Electrical Activity of the Heart: Cardiac Action Potential & ECG Basics

The Heartbeat & Intrinsic Control

"Every heartbeat, or **cardiac cycle**, is a symphony of coordinated contractions and relaxations. The atria contract first (**atrial systole**), pushing blood into the ventricles. After a brief pause, the ventricles contract (**ventricular systole**), ejecting blood to the lungs and body. The iconic 'lub-dup' sounds arise from the closure of the **atrioventricular valves** (mitral and tricuspid) followed by the **semilunar valves** (aortic and pulmonary). These sounds are not just noise—they are vital clues to valve function and heart health."

"The heart's **automaticity** stems from its specialized conduction system:

- **SA Node (Sinoatrial Node)**: Nestled in the right atrium, this natural pacemaker fires impulses at ~75 beats/minute, setting the heart's rhythm.
- **AV Node (Atrioventricular Node)**: Acts as a gatekeeper, delaying the signal by 0.1 seconds to ensure the atria empty fully before ventricular contraction.
- **Bundle of His and Purkinje Fibers**: These high-speed pathways distribute the impulse across the ventricles, ensuring a synchronized, powerful squeeze. Without this delay and coordination, the heart's efficiency would plummet."

3. Cardiac Action Potential

*"Cardiac cells communicate via **action potentials**—electrical impulses that trigger contraction. However, not all cells behave the same:

- **Pacemaker Cells (SA/AV Nodes)**: These cells are **self-excitable**. Their membrane potential drifts upward due to 'funny currents' (If), primarily carried by sodium ions. Upon reaching threshold, calcium channels open, causing depolarization. This spontaneous activity makes the SA node the heart's conductor.
- **Contractile Cells (Atria/Ventricles)**: These cells remain stable at rest (-90mV) until stimulated. Their action potential includes a rapid **sodium influx** (Phase 0), a brief repolarization (Phase 1), a prolonged **calcium-mediated plateau** (Phase 2), and final repolarization (Phase 3). This plateau is critical—it prevents tetany and ensures adequate ejection time."

Phases of Ventricular Action Potential (Detailed Breakdown)
"Let's dissect the **5 phases** in contractile cells:

1. **Phase 4 (Resting Potential)**: Potassium dominates, maintaining -90mV.
2. **Phase 0 (Depolarization)**: Voltage-gated sodium channels open, causing a sharp upstroke.
3. **Phase 1 (Early Repolarization)**: Sodium channels close; potassium begins to exit.
4. **Phase 2 (Plateau)**: L-type calcium channels open, balancing potassium efflux. This unique phase distinguishes cardiac from skeletal muscle.
5. **Phase 3 (Repolarization)**: Calcium channels close; potassium efflux restores resting potential."*

4. ECG Basics & Interpretation 6 minutes)

*"The **electrocardiogram (ECG)** is a surface recording of the heart's electrical activity. Each wave corresponds to a specific event:

- **P Wave**: Atrial depolarization—a smooth upward deflection as impulses spread from the SA node.
- **QRS Complex**: Ventricular depolarization—a sharp spike due to the massive ventricular muscle mass. Notice how it dwarfs the P wave; the atria repolarize simultaneously but are masked.
- **T Wave**: Ventricular repolarization—a gentler wave as potassium exits the cells."*

Intervals & Segments (Clinical Significance)
*"Beyond waves, **intervals** and **segments** reveal conduction health:

- **PR Interval (0.12–0.20 sec)**: Measures atrial-to-ventricular conduction time. Prolongation suggests AV block.
- **ST Segment**: Should be flat; elevation indicates myocardial infarction (e.g., STEMI), while depression signals ischemia.
- **QT Interval**: Prolongation risks **torsades de pointes**, a lethal arrhythmia."*

Step-by-Step ECG Interpretation (Demonstration)
*"To analyze an ECG systematically:

1. **Rate**: Count QRS complexes in a 6-second strip (30 large squares) × 10. Normal: 60–100 bpm.
2. **Rhythm**: Are P-P and R-R intervals regular? Irregularity may indicate atrial fibrillation.
3. **P Waves**: Is there one before every QRS? Are they uniform? Absent P waves suggest nodal rhythms.
4. **QRS Width**: Narrow (<0.12 sec) implies normal conduction; wide suggests bundle branch block.
5. **ST/T Changes**: Elevation/depression or inverted T waves demand immediate attention."*

5. ECG Abnormalities (3 minutes)

Visual: Case Comparisons (Normal vs. Atrial Fibrillation, STEMI, PVCs)
*"Let's diagnose common abnormalities:

- **Atrial Fibrillation**: Chaotic baseline with absent P waves and irregularly irregular QRS. Risk: Stroke due to stagnant blood.
- **ST-Elevation Myocardial Infarction (STEMI)**: ST segments rise like 'tombstones' in leads corresponding to the infarcted area (e.g., V1–V4 for anterior MI).
- **Premature Ventricular Complexes (PVCs)**: Wide, bizarre QRS without preceding P waves. Frequent PVCs may precede ventricular tachycardia."*

Clinical Pearl:
"A patient with **crushing chest pain and ST elevation** needs **immediate reperfusion**—every minute counts!"

Visual: Key Concepts Recap with Animated Heart & ECG

1. The **SA node** initiates impulses, while the **AV node and Purkinje system** ensure orderly conduction.
2. **Action potentials** differ between self-firing pacemaker cells and contractile cells with plateaus.
3. The **ECG** is a window into the heart's electrical activity—mastery of its waves and intervals is essential for detecting ischemia, infarction, and arrhythmias.
4. **Abnormalities like AFib and STEMI** require swift intervention."*