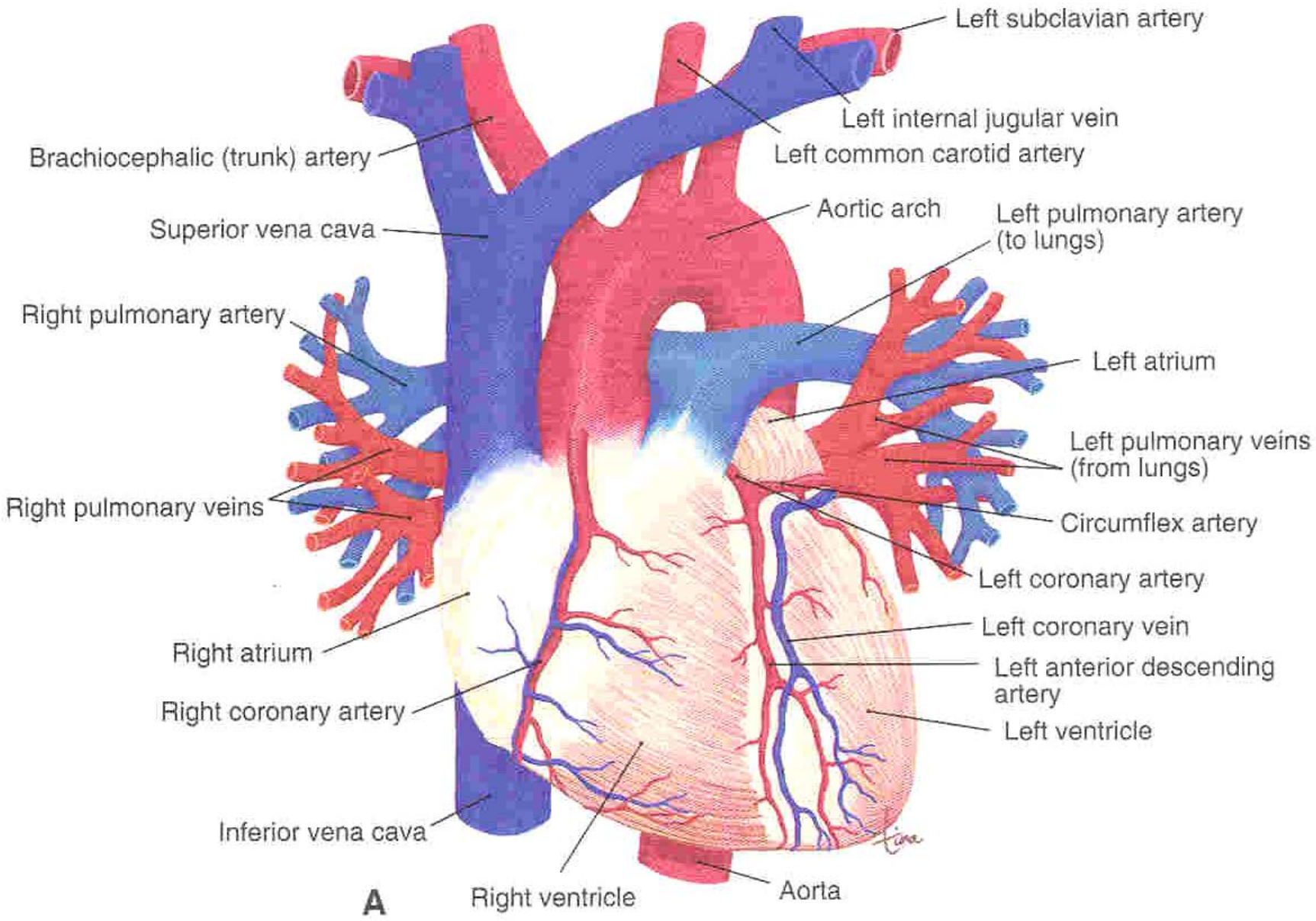
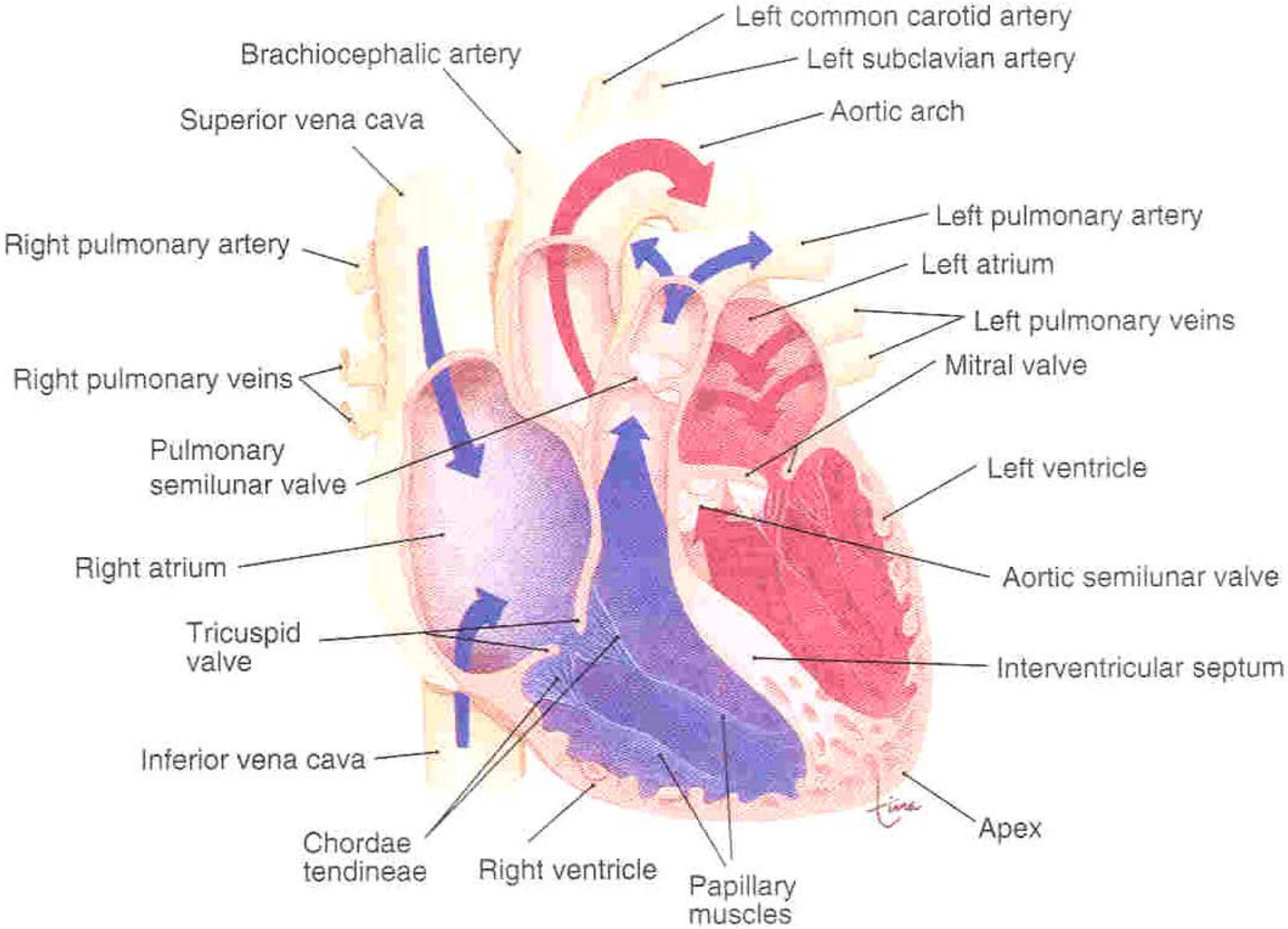
BME 5742 Bio-Systems Modeling and Control

Lecture 41
Heart & Blood Circulation
Heart Function Basics

Pumps

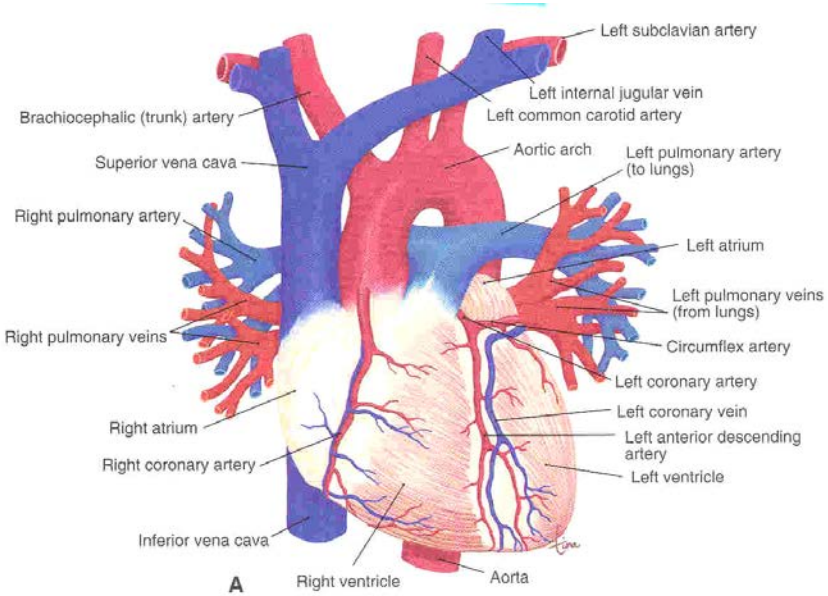
- A <u>pump</u> is a device that accepts fluid at a low pressure P_1 and outputs the fluid at a higher pressure $P_2>P_1$.
- A pump performs work on the fluid.
- Pump's power is the product of the flow Q by the pressure difference P_2-P_1.
- Different pumps have different characteristics $Q=f(P_1,P_2)$.


Left subclavian artery
Left internal jugular vein
Left common carotid artery
Brachiocephalic (trunk) artery
Aortic arch
Superior vena cava
Left pulmonary artery
(to lungs)
Right pulmonary artery
Left atrium
Left pulmonary veins
(from lungs)
Right pulmonary veins
Circumflex artery
Left coronary artery
Left coronary vein
Right atrium
Left anterior descending
artery
Right coronary artery
Left ventricle
Inferior vena cava
A
Right ventricle
Aorta


Left common carotid artery
Brachiocephalic artery
Left subclavian artery
Superior vena cava
Aortic arch
Left pulmonary artery
Right pulmonary artery
Left atrium
Left pulmonary veins
Right pulmonary veins
Mitral valve
Pulmonary
semilunar valve
Left ventricle
Right atrium
Aortic semilunar valve
Tricuspid
valve
Interventricular septum
Inferior vena cava
Apex
Chordae
tendineae
Right ventricle
Papillary
muscles

B

The Upper and Lower Chambers of the Heart



- The upper chambers of the heart are the <u>right and left atria</u>, which have relatively thin walls and are separated by a common wall (the <u>internal septum</u>).

The Upper and Lower Chambers of the Heart

- The upper chambers of the heart are the right and left atria, which have relatively thin walls and are separated by a common wall (the internal septum).
- The lower chambers of the heart are the right and left ventricles, which have thicker walls and are separated by the interventricular septum.
- Atria receive blood (from body or lungs) and ventricles pump blood to the body or the lungs.

The Right Atrium

- Two large veins return blood from the body to the right atrium.
- From the right atrium, blood flows through the right AV valve (also known as the tricuspid valve), into the right ventricle.
- The AV valve prevents backflow of blood from the right ventricle to the right atrium, when the right ventricle contract.

The Left Atrium

- The left atrium receives blood from the lungs, by way of four pulmonary veins.
- From the left atrium, blood flows through the left AV valve (also known as the bicuspid valve or the mitral valve), into the left ventricle.
- The mitral valve prevents backflow of blood from the left ventricle to the left atrium, when the left ventricle contract.

Another function of the atria

- Production of a hormone involved in blood pressure maintenance.
- When walls of the atria are stretched (by increased blood volume or pressure), the cells produce atrial natriuretic hormone (ANH).
- ANH decreases the re-absorption of sodium ions by the kidneys, so that more sodium ions are excreted in urine → Increase elimination of water → Blood volume is lowered → Blood pressure is lowered.

The Right Ventricle

- When the right ventricle contracts, the tricuspid valve closes, and the blood is pumped to the lungs through the pulmonary artery. There is a <u>pulmonary semilunar valve</u> in between.
- Valve's three flaps open up when ventricle contracts (flaps are kept from being inverted by special muscles in the ventricle). When ventricle relaxes, blood accumulating in the flaps cause the valve to close.

The Left Ventricle

- The walls of the left ventricle are thicker than those of the right ventricle, to allow the left ventricle to contract more forcefully.
- Left ventricle pumps blood to the body through the aorta (via the aortic valve).
- When left ventricle contracts, mitral valve is closed and aortic valve is open. When ventricle relaxes, aortic valve closes, and mitral valve opens up.

The Heart as a Two-sided Pump

- Heart is a double pump:
- Right side of the heart receives deoxygenated blood from the body and pumps it to the lungs to pick up oxygen and release CO_2.
- Left side receives oxygenated blood from the lungs and pumps it to the body.

Cardiac Cycle

- Both pumps work simultaneously:
  Both atria contract together, followed (a fraction of a second later) by the contraction of both ventricles.
- Systole: Contraction.
- Diastole: Relaxation.
- Cardiac cycle is a precise sequence of events that keep blood flowing from the veins, through the heart, and into the arteries.

Typical Cardiac Cycle (assuming a pulse rate of 75 beats/minute) -1

- Blood is constantly flowing from the veins into both atria.
- As more blood accumulates, its pressure forces open the left and right AV valves.
- 2/3 of the atrial blood flows passively into the ventricles.
- Atria contract (for about 0.1 s) to pump the rest of the atrial blood into the ventricles.

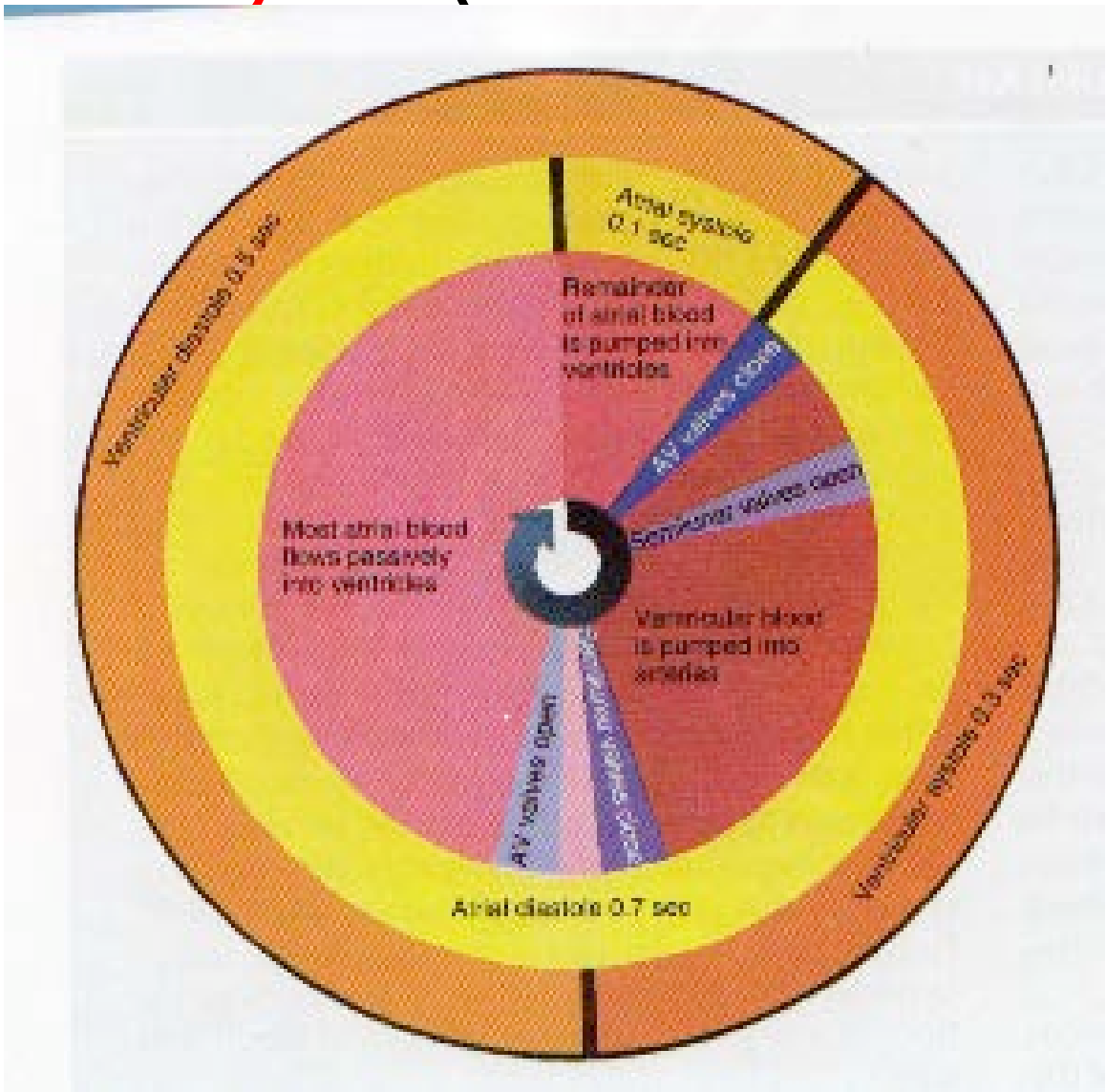
Typical Cardiac Cycle (assuming a pulse rate of 75 beats/minute) -2

- Atrial diastole (relaxation) and Ventricular systole (contraction) begin. Immediately next:
- AV valves close.
- Shortly after (less than 0.1s), the outflow valves open.
- Ventricular systole lasts about 0.3s, pumping 60-70% of ventricles blood to the arteries, and then outflow valves close.
- Very shortly after, AV valves open, and ventricular diastole begins.

Typical Cardiac Cycle (assuming a pulse rate of 75 beats/minute) -3

- Atria diastole lasts about 0.7s and then atria contract.
- All in all, ventricular diastole lasts 0.5s (it ends at the end of atria's systole, which as we mentioned earlier, is 0.1s after atria diastole ends).
- Total period (for heart beat of 75) is 0.8s (0.1s atria systole + 0.7s atria diastole; 0.3s ventricles systole + 0.5s ventricles diastole).

Summary Diagram of the Cardiac Cycle (from Scanlon & Sanders)



Outer circle: ventricles

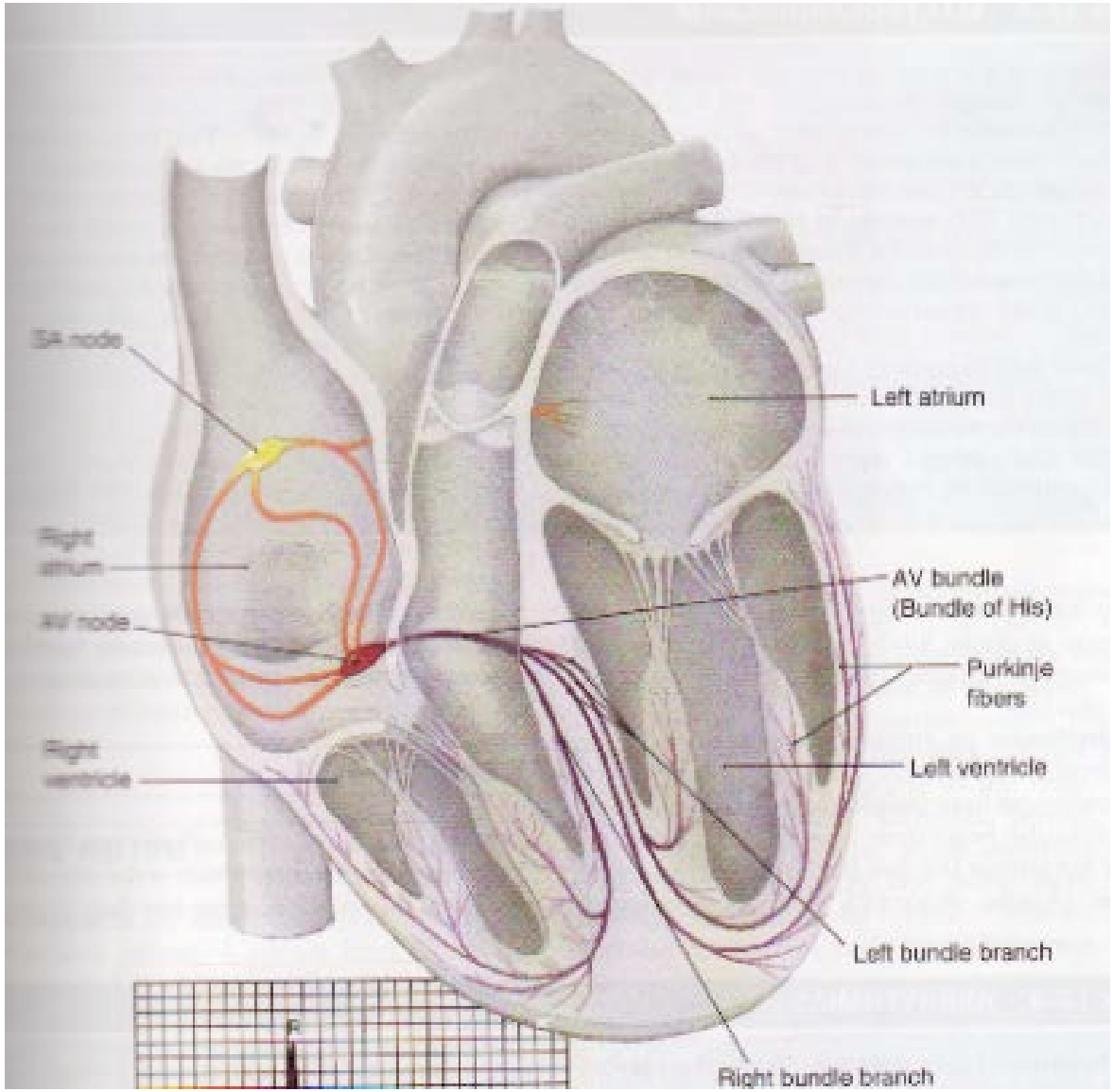
Mid-circle: atria

Inner circle: blood movement & effect on valves

Cardiac Conduction Pathway

- The cardiac cycle is a sequence of mechanical events that is regulated by the electrical activity of the myocardium.
- Cardiac muscle cells have the ability to contract spontaneously (that is, nerve impulses are not required to cause contraction).
- The heart generates its own beat → Electrical impulses follow a very specific route throughout the myocardium.

Cardiac Conduction Pathway



The SA Node

- The natural pacemaker of the heart is the sinoatrial node (SA).
- SA is a specialized group of cardiac muscle cells located in the wall of the right atrium.
- The SA node has the most rapid rate of contraction.
- As will be studied in detail regarding our textbook's Chapter 3, this is associated with Na^+ channels.

The SA Node

- SA cells depolarize more rapidly than other myocardium cells.
- Depolarization is the rapid entry of Na^+ ions, and reversal of charges on either side of the cell membrane.
- Cells of SA node are more permeable to Na^+ ions.

The AV Node

- From the SA node, impulses for contraction travel to the atrioventricular node (AV).
- It is located in the lower inter-atrial septum.
- The transmission of impulses from the SA node to the AV node and to the rest of the atrial myocardium brings about the atrial systole.

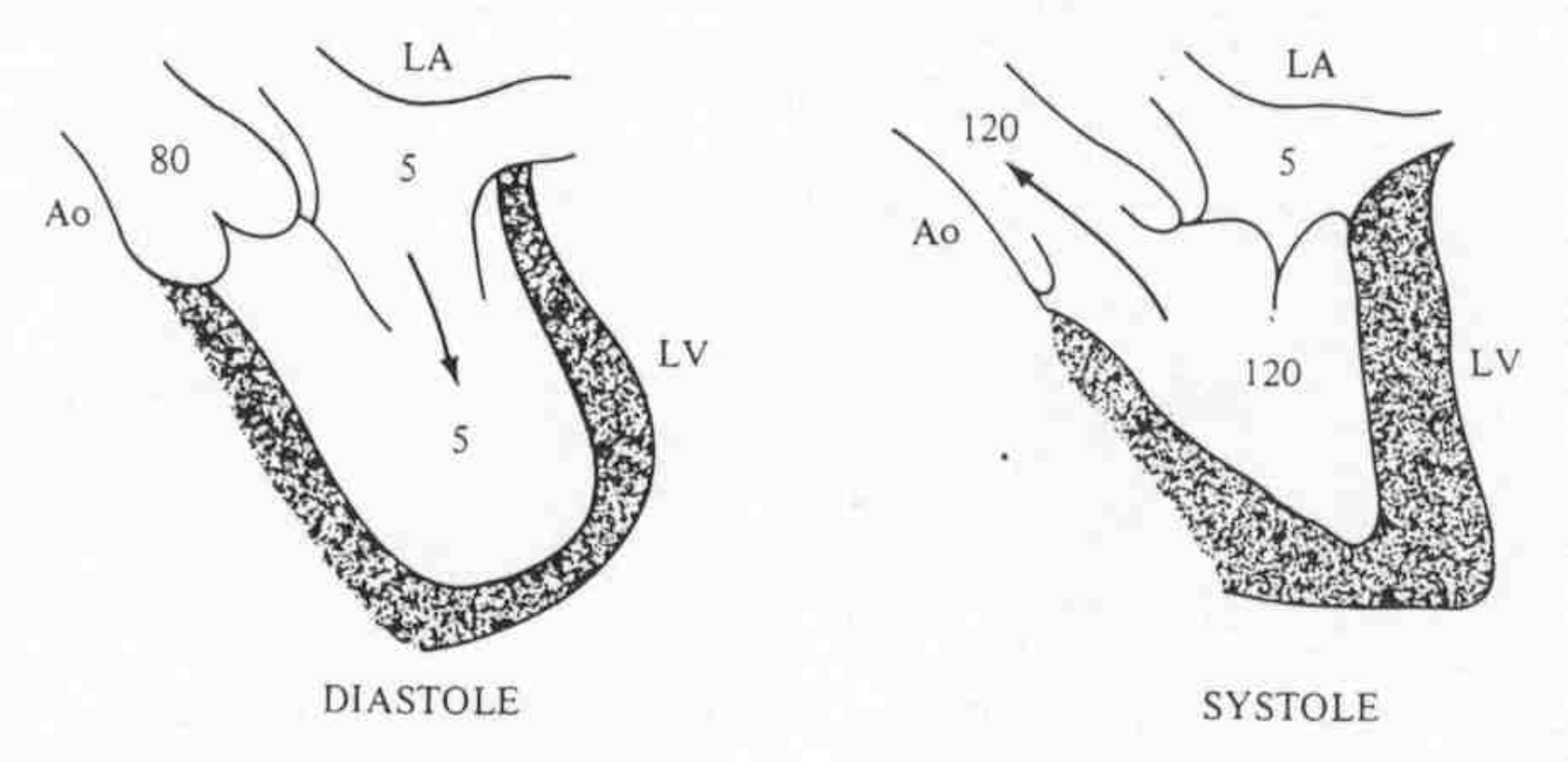
Ventricular Systole

- Within the upper inter-ventricular septum is the bundle of His (AV bundle), which receives impulses from the AV node and transmits them to the right and left bundle branches.
- From the bundle branches impulses travel along Purkinje fibers to the rest of the ventricular myocardium → Ventricular systole.

Heart Beat generation scenarios

- If SA node does not function → AV node takes over but at a slower rate (50-60 bpm).
- Bundle of His is also capable of generating the ventricles beat (at 15-40 bpm).
- Arrhythmias are caused by damage to parts of the conduction pathway, or by beats generated in places other than the SA node (palpitations, flutters, fibrillation).

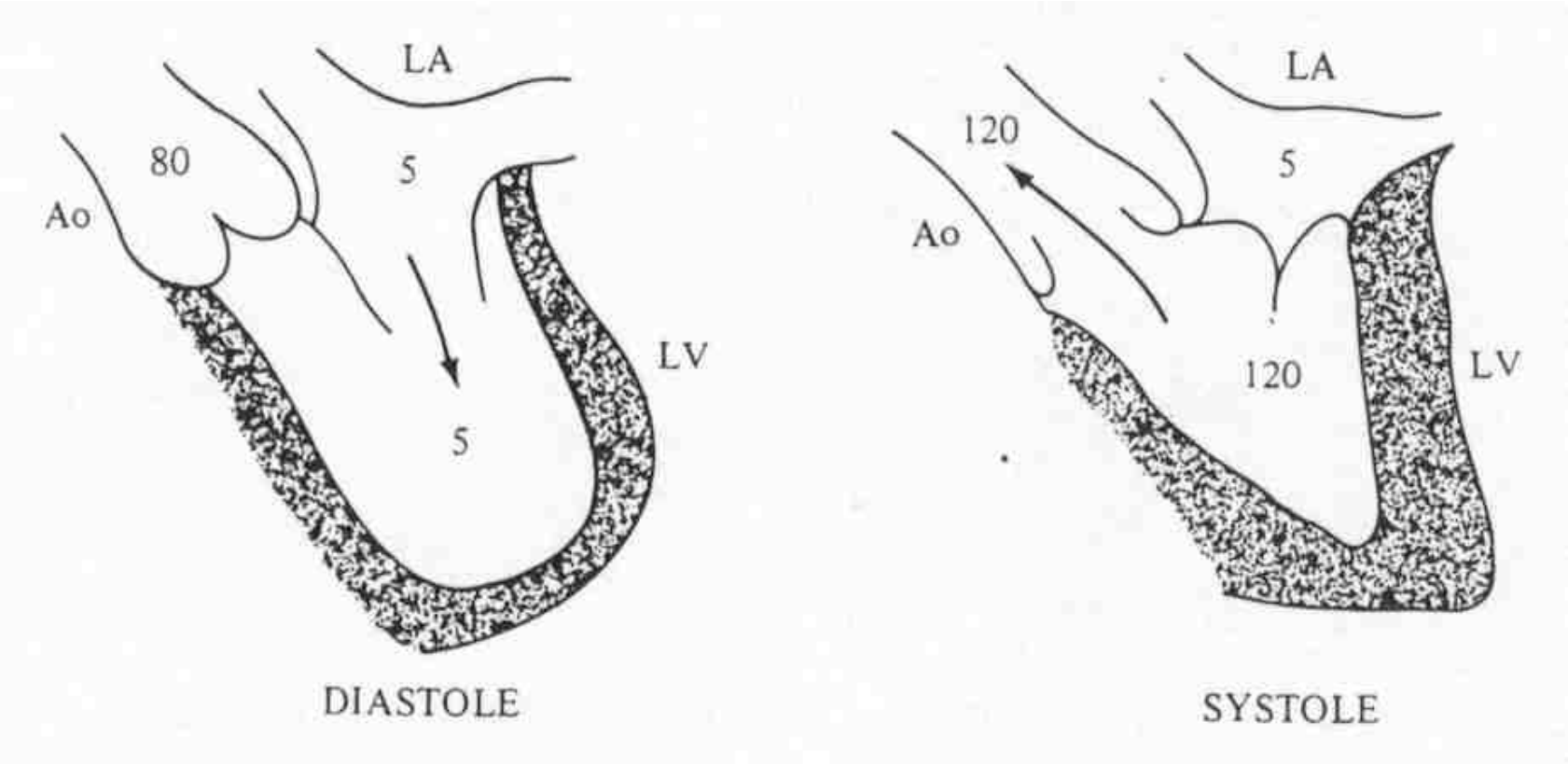
Cross section of the left side of the heart: (notation: LA=left atrium, LV=left ventricle, Ao = aorta)



Diastole: Ventricle relaxed

Systole: Ventricle contracts

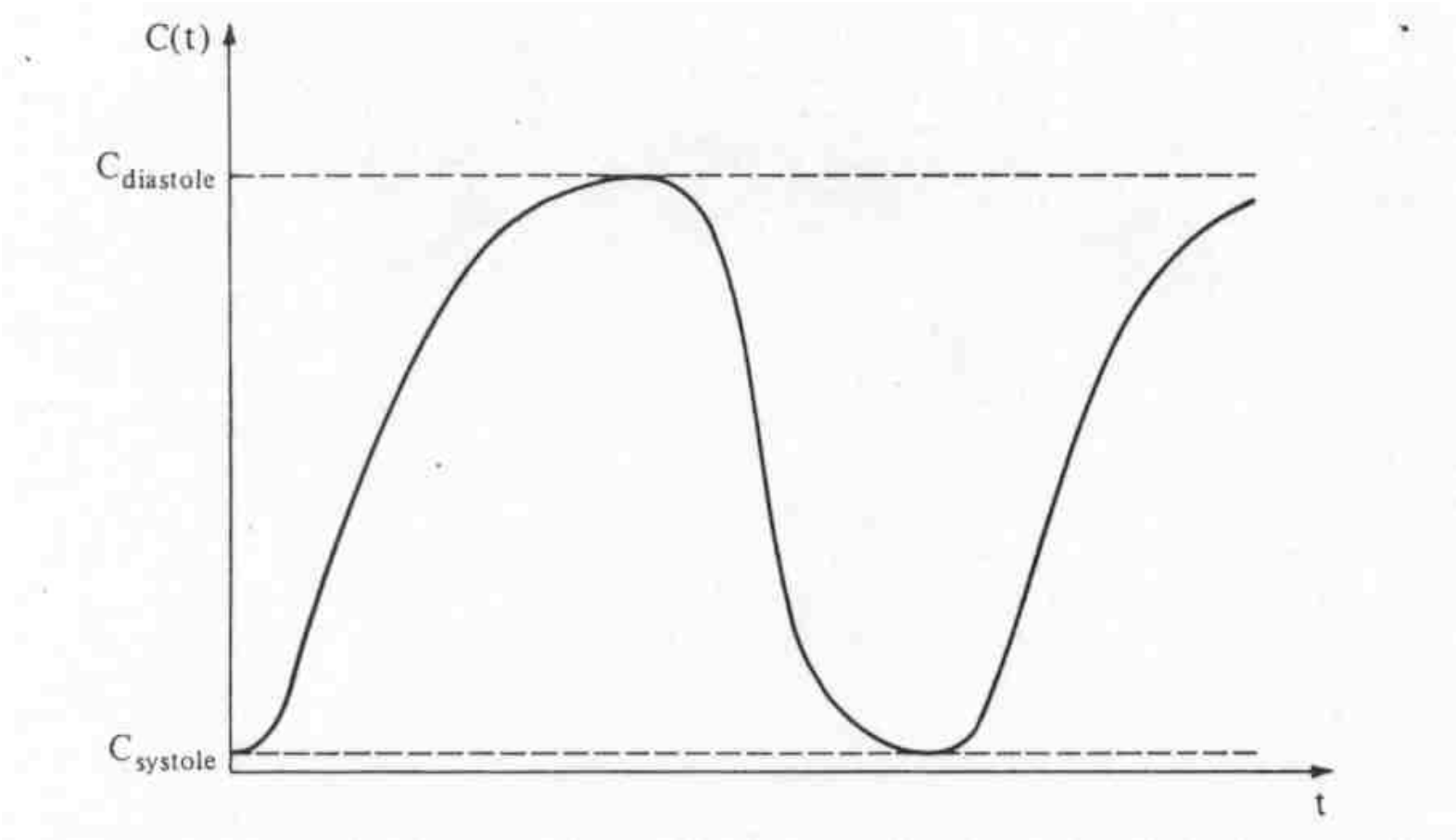
Pressures in the chambers are shown in [mmHg]



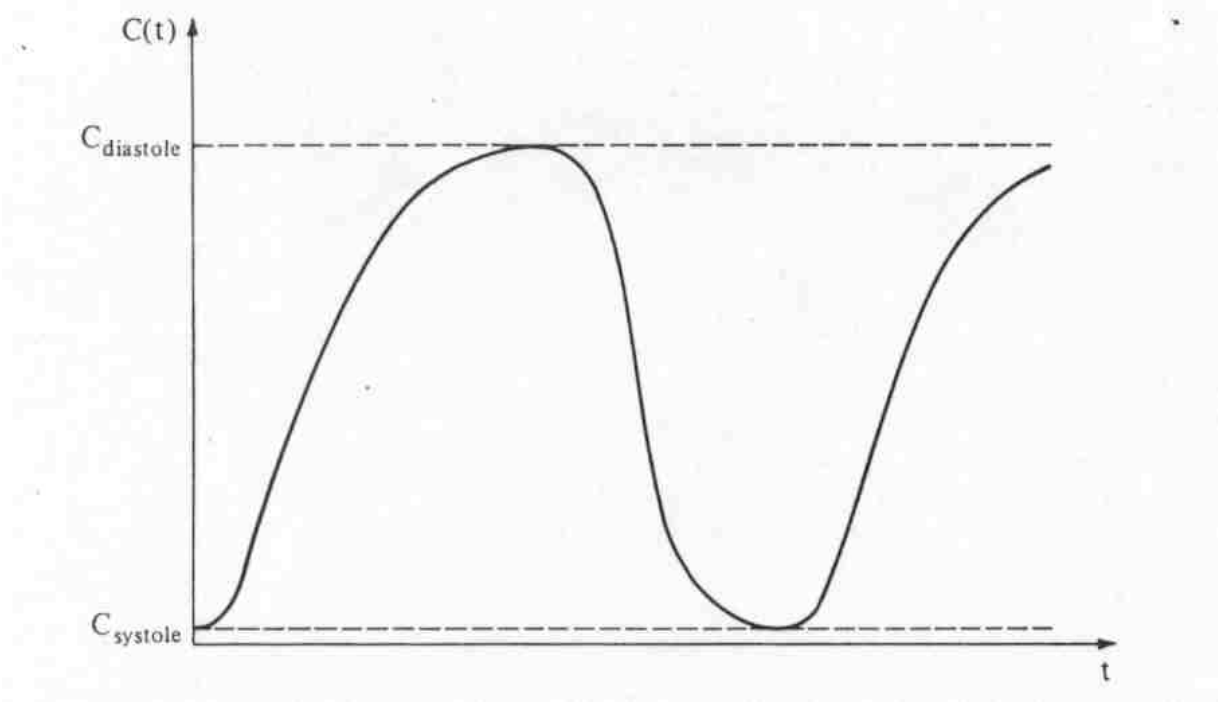
Diastole: Ventricle relaxed

Systole: Ventricle contracts

Model the ventricle as a compliance vessel, with a periodic time behavior of the compliance C

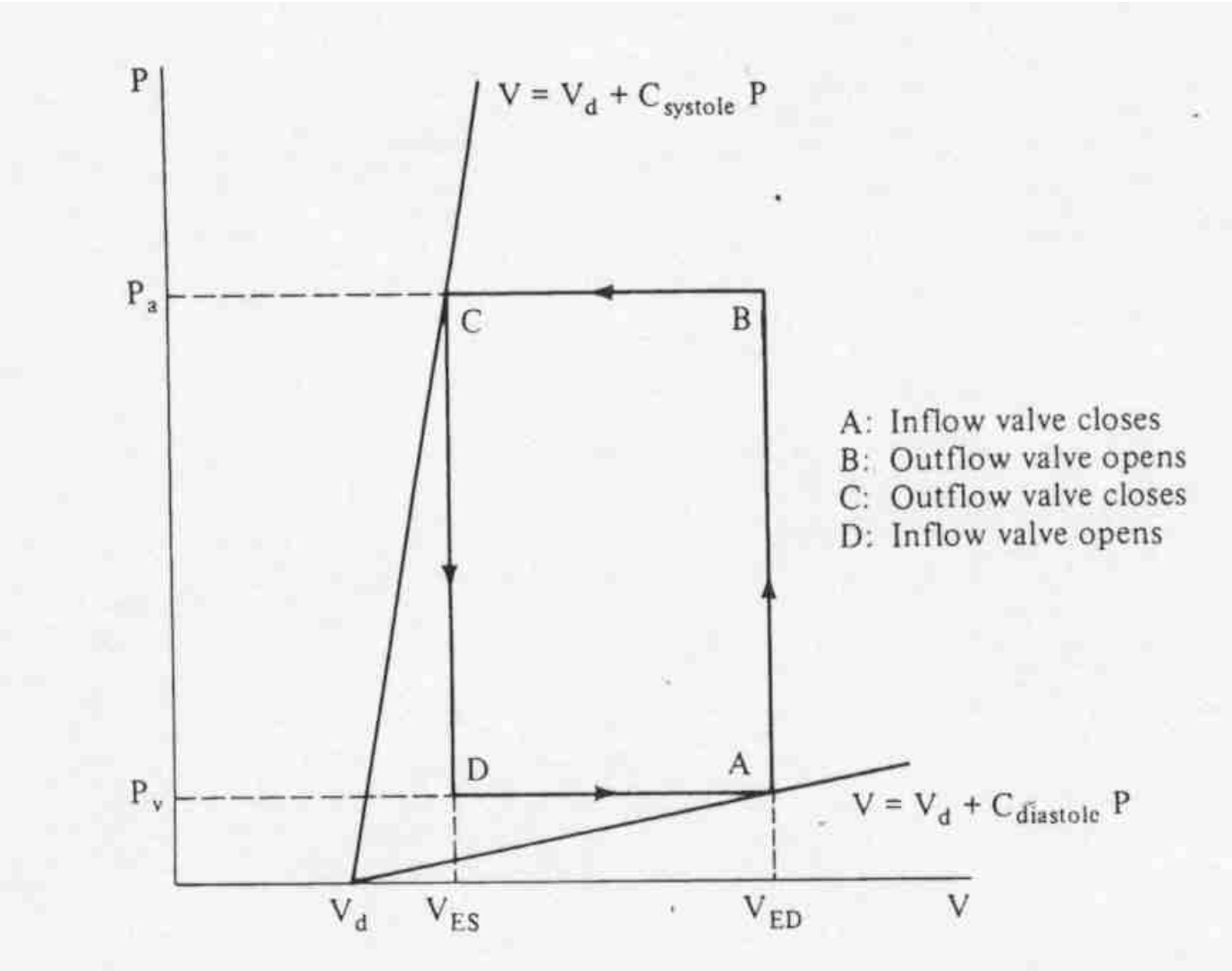


Ventricle Compliance



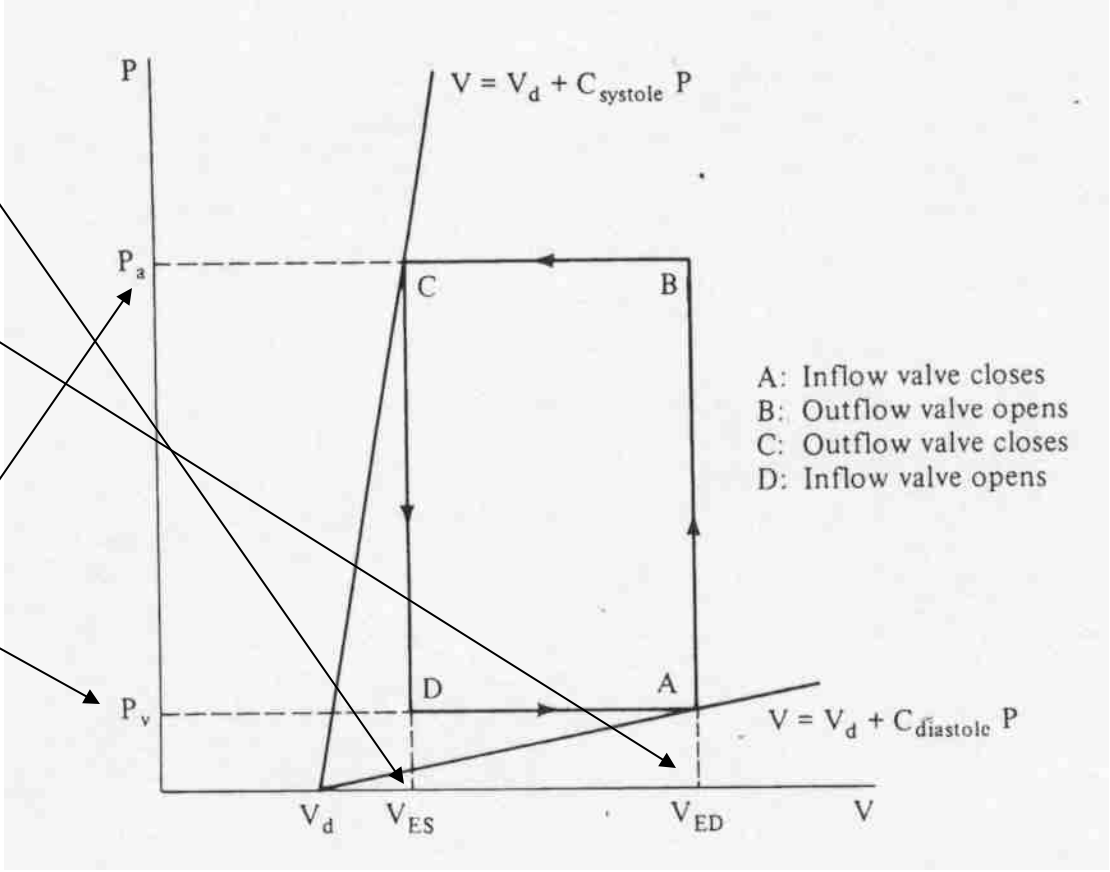
- $V(t)=V_d+C(t)P(t)$, where V_d is the “dead volume” and $P(t)$ is the pressure at the ventricle.
- Compliance is very small at systole and much larger at diastole.

Pressure-Volume Diagram of the Cardiac Cycle



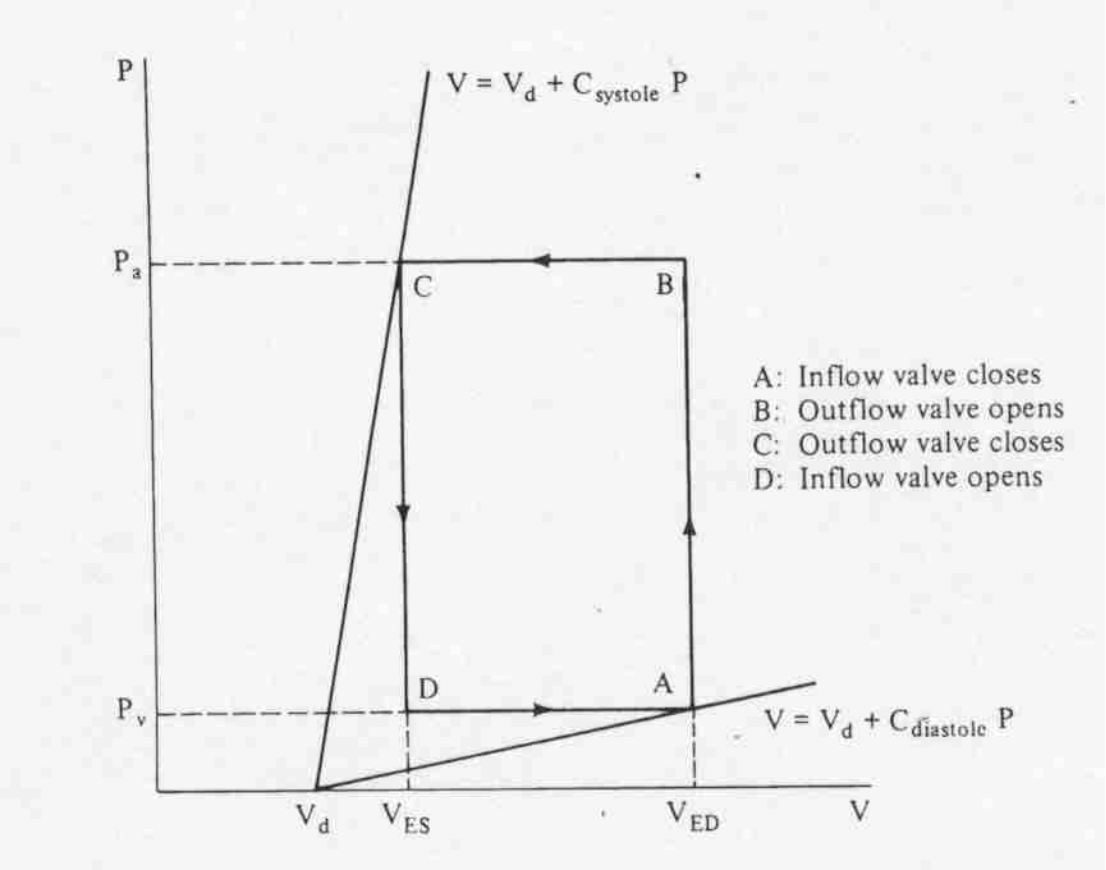
Pressure-Volume Diagram of the Cardiac Cycle Explained - Notation

- V_{ES}=end-systolic volume
  V_{ED}=end-diastolic volume.
- P_v=Venous (atrial) pressure (inflow)
  P_a=arterial pressure (outflow)



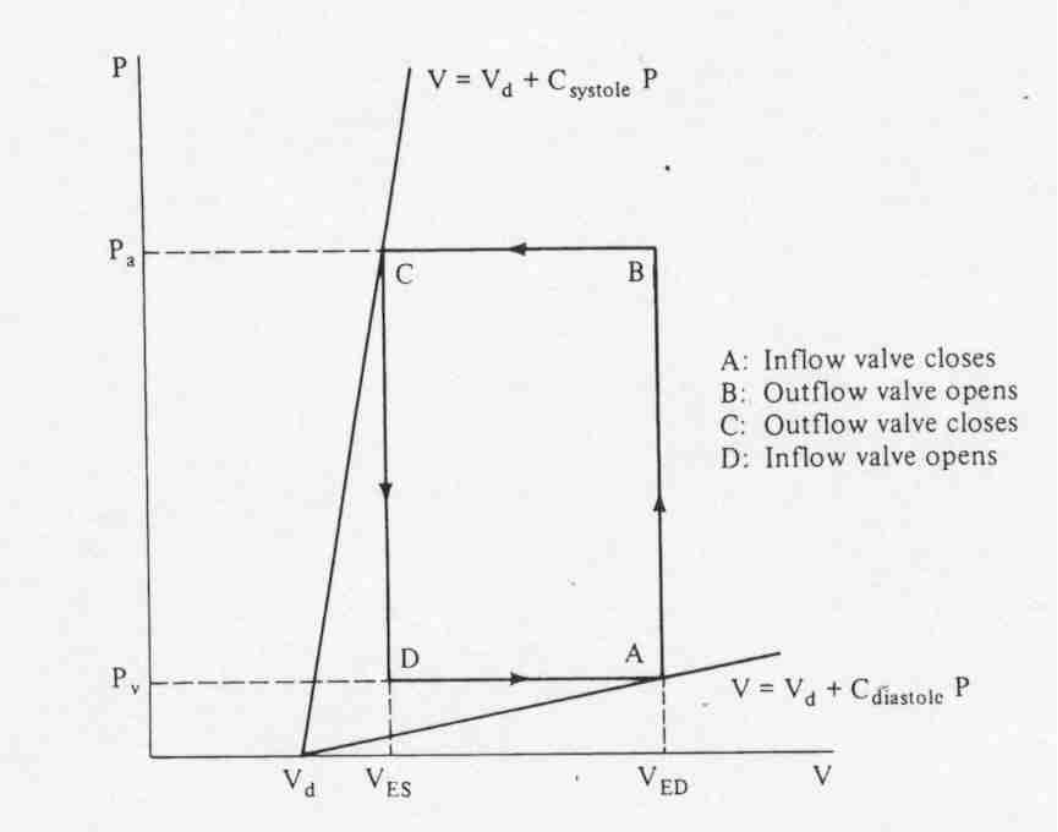
Pressure-Volume Diagram of the Cardiac Cycle: Iso-volumetric Contraction and Relaxation (AB and CD)

- On the vertical branches (AB, CD): Both valves are closed.
- Chamber volume is constant.
- Rapid change of pressure due to contraction & relaxation



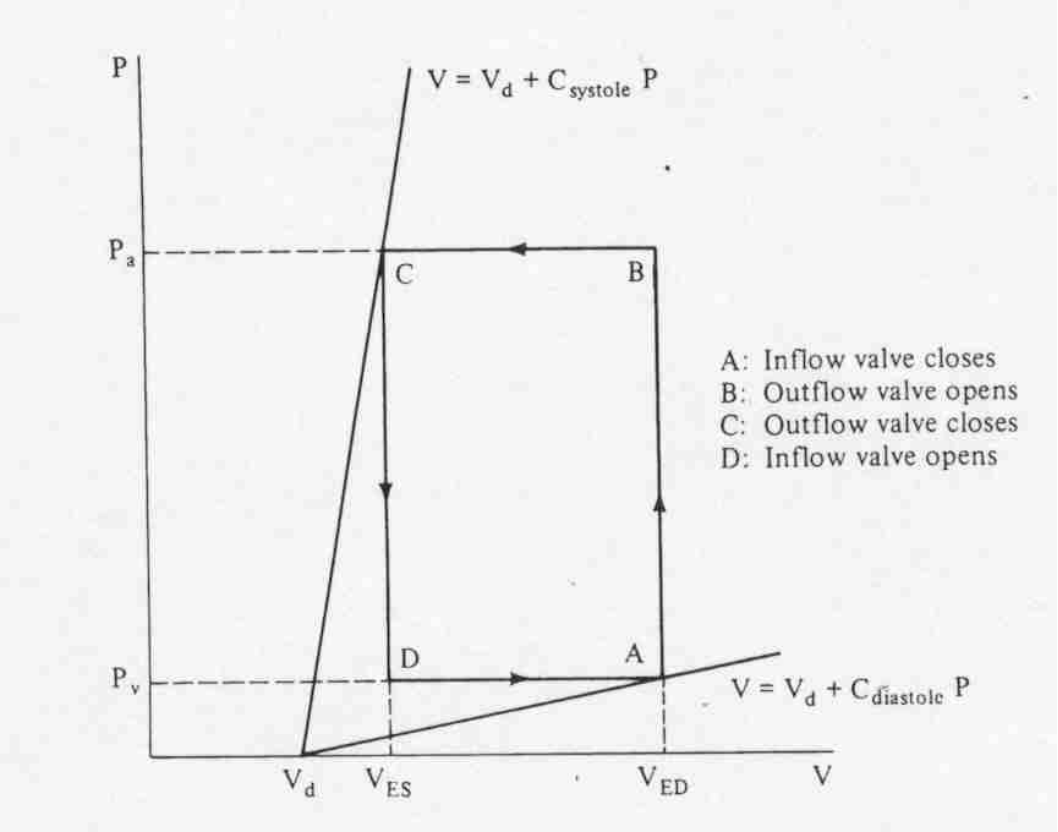
Pressure-Volume Diagram of the Cardiac Cycle: Inflow and Outflow (DA and BC)

- On the horizontal branches (DA, BC): One valve is open, other is closed.
- Chamber pressure is constant.
- Change of volume due to inflow & outflow.

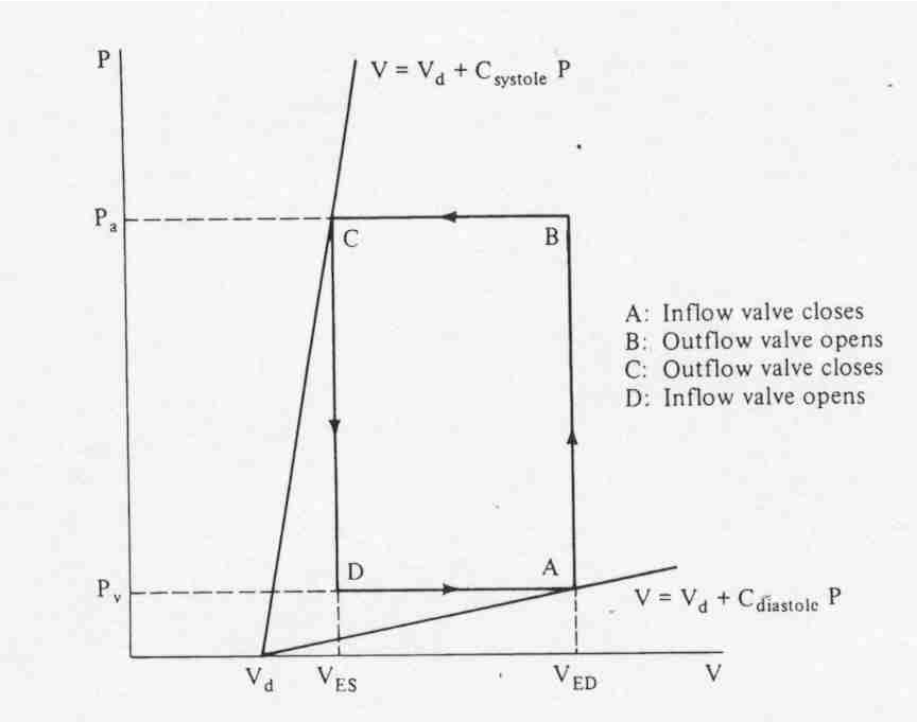


Pressure-Volume Diagram of the Cardiac Cycle: Filling (DA) and Ejection (BC)

- DA: Inflow valve is open (right AV or Mitral).
- BC: Outflow valve is open (Pulmonary or Aortic).



Pressure-Volume Diagram of the Cardiac Cycle: Maximum and Minimum Volumes



- Maximum volume: $V_{ED}=V_d+C_{diastole}P_v$
- Minimum volume: $V_{ES}=V_d+C_{systole}P_a$

Stroke Volume and Cardiac Output

- Maximum volume: $V_{ED}=V_d+C_{diastole}P_v$
- Minimum volume: $V_{ES}=V_d+C_{systole}P_a$
- Stroke Volume: $V_{stroke} = V_{ED} - V_{ES} =$
  $= C_{diastole}P_v - C_{systole}P_a \approx C_{diastole}P_v$
  assuming that $C_{systole}$ is very small.
- Let F be the heart rate [beats/minute], then:
- Cardiac Output = $Q = FV_{stroke} \approx FC_{diastole}P_v$

Heart's "Pump Coefficients"

- Cardiac Output = $Q = FV_{stroke} \approx FC_{diastole}P_v$
- $Q \approx KP_v$ where $K=FC_{diastole}$ is the pump coefficient.
- Let K_R,K_L be the right and left heart pump coefficients.
- $C_{diastole}$ of the thin-walled right ventricle is larger than that of the left ventricle.
- Note: The two sides of the heart are connected to two different venous systems.

Left and Right Cardiac Outputs

- $Q_R \approx K_R P_{sv}$ where P_{sv} is the systemic venous pressure.
- $Q_L \approx K_L P_{pv}$ where P_{pv} is the pulmonary venous pressure.
- At steady-state both flows must be equal.
- While $K_R > K_L$ (because right ventricle wall is more compliant than that of left ventricle) we must have $P_{pv} > P_{sv}$ by the same ratio.
- We assume that both pressures are with respect to a reference pressure P_{thorax} (in the chest). Interestingly, P_{thorax} is actually slightly negative (compared to the atmospheric pressure).

Starling's Law

- The more the cardiac muscle fibers are stretched, the more forcefully they contract.
- During exercise → More blood returns to the heart (venous return) → cardiac muscles contract more → More blood is pumped → Stroke Volume increases → Pulse rate increases (by other mechanisms)