SPLASH Spring 2025
Introduction to Cardiac Anatomy and Physiology
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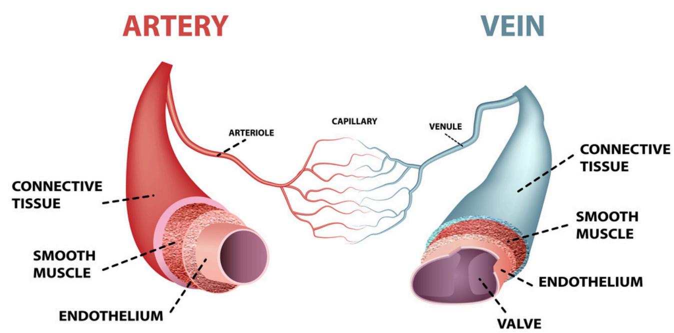
I. Cardiac Anatomy

A. Arteries vs. Veins

- Blood vessels throughout the body include veins, venules, arteries, arterioles, and capillaries.
- **Arteries** bring blood away from the heart, usually **oxygenated** blood as indicated with red.
- **Veins** bring blood towards the heart, usually **deoxygenated** blood as indicated with blue.
- **Arterioles** are smaller arteries, **venules** are smaller veins.
- **Capillaries** are the tiniest form of blood vessel that allow for cells of the body to take oxygen from the bloodstream.

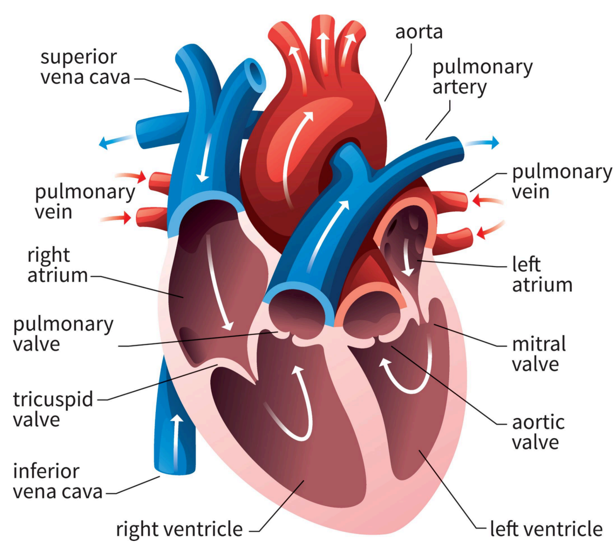


B. Atria, Ventricles, and Valves

- The heart consists of four chambers: two upper chambers called **atria** (right and left) and two lower chambers called **ventricles** (right and left).
- A wall of muscle called the **septum** separates the left and right sides of the heart.
- Control of blood flow is achieved through the opening and closing of several **valves**.

C. Circulation Inside the Heart

- Deoxygenated blood enters the heart from the **superior and inferior vena cava** into the **right atrium**.
- After enough blood has been collected in the right atrium, the **tricuspid valve** opens and allows blood into the **right ventricle** (a process we will discuss later).
- Deoxygenated blood leaves the right ventricle through the **pulmonary valve** and into the **pulmonary artery**, entering the lungs to be oxygenated.
- Oxygenated blood returns to the heart through the **pulmonary veins** into the **left atrium**.



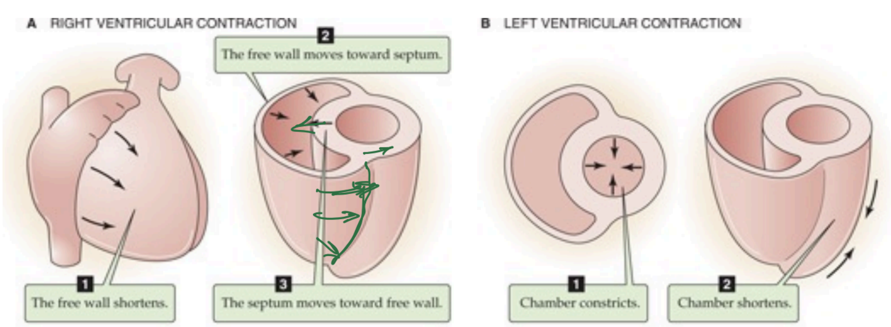
- Oxygenated blood enters the **left ventricle** through the **mitral valve**.
- Blood is then pumped to the rest of the body by the **contraction** of the left ventricle, allowing blood through the **aortic valve** and into the **aorta**, where the oxygenated blood can enter **systemic circulation**.
    - Systemic Circulation = Whole Body Blood Circulation

II. The Heart as a Pump

A. Why is the Heart Important?

Main Idea: The Heart is responsible for pumping blood throughout the body.

Why is Blood Important? Blood carries oxygen towards the various organ systems in the body.



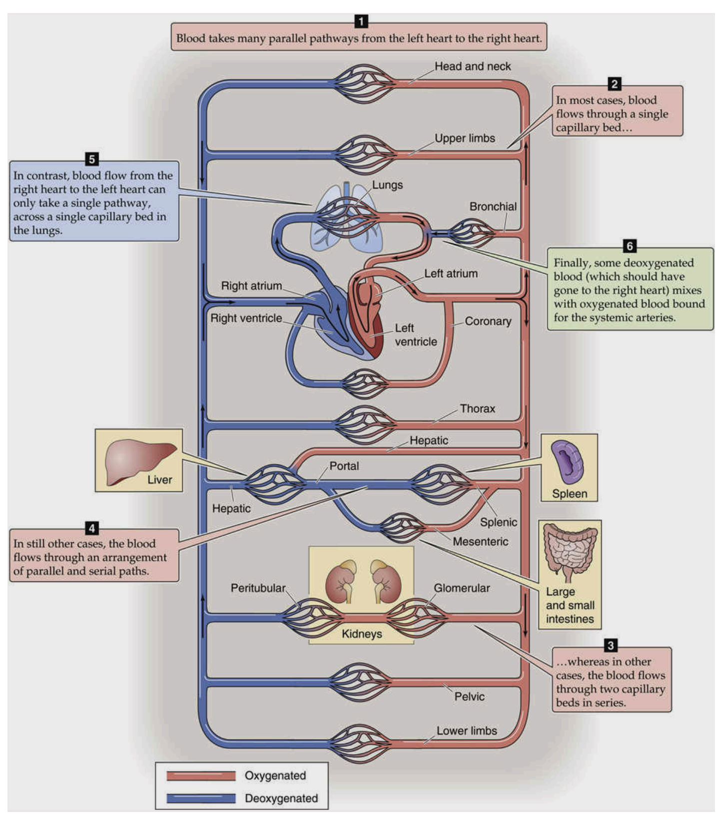
On average, the heart beats about 100,000 times per day, pumping approximately 2,000 gallons (7,571 liters) of blood.

The left ventricle is thicker than the right ventricle. **Why?**

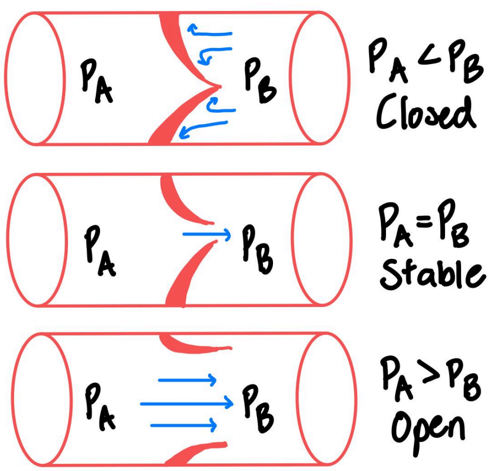
The **Digestive System** includes the Hepatic, Splenic, and Mesenteric arteries alongside the Portal and Hepatic Veins. Essential for detoxifying food and isolating only useful nutrients to enter the bloodstream.

The **Urinary System** has high circulating blood through the Glomerular and Peritubular capillary beds. Essential for filtering out toxins in the blood to be excreted in the urine.

The figure on the right showcases a simplified route of **systemic circulation**.



B. Cardiac Valves



- Each valve of the heart (Tricuspid, Pulmonary, Mitral, Aortic Valves) **ONLY** opens when there is a **greater pressure** of blood flow pushing it to open.

- The valve remains **closed** if the pressure beyond the valve is too great ($P_A<P_B$).

- There is minimal diffusion (**stable**) of blood if the pressure across the valve is equal ($P_A=P_B$).

- The valve is **open** if the pressure of blood flow before the valve is greater than the pressure after the valve ($P_A>P_B$).

- P_A is the pressure of the chamber before the valve.
- P_B is the pressure of the chamber after the valve.

- The purpose of cardiac valves is to prevent **retrograde flow** of blood in the heart. Without cardiac valves, there would be reduced cardiac efficiency as the heart will be unable to maintain **unidirectional flow**, and would have to work harder to compensate.

- This can lead to **cardiac hypertrophy, tachycardia, and heart failure** while also leading to lack of oxygen supply to the rest of the body as a result of lack of cardiac output.

III. The Cardiac Cycle

A. Cardiac Cycle

We discussed circulation in the heart in section **I. Cardiac Anatomy**, but we will dive deeper into the cycling that allows the heart to keep pumping blood automatically here and in section **V. Cardiac Electrophysiology.**

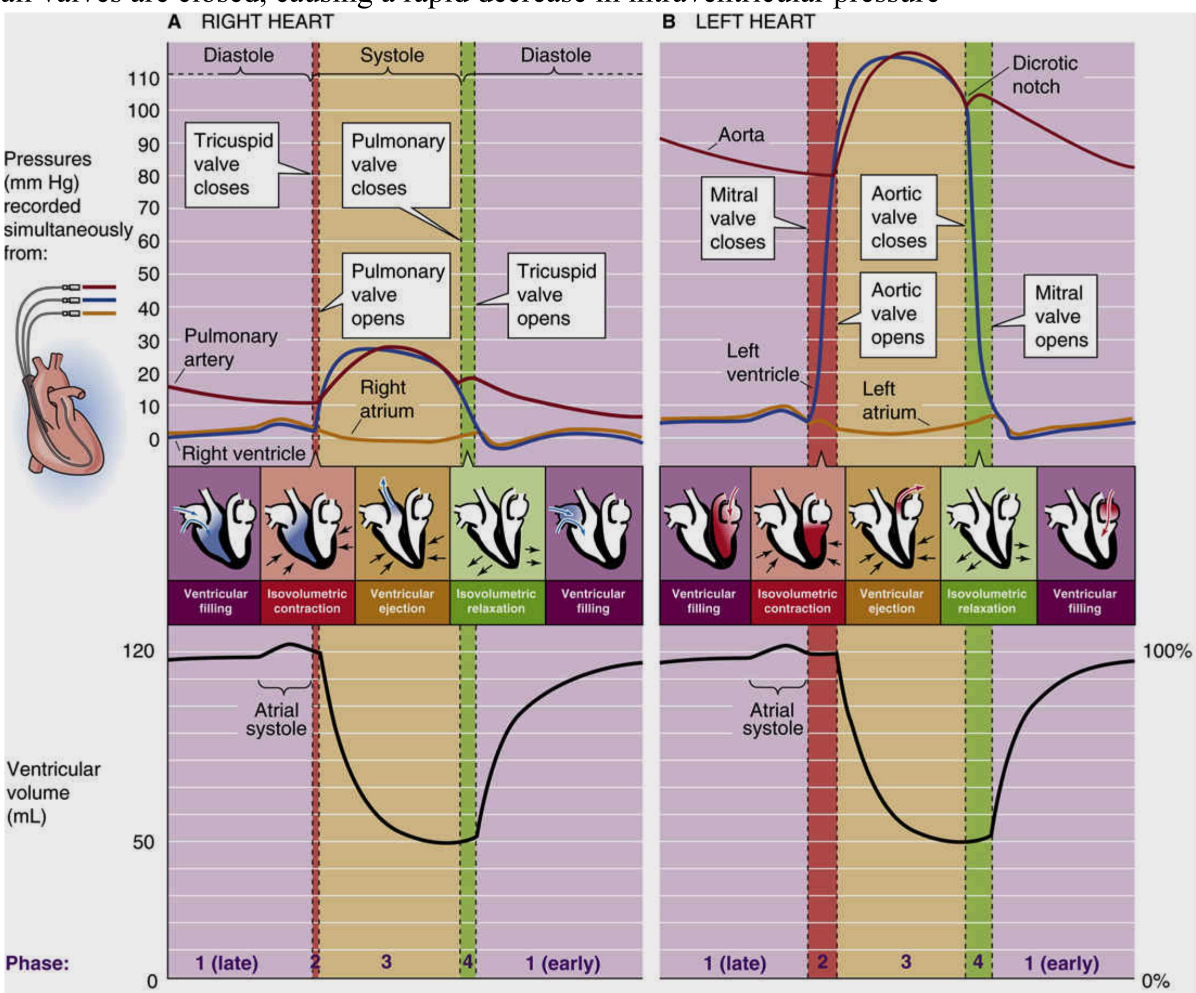
The opening and closing of the cardiac valves allows us to separate the stages of blood flow throughout the heart.

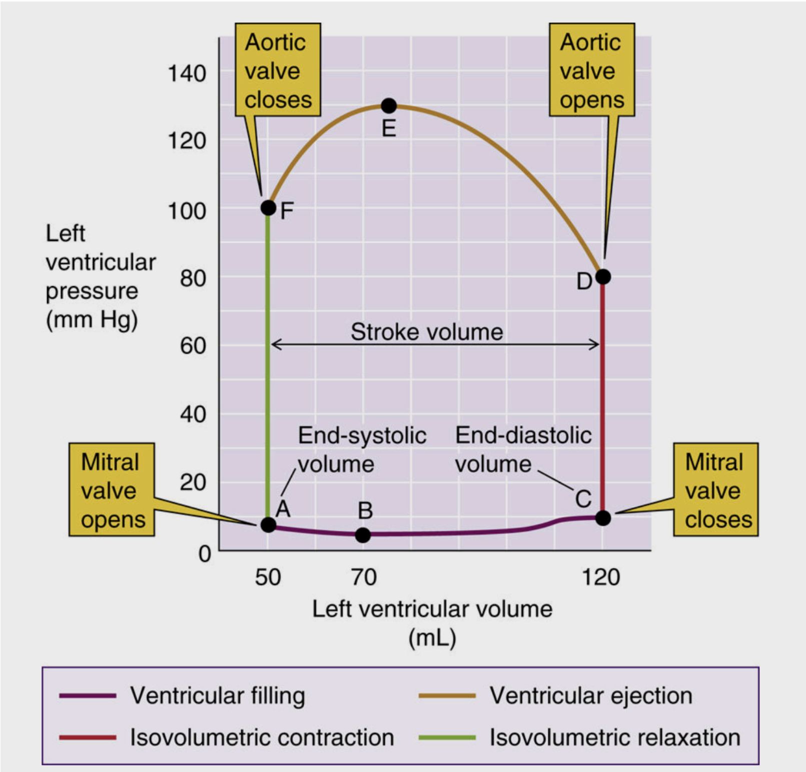
Ventricular Filling: The atrioventricular valves (tricuspid and mitral valves) open, allowing blood to flow from the atria into the ventricles. This phase begins with rapid passive filling, followed by a small contribution from atrial contraction, which adds about 10% to the ventricular volume

Isovolumetric Contraction: Occurs when all heart valves are closed, and the ventricles contract without changing volume. During this brief phase, ventricular pressure rises sharply as the myocardium *(myo = muscle, cardium = related to the heart)* contracts, preparing to overcome the pressure in the aorta and pulmonary artery. Recall the pressure requirement to open the valves.

Ventricular Ejection: Ventricular ejection begins when the semilunar valves (pulmonary and aortic valves) open as ventricular pressure exceeds atrial pressure. Blood is rapidly ejected from the ventricles into the aorta and pulmonary artery, with the rate of ejection decreasing towards the end of this phase

Isometric Relaxation: Isovolumetric relaxation starts when the semilunar valves close due to falling ventricular pressure. During this phase, the ventricles relax without changing volume, as all valves are closed, causing a rapid decrease in intraventricular pressure





Diastolic pressure measures Ventricular Filling and Isometric Relaxation.

Systolic pressure measures Isovolumetric Contraction and Ventricular Ejection.

- When the doctor takes blood pressure, the Systolic/Diastolic blood pressure is what is measured, with the first number indicating the force of how much blood is pushed out of the heart, and the second number indicating the force of blood as the heart relaxes and refills. A blood pressure of 120/80 mmHg (Systolic/Diastolic) is considered normal.

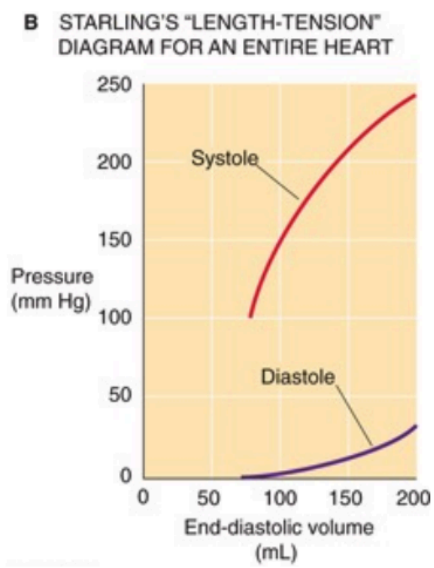
The **stroke volume** (i.e. amount of blood entering systemic circulation) is the difference of volumes between Isovolumetric contraction and Isometric Relaxation.

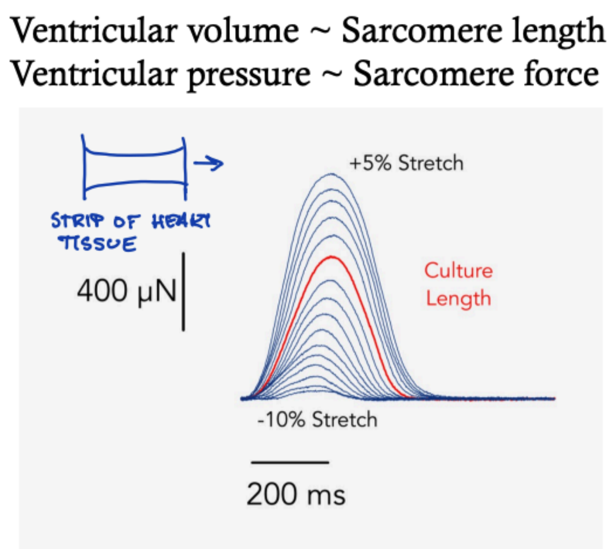
B. Comparison of Left and Right Ventricles

- Looking at the previous graph, there are two graphs representing the Right Heart (Right Atrium and Ventricle) compared to the Left Heart (Left Atrium and Ventricle).
- Looking at pressure readings, the **left heart** exerts **more pressure** in order to push blood into systemic circulation in isometric contraction and ventricular ejection.
- The **right heart** only has to pump blood towards **pulmonary circulation** in order for deoxygenated blood to be converted to oxygenated blood.
- The left atrium has a **thicker myocardial wall** and operates at higher pressure compared to the right atrium, and the left ventricle has a **much thicker myocardial wall** and a **near-conical shape** compared to the right ventricle. Recall Section IIA The Heart as a Pump.
- While the amount of blood volume **ENTERING** the heart is the same as the amount of volume **LEAVING** the heart, the left ventricle still plays an important role in directing blood through systemic circulation. That is why blood pressure can be measured at the arm, and pulse can be measured at the wrist.

C. Regulation of Cardiac Contractility (Frank-Starling Law)

- The **myocardium** (muscle of the heart) is made up of fibers called **sarcomeres**, and its elastic properties allows the heart to stretch and contract to pump blood.
- The **Frank-Starling Law of the Heart** describes a fundamental mechanism by which the heart adjusts its cardiac output in response to changes in blood volume. This intrinsic property of cardiac muscle allows the heart to match cardiac ejection with ventricular filling on a beat-to-beat basis.
- Physiologists **Otto Frank** and **Ernest Starling** found that by mechanically stretching the sarcomeres of the heart, the fibers of the heart increased its power of contraction.
- The reverse is true, where **low stretch** of the myocardial fibers will lead to **lower stroke volume and cardiac output.**





Why is this Important?

- This mechanism allows the heart to accommodate changes in venous return (amount of deoxygenated blood entering the heart) without relying on external regulation, maintaining balance.

<u>Case Study</u>
A 68-year-old woman is brought to the emergency department following a severe car accident. She has sustained significant blood loss from a deep laceration in her thigh, estimated at approximately 1.5 liters. The bleeding has been controlled, but her vital signs show hypotension with a blood pressure of 93/52 mmHg. The emergency physician decides to administer intravenous fluids to improve her hemodynamic status before further measures can be provided.

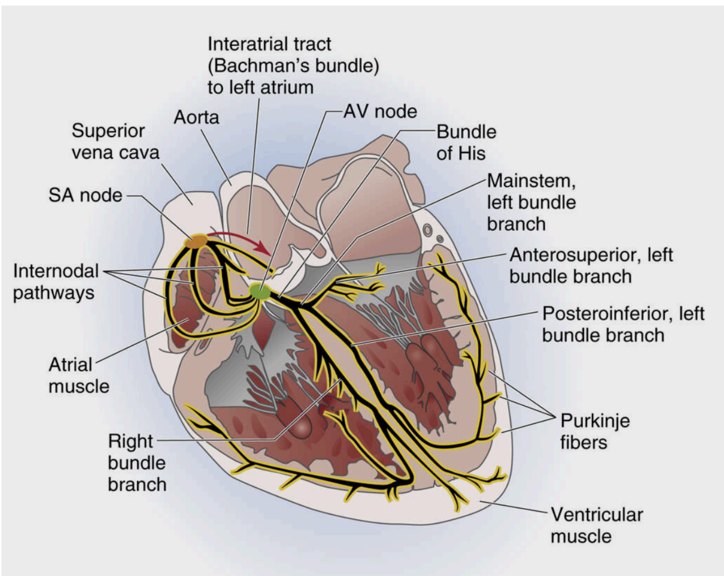
Question: How does the Frank-Starling mechanism explain the rationale for administering intravenous fluids to this patient?

Answer: *Administering IV fluids will increase venous return to the heart (more volume returning to the heart), leading to greater myocardial stretch. This will activate the Frank-Starling mechanism, leading to greater stroke volume and cardiac output, resulting in improved blood pressure to a stable ~120/80 mmHg.*

IV. Introduction to Cardiac Electrophysiology

A. How Electrical Signals Relay in the Heart

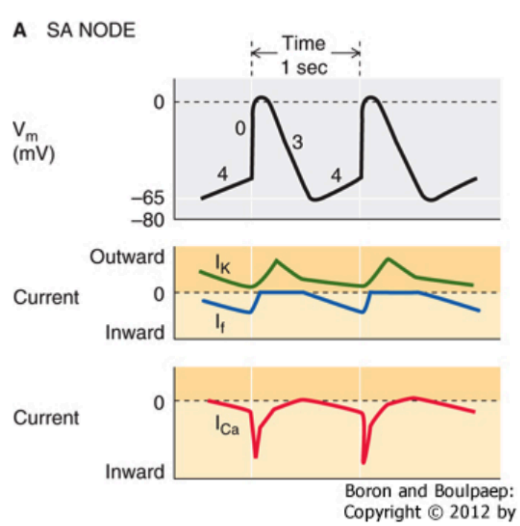
- The **Sinoatrial (SA) Node** is the heart's primary pacemaker. It is a special cardiac muscle cell that is capable of self-excitation, generating electrical impulses 60-100 times per minute in adults to initiate each heartbeat.



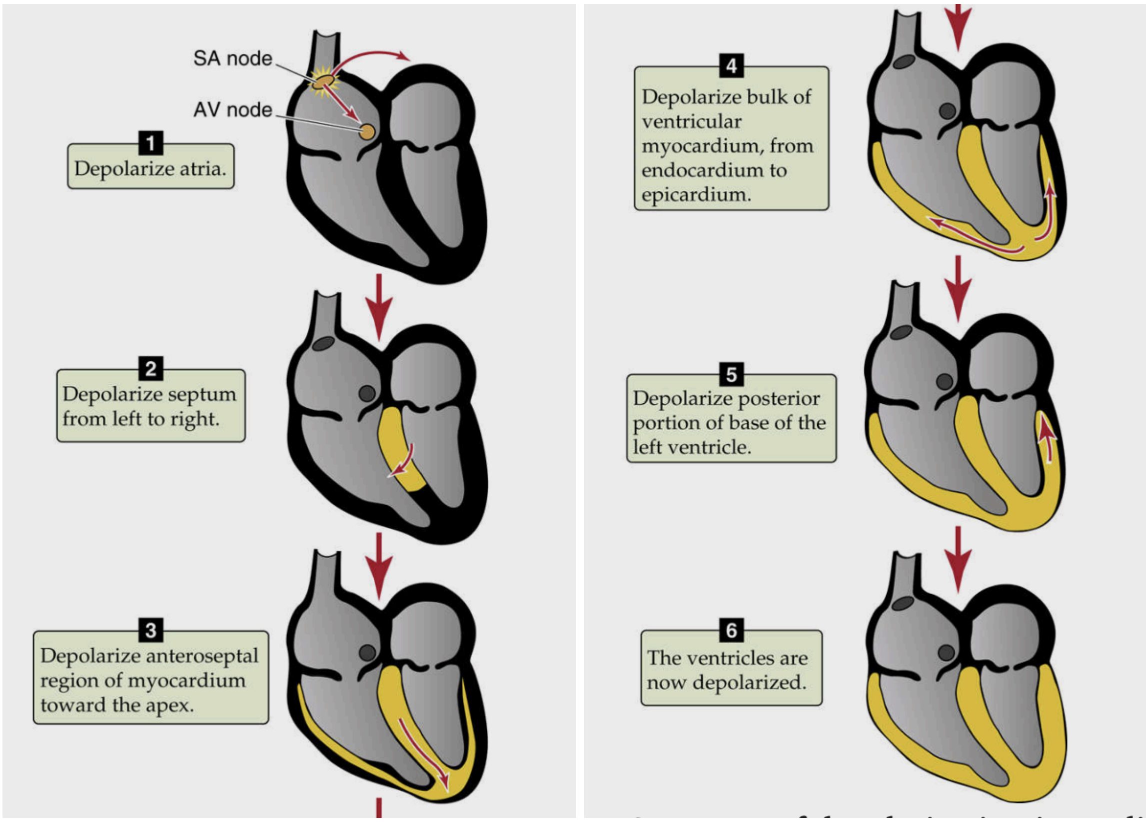
- The **Atrioventricular (AV) Node** is situated between the atria and ventricles, acting as a relay station between the SA node and the rest of the heart.
- The situation of the AV node at the intersection of the Atria and Ventricles allows the Atria to contract first before the ventricles. **Why is this important?**
- **General Flow of Signal:** Sinoatrial (SA) Node, Atrial Muscle, Atrioventricular (AV) Node, Bundle of His, Left/Right Bundle Branches, Purkinje Fibers, Ventricular Muscle

B. Pacemaking

- The SA Node's pacemaker cells have a self-generating current called the **Funny Current (I_f).**
- We won't dive deeper into the mechanism, but the Funny Current **self-depolarizes** (4) until a threshold is reached at ~55 mV, triggering the activation of another current, I_{Ca} (calcium channel).
- The activation of the $\mathbf{I_{Ca}}$ allows for **rapid depolarization** (0) to send a signal to the rest of the heart. This activates the $\mathbf{I_K}$ (Potassium channel) to bring the current back to its normal state (3), restarting the cycle.



C. Depolarization of the Heart



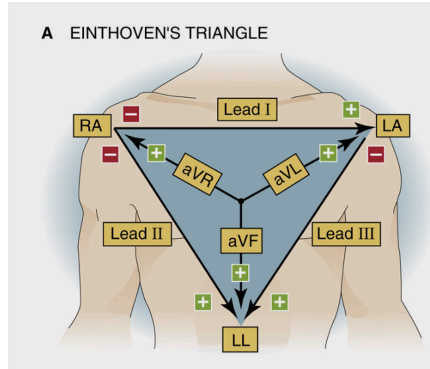
- The **SA Nod**e depolarizes the **atria** and signals to the **AV Node**.
- The **AV node** depolarizes the **septum** (between the left and right ventricles) from **left to right** through the **Bundle of His and Left/Right Bundle Branches.**
- Depolarization continues to the **anteroseptal region** (bottom of the septum) toward the **apex** (peak) of the heart.
- Depolarization of most of the **ventricular myocardium** from inside (endocardium) to outside (epicardium) through the **purkinje fibers**.
- The ventricles are now depolarized.

Note: After depolarization, which is from endocardium to epicardium, **the ventricles repolarizes the epicardium (outside) BEFORE the endocardium (inside).**

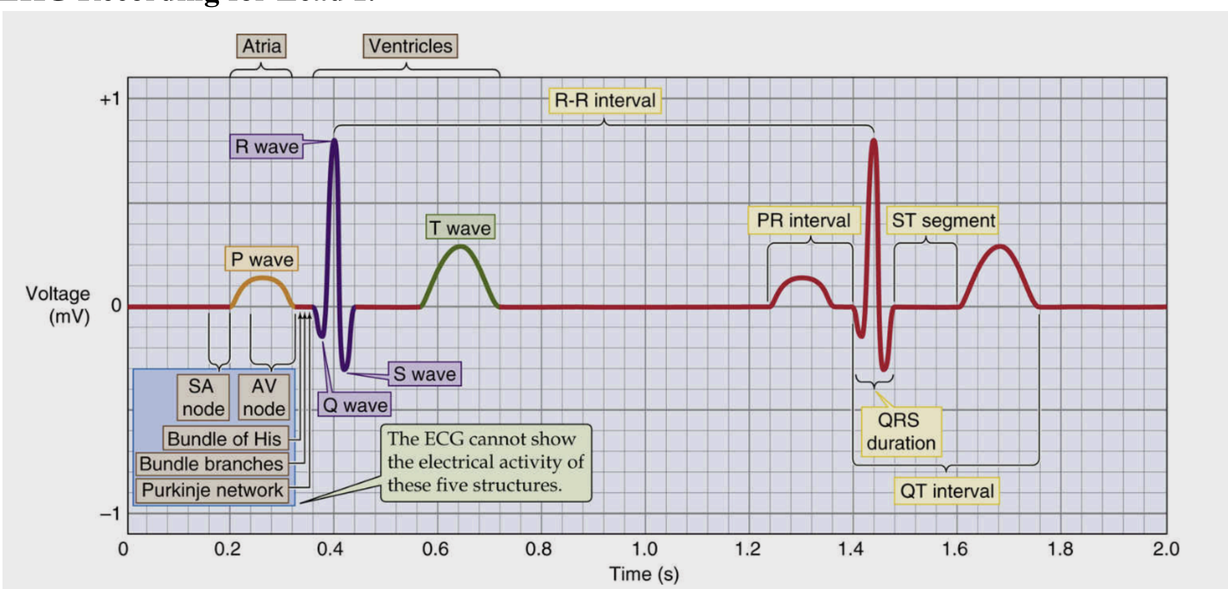
The depolarization of the heart can be tracked by an electrocardiogram (EKG), giving you the classic heartbeat monitor on the computer screens in a hospital room.

D. Electrocardiograms (ECG/EKG)

- An **electrocardiogram (EKG)** is a diagnostic test to evaluate the electrical activity of the heart. It allows physicians to assess the heart rhythm and rate, identify irregularities in the heartbeat, find signs of heart conditions and dangers to blood flow, and monitor heart health.
- An EKG is measured by placing a couple of electrodes on the right arm (RA), left arm (LA), and left leg (LL), allowing for the measurement of three distinct EKG graphs. Here, we are concerned with **Lead I**, which is from Right Arm to Left Arm.



EKG Recording for Lead I:

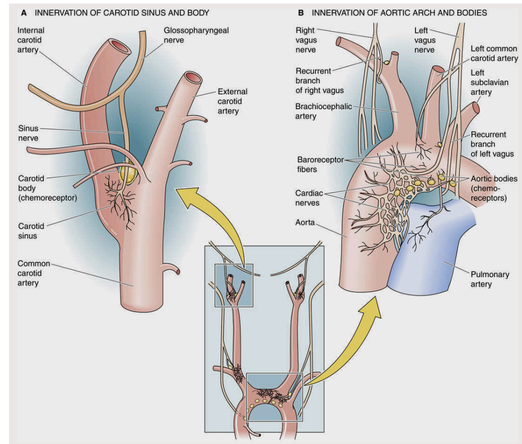


Refer to the previous section (C).

- **P Wave:** The initial depolarization of the atrium by the SA Node in the right direction.
- **Q Wave:** The depolarization of the septum from left to right.
- **R Wave:** The large R wave is due to the depolarization of the septum in the right direction.
- **S Wave:** Depolarization of the ventricular myocardium. Greater leftward depolarization of the right ventricle versus the upward depolarization of the left ventricle provides a negative voltage.
- **T Wave:** Full repolarization of the heart, from epicardium to endocardium.
    - (The T wave is positive due to the epicardium maintaining depolarization for a greater amount of time than the endocardium, but you should not need to know this).

VII. Regulation of Blood Pressure

A. Baroreceptor Reflex

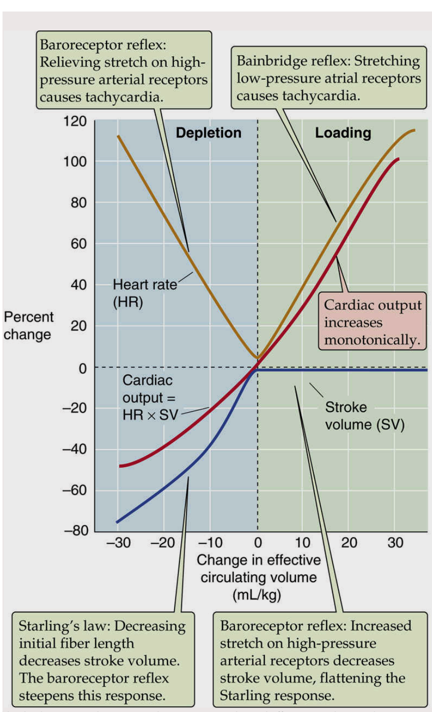


- The **Baroreceptor Reflex** is a mechanism that stabilizes blood pressure by responding to changes in arterial pressure.
- **Baroreceptors** (Baro=related to pressure) are located in the carotid sinus and the aortic arch.
- Increased blood pressure **stretches** baroreceptors, increasing nerve signals to the brain and leading to **decreased heart rate**. This decreases blood pressure as a result.
- **GOAL**: Decrease heart rate when blood pressure is high.

B. Bainbridge Reflex

- The **Bainbridge Reflex** (discovered by Francis Arthur Bainbridge) is a mechanism that increases heart rate in response to increased blood volume to the right atrium.
- **Bainbridge receptors** are stretch receptors that are located in the walls of the right atrium and vena cava.
- **Increased blood volume** (and blood pressure) and venous return (i.e. blood returning to the right atrium) stretches these receptors, sending signals via the **vagus nerve** (one of the cranial nerves) to the medulla oblongata of the brain. This results in an **increased heart rate** to match the amount of blood returning to the heart.

C. Baroreceptor Reflex, Bainbridge Reflex, and Frank-Starling Effects on Cardiac Output



- Combining what you have learned about Baroreceptor Reflex, Bainbridge Reflex, and Frank-Starling law of the heart, you can now predict what happens when there are changes to circulating volume (i.e. blood volume).
- **Increasing blood volume** (through drinking more water or blood transfusion) will activate the **bainbridge reflex**, increasing cardiac output by increasing heart rate (tachycardia). However, the **baroreceptor reflex** will activate due to increased stretch, flattening the starling response.
- **Decreasing blood volume** (through severe blood loss) deactivates **Starling Forces**, decreasing stroke volume. Furthermore, deactivation of **baroreceptor** reflex due to low stretching of baroreceptors increases heart rate (tachycardia) but at the expense of lower stroke volume.

Case Studies

Case Study 1: Atrial Fibrillation

Scenario: A 72-year-old female presents to the emergency department complaining of palpitations and shortness of breath. An electrocardiogram (EKG) reveals an irregularly irregular rhythm with absent P waves.

Questions:

1. What is the significance of the absent P waves on the EKG in this scenario?
2. Explain how the atrial fibrillation (irregular depolarization of the atria) impacts ventricular filling and overall cardiac output.
3. If the patient's ventricular ejection rate is very high, how might this affect diastolic and systolic pressures?

Case Study 2: Aortic Valve Stenosis

Scenario: A 65-year-old male with a history of rheumatic fever presents with progressive shortness of breath and chest pain. Physical examination reveals a loud murmur during systole. Echocardiography confirms severe aortic valve stenosis (narrowing).

Questions:

1. Explain how aortic stenosis (narrowing of the aorta) affects the pressure difference between the left ventricle and the aorta during ventricular ejection.
2. How does the Frank-Starling mechanism initially compensate for the increased afterload (resistance the heart must pump against) caused by the stenosis?
3. Over time, what changes might occur in the left ventricle as a result of chronic aortic stenosis, and why?

Case Study 3: The Marathon Runner

Scenario: A 28-year-old male collapses shortly after finishing a marathon. He is conscious but weak and complains of dizziness. His heart rate is 180 bpm, and his blood pressure is 90/60 mmHg. He is sweating profusely.

Questions:

1. What immediate compensatory mechanisms are likely at play in this runner's body?
2. How does the Frank-Starling mechanism contribute to maintaining cardiac output during exercise?
3. Explain how both the Bainbridge and baroreceptor reflexes might be involved in his condition.