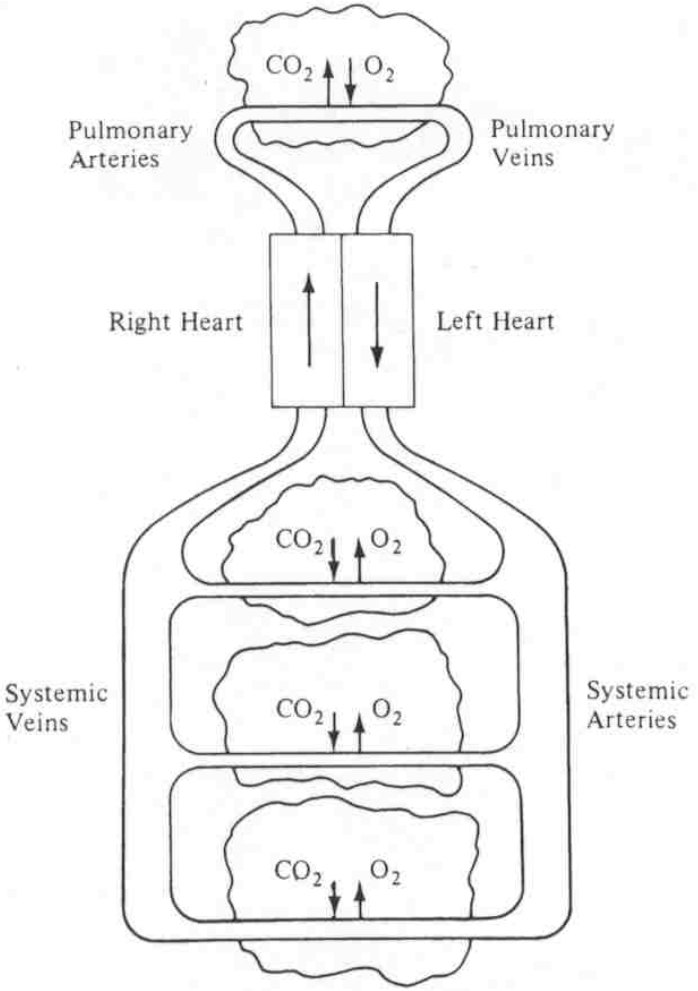
The systemic capillaries -1

- From the smallest systemic arteries blood flows into the systemic capillaries.
- Typical diameter of a capillary roughly equals the diameter of a single red blood cell.



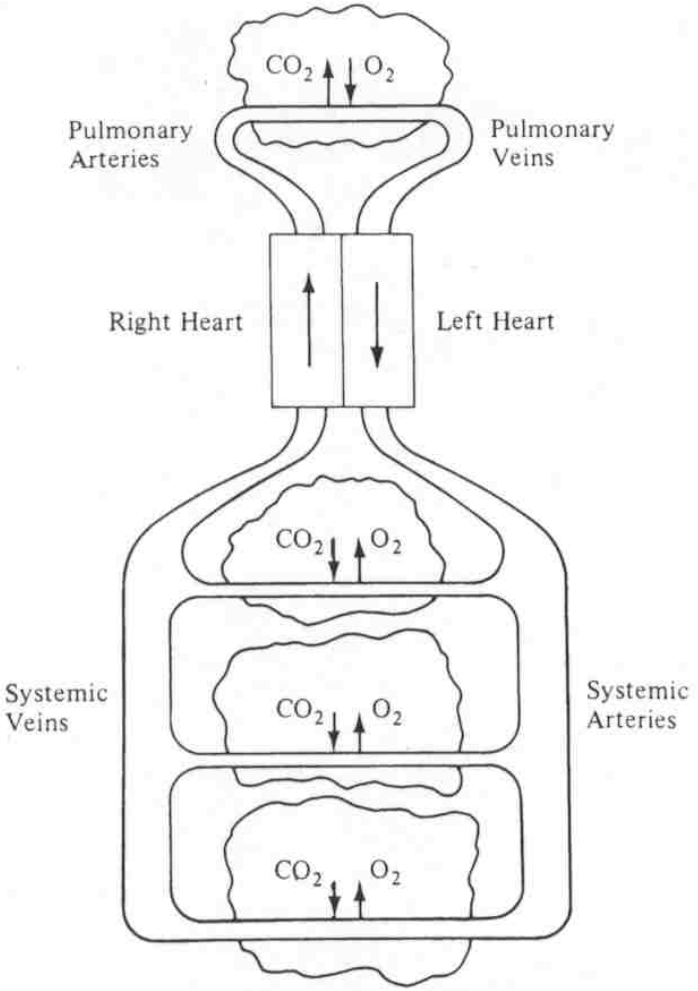
The systemic capillaries -2

- It is in the capillaries that the actual exchange of O_2 and CO_2 takes place.
- The blood that leaves the systemic capillaries carries less O_2 and more CO_2 than the blood that entered.



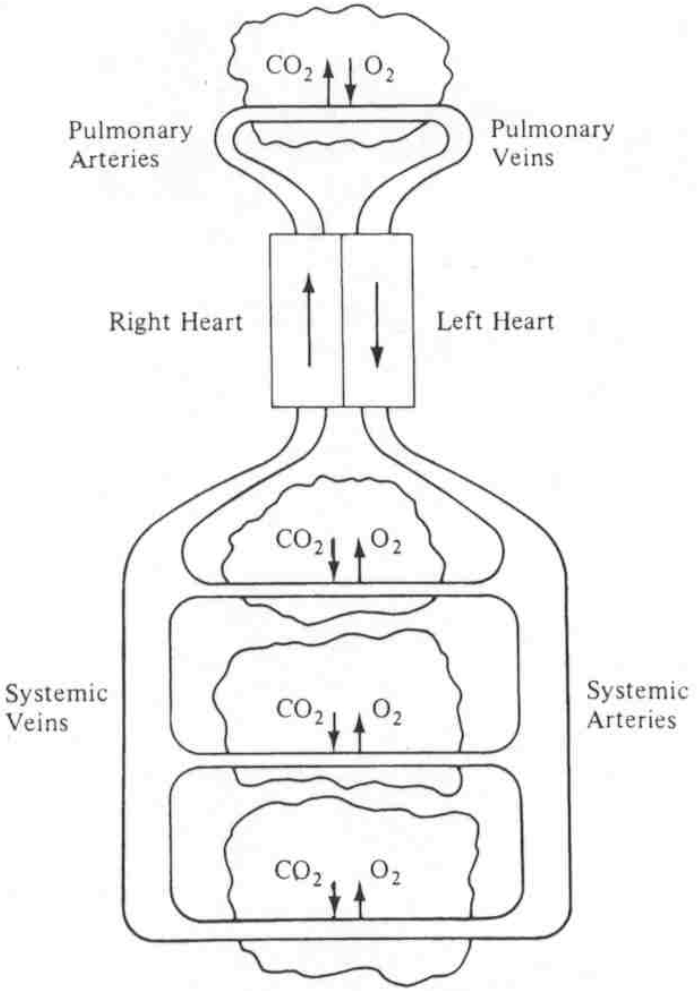
The Systemic Veins

Leaving the systemic capillaries, the blood enters the <u>systemic veins</u>, through which it flows in vessels of progressively increasing size, toward the right side of the heart.



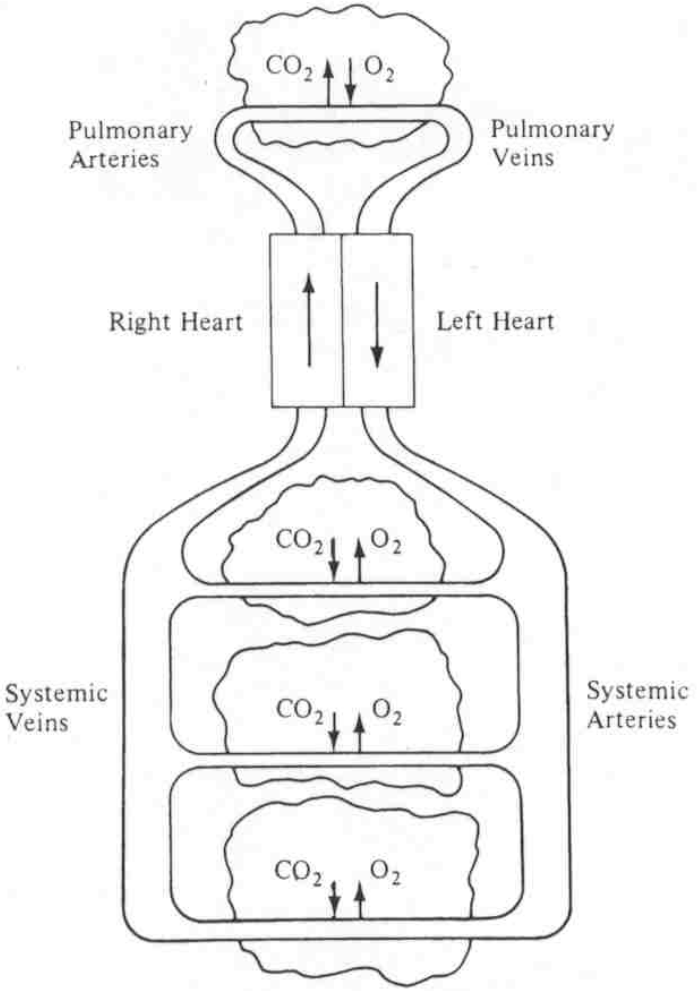
The Pulmonary Arteries and Capillaries

- The pulmonary arteries form a tree that distribute the blood to the tissues of the lung.
- The smallest arteries feed into the <u>pulmonary capillaries</u> where CO_2 leaves the blood stream and O_2 enters.



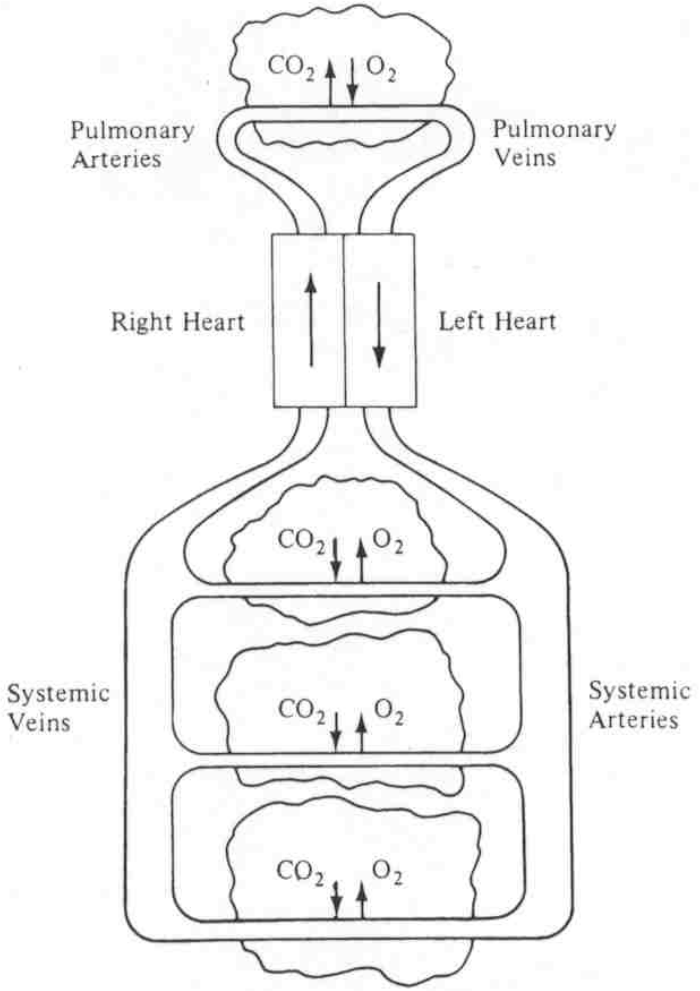
The Pulmonary Veins

- Leaving the pulmonary capillaries, the oxygenated blood flows back to the left heart through the pulmonary veins.
- The average time required for a red blood cell to complete the full loop travel is about 1 minute.



Two Blood Circulation Paths:

- Left heart → Systemic arteries → Systemic capillaries → Systemic veins → Right heart.
- Right heart → Pulmonary arteries → Pulmonary capillaries → Pulmonary veins → Left heart.



Scope of the Model Symmetry

- There will be two symmetric sets of flow circulation equations – same mathematical form.
- No symmetry in magnitudes of variables and coefficients.
- Systemic blood volume is about 10 times larger than pulmonary blood volume.
- Systemic arterial pressure is about 6 times larger than pulmonary arterial pressure.

Typical Resting (Average) Pressures and Volumes of the Systemic and Pulmonary Arteries and Veins

	P [mmHg]	V [liters]
Systemic Arteries (sa)	100	1.0
Systemic Veins (sv)	2	3.5
Pulmonary Arteries (pa)	15	0.1
Pulmonary Veins (pv)	5	0.4

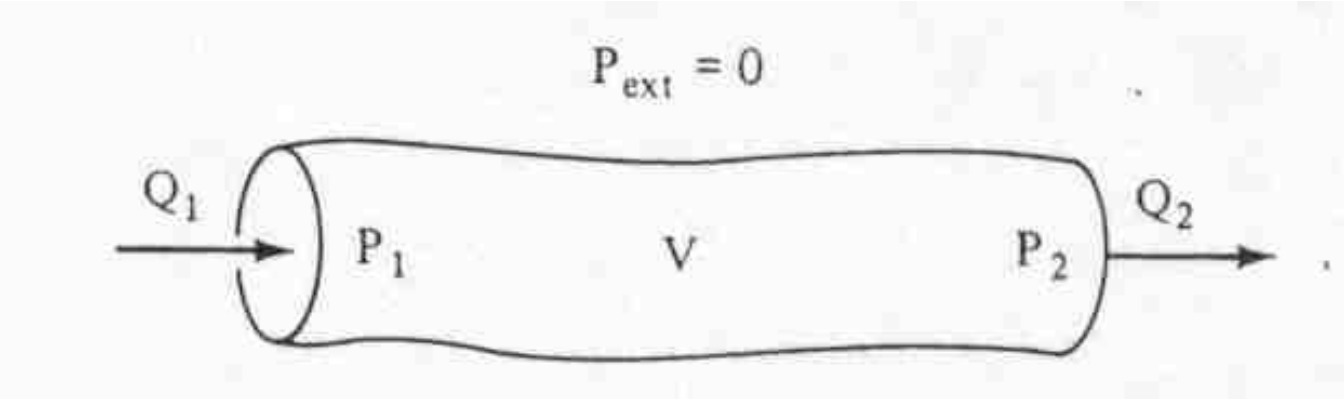
Comments about pressures and volumes

- Since blood is nearly incompressible, the blood volume serves as a convenient measure of the blood amount in any part of the circulation system.
- Total blood volume V is about 5 liters.
- Cardiac Output = Q = Flow (i.e. blood volume per time unit) by either side of the heart = Stroke Volume (volume of blood pumped per beat) x Heart Rate (# beats per time unit)

Typical Flow-related Values:

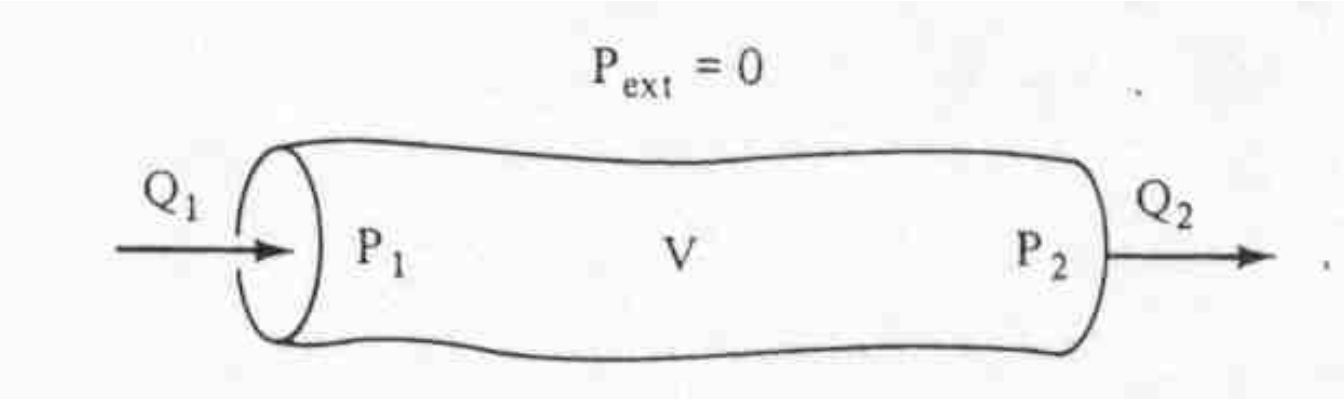
- Stroke Volume = 70 [cm^3/beat] = 0.07 [liters/beat]
- Heart Rate = 80 [beats/minute]
- Cardiac Output = 5.6 [liters/minute]

Flow Variables in a Blood Vessel



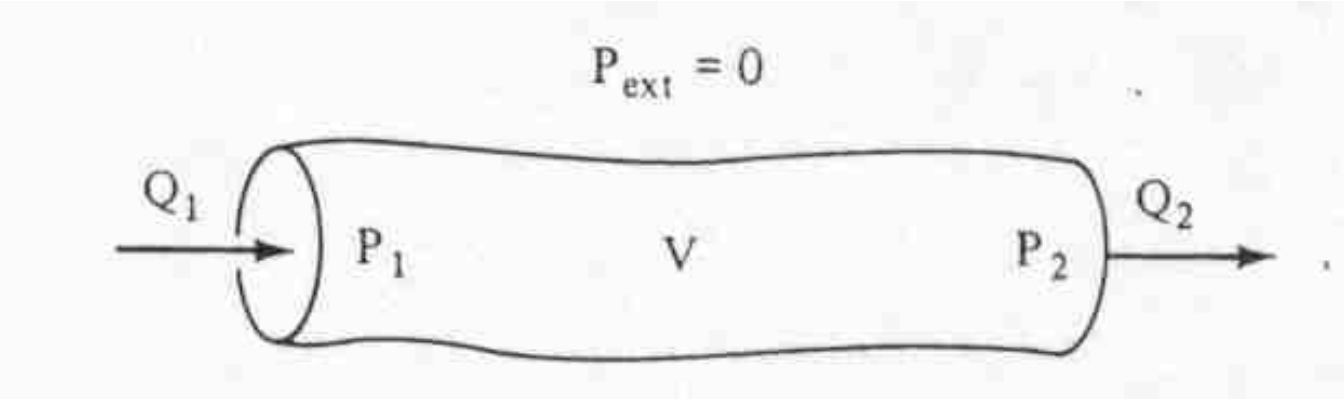
- V = vessel volume
- Inflow: Flow rate Q_1 at a pressure of P_1.
- Outflow: Flow rate Q_2 at pressure P_2.
- External pressure = Reference pressure = 0

Steady-State Flow in a Blood Vessel



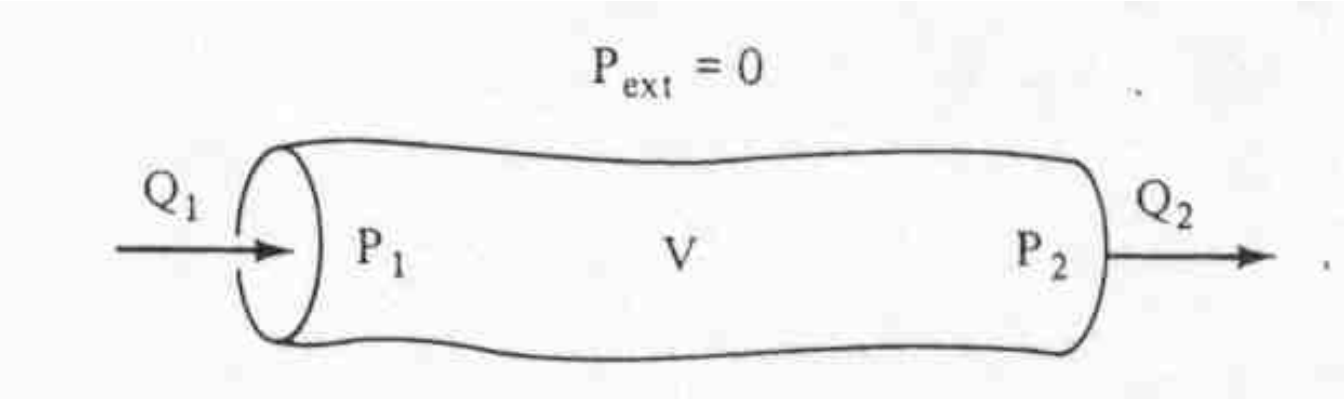
- "Steady-State": Q_1, Q_2, P_1, P_2, V are constant.
- This implies that $Q_1 = Q_2$, otherwise V must change.
- Let us (at steady-state) denote $Q_1 = Q_2 = Q$

Extreme Case: Rigid Blood Vessel



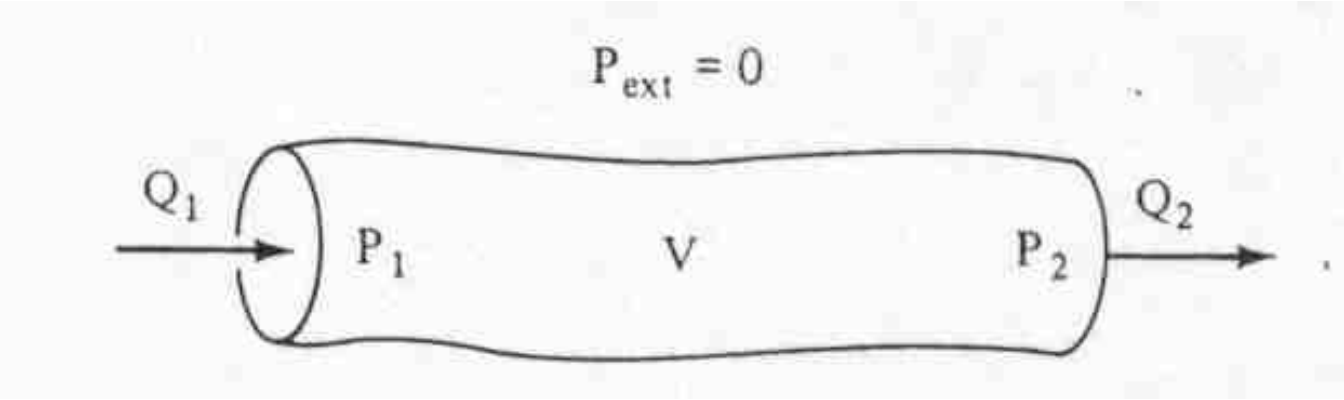
- If blood vessel is rigid then V=const.
- Assuming laminar flow, we have at steady-state: $Q = (P_1 - P_2)/R$, where R is the <u>resistance</u> of the vessel.
- We call such a vessel a <u>Resistance Vessel</u>

Extreme Case: Fully-Compliant Blood Vessel



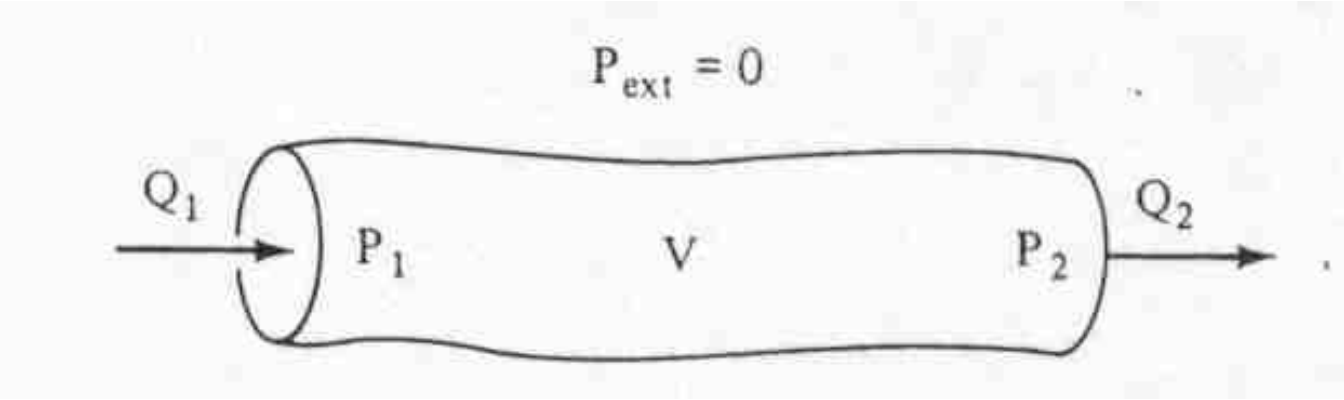
- If a blood vessel is fully elastic, it has no resistance to the flow, but its volume changes to accommodate the flow.
- → Pressures at the two ends are equal for all Q
- → $P_1=P_2=P$ and $V=CP$, where C is constant.
- C is called the Compliance of the Vessel.

Any blood vessel has some resistance and some compliance



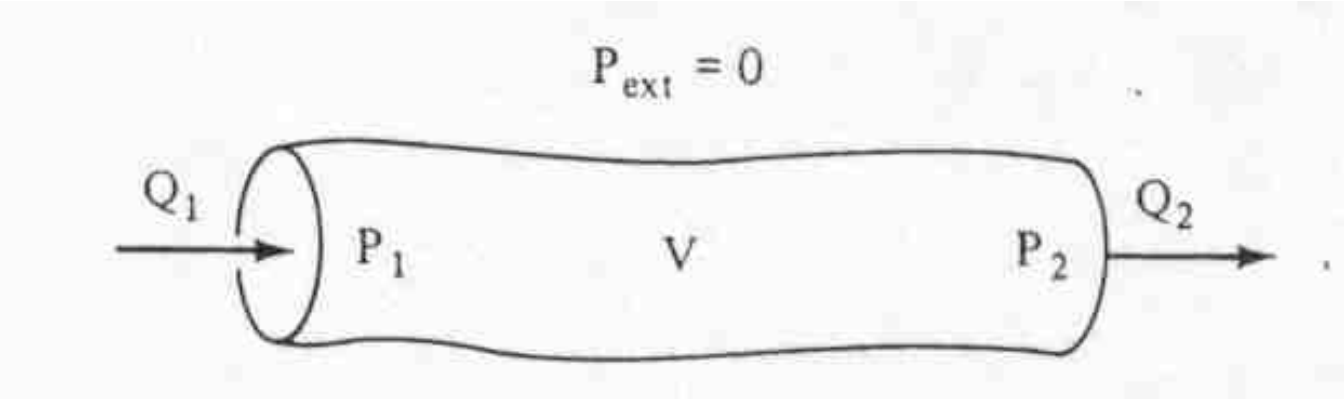
- For fully-compliant vessels (called <u>compliance-vessels</u>), the relationship V=CP implies that at P=0 we have V=0. This is often not so. A better model is $V=V_d+CP$, where V_d is the "dead volume" at P=0.
- Real blood vessel often feature nonlinear R,C.

Which arteries/veins tend to be more compliant?



- Large arteries and veins are primarily compliance vessels: Only a small pressure difference is needed to drive the cardiac output through these vessels.
- All large arteries and veins feature significant volume variations.

Which arteries/veins tend to be more resistive?



- Much of the resistance arises at the tissues themselves.
- The smallest arteries, called arterioles, feature insignificant volume changes and very significant pressure drops.
- In tissue vessels $R=(P_1-P_2)/Q$ is observed to be pretty constant.

Can R of tissue vessels change?

- R can change due to stimulus that leads to contraction or relaxation of the smooth muscles in the walls of the arterioles.
- Such stimuli may be generated by the nervous system, by circulating hormones (or other substances), or by the action of locally produced products of metabolism.