

Chapter 2: Basic Electrophysiology

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After this chapter you should be able to distinguish myocardial from pacemaker cells and name the four cell properties; trace the cardiac action potential through phases 0 to 4; separate the absolute from the relative refractory period; name the conduction pathway in order with the intrinsic rate of each site; measure time and voltage on ECG paper; identify every waveform, segment and interval with its normal value; and apply the Five-Question Method to any strip. **Reading:** Aehlert, *ECGs Made Easy*, 7th ed., Chapter 2 (p. 21 to 65).

Note to students: Rates and cutoffs in this guide follow **Aehlert, 7th edition**, because that is the edition this guide follows. Other references disagree on some numbers, and that is normal rather than a sign that someone is wrong. The intrinsic rate of the SA node is this chapter's clearest example: your textbook teaches **60 to 100**, while the electrophysiology literature reports that an SA node removed from the body and studied on its own fires at about **100 to 110**. Both are correct. The 60 to 100 figure is the in-vivo rate after resting vagal tone has already slowed the node down. Answer 60 to 100 when you are asked, and keep the other number, because it answers a question students ask constantly: if the SA node is 60 to 100, why does a marathon runner sit at 45? **What the last chapter gives you:** it gave you the chambers, the valves, the coronary arteries and the mechanical cardiac cycle. This chapter wires that heart for electricity. It is the chapter the other eight are built on, so read it twice rather than once.

At a Glance: this chapter in one box

Numbers you must know

- Paper speed **25 mm/s**; calibration **10 mm/mV**.
- Small box **1 mm** = **0.04 s** across, **0.1 mV** tall. Large box **5 mm** = **0.20 s** across, **0.5 mV** tall.
- 5 large boxes per second, 30 per six seconds, **300** per minute.
- P wave under **0.12 s**; PR **0.12 to 0.20 s** (3 to 5 small boxes); QRS **0.06 to 0.10 s** (under 3 small boxes), wide at **0.12 s or more**; QT **0.44 s or less**.
- Intrinsic rates: SA node **60 to 100**, AV junction **40 to 60**, ventricles **20 to 40**. Four numbers, stepping down in 20s: 100, 60, 40, 20.

The two rules the whole book is built on

- **The Five-Question Method.** Regular? Rate? P waves, one per QRS? PR? QRS width? In that order, on every strip, every time.
- **The deflection rule.** Depolarization moving *toward* a positive electrode writes **upward**; moving *away* writes **downward**; moving *perpendicular* writes little or nothing.

Top 3 traps

- Thinking ten wires means ten leads. Ten electrodes produce **twelve** leads.
- Using the 300 sequence on an irregular rhythm. It is valid only when the rhythm is regular.
- Reading a complex as a heartbeat. Depolarization is electrical, contraction is mechanical, and they are not the same event.

The Five-Question Method: Ask These, In This Order, On Every Strip

1. **Is it regular?** March out the R-R intervals with calipers or a paper edge.
2. **What is the rate?** 300 sequence if regular, 6-second method if irregular.
3. **Are there P waves, and is there one for every QRS?** One P, one QRS, in that order.
4. **What is the PR interval?** Measure it in seconds. Normal is 0.12 to 0.20.
5. **How wide is the QRS?** Measure it in seconds. Normal is 0.06 to 0.10.

These five questions, asked in this order, resolve **every rhythm in this book**; no rhythm in Chapters 3 through 8 needs a sixth. Write all five answers down *before* you name anything, including the strips you think you recognize on sight, because those are the ones you will misname.

The Deflection Rule

An ECG electrode does not see chambers or valves. It sees one thing: current moving through tissue, either coming at it or going away from it.

Depolarization moving *toward* a positive electrode writes an *upward* deflection. Moving *away* writes a *downward* deflection. Moving *perpendicular* writes little or nothing, often a small biphasic wiggle.

Everything else in this chapter hangs off that sentence, and two payoffs prove it immediately. **Payoff one: why aVR is normally inverted.** Its positive electrode sits at the right shoulder, and normal depolarization sweeps from the SA node down and to the left, directly away from it, so P, QRS and T are all normally negative there. An **upright** complex in aVR is the abnormal finding, usually a swapped pair of arm electrodes.

Payoff two: why R waves grow across the chest. Ventricular depolarization travels mostly leftward and posteriorly, away from V1 (right of the sternum) and toward V6 (left midaxillary line). Apply the rule: V1 is mostly negative (small r, deep S), complexes grow progressively more upright leftward, and V6 is a tall R. That is **R wave progression**, transition normally at **V3 or V4**. You did not memorize six lead appearances; you applied one rule six times.

Two Kinds of Cardiac Cell

Myocardial (working) cells are the contractile muscle, and shortening is what moves blood. They hold three properties: **excitability** (they respond to a stimulus), **conductivity** (they pass it to the neighbor), and **contractility** (they squeeze). **Pacemaker (electrical) cells** are specialized conduction tissue, and they add a fourth, **automaticity**, the ability to fire with no outside stimulus at all, which is why a heart removed from the body keeps beating.

Memory hook: working cells **do** the work, pacemaker cells **call** the work. Only pacemaker cells have all four.

The Cardiac Action Potential

A resting cell is **polarized**, negative inside relative to outside at roughly -90 mV in working myocardium. **Depolarization** is the loss of that difference and is the electrical event the ECG records; **repolarization** is the recovery back to rest.

Phase	What happens	Ion movement
0	Rapid depolarization, the upstroke	Fast sodium channels open, Na^+ rushes in
1	Early rapid repolarization	Sodium channels close, brief K^+ out
2	Plateau , the long flat shoulder near 0 mV	Ca^{2+} in balanced against K^+ out
3	Rapid repolarization back toward rest	K^+ out

Phase	What happens	Ion movement
4	Resting membrane potential	Sodium-potassium pump restores the gradient

The plateau is the point of the whole diagram. Skeletal muscle has no phase 2, which is why a bicep can hold a sustained contraction. Cardiac muscle cannot be re-fired mid-beat and so cannot tetanize, and a heart that could tetanize would seize instead of pump. The calcium entering during phase 2 is also what triggers contraction, so phase 2 is where the electrical event hands off to the mechanical one.

Common Trap

Two statements about the action potential appear on nearly every online summary. Which is wrong: “the plateau sits near +50 mV,” or “phase 4 is the resting phase”?

The first is simply wrong. Several widely-shared sites publish +50 mV; the plateau sits near **0 mV**, and memorizing +50 will make you misread every diagram you are shown.

The second is a subtler trap: true, but only for **working myocardium**. In **pacemaker cells** phase 4 is not rest. It is a slow spontaneous drift upward from about -60 mV toward threshold, and when the drift arrives the cell fires without anyone asking it to. **That drift is automaticity.** Pacemaker cells also run phase 0 on **calcium** rather than sodium, which is why their upstroke and conduction are slower. Learn one action potential and assume it applies everywhere and you cannot explain automaticity at all. Steeper drift, faster rate; flatter drift, slower rate; that single mechanism sits behind sinus bradycardia, sinus tachycardia and every escape rhythm in this book.

Refractory Periods

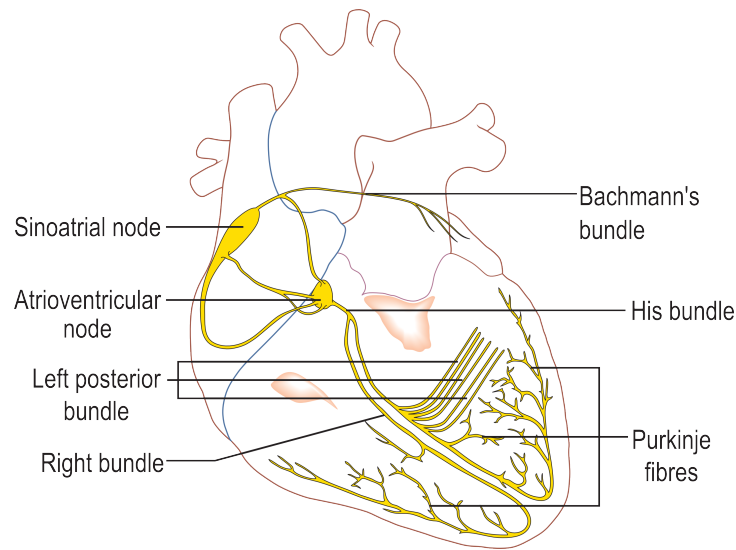
Think of a camera flash. Right after it fires, pressing the button does nothing. That is the **absolute refractory period**, phase 0 through most of phase 3, roughly the onset of the QRS to the peak of the T wave, and it is protective. Then comes a window where a very firm press does fire it, slower and weaker: the **relative refractory period**, on the **downslope of the T wave**, where a strong stimulus can capture partially recovered tissue.

That downslope is the **vulnerable period**. A ventricular beat landing there is the **R-on-T** phenomenon, by which one early beat starts ventricular tachycardia or fibrillation. You meet the term here so it is familiar when the ventricular rhythms chapter needs it.

The Conduction System and the Intrinsic Rate Hierarchy

Conduction is **falling dominoes**, not water poured across a table: one initiating event tips the first cell, each cell excites only the neighbor it touches, and each falls completely or not at all. So conduction has a **speed**, a **direction**, and it is **all-or-none**.

SA node → internodal pathways and Bachmann’s bundle → AV node → bundle of His → right and left bundle branches → Purkinje fibers → ventricular muscle



The conduction system: SA node, AV node, bundle of His, bundle branches, and Purkinje fibers. Madhero88, CC BY 3.0, via Wikimedia Commons.

The AV node is a gatekeeper, and its delay is a design feature, not a defect. It holds the impulse about a tenth of a second on purpose, like the metering light on a freeway on-ramp, so the atria finish emptying before the ventricles contract. That is **atrial kick**. It is also the **slowest tissue in the heart, roughly ten times slower than atrial muscle**, placed deliberately between two of the fastest. That slowness is what you measure every time you measure a PR interval, what fails in the atrioventricular blocks chapter, and what stops a 400-per-minute atrium from driving a 400-per-minute ventricle in the atrial rhythms chapter.

Bundle branches are the interstate; Purkinje fibers are the neighborhood streets, which gives the rule the rest of the book depends on:

\begin{center} A rhythm starting **above** the bundle branch bifurcation gets on the interstate and is **narrow**. Starting **below** it, the impulse is too late for the on-ramp, so it crawls muscle cell to muscle cell on the surface streets, and it is **wide**. \end{center}

★ **That one sentence explains Chapters 4 through 8:** why atrial and junctional rhythms are both narrow although they start in different places, why ventricular rhythms are wide, why bundle branch block widens an ordinary sinus beat, and why the level of an AV block sets how wide the escape beats below it are.

Every level has its own intrinsic rate, because every level has pacemaker cells with their own phase 4 drift. Rank in this **chain of command** is set by speed, so an escape rhythm signals **failure above**, never enthusiasm below, which is why suppressing one can kill the patient.

Site	Intrinsic rate	Role
SA node	60 to 100	The manager. Fastest, so normally in charge.
Atria (ectopic)	under 60	
AV junction	40 to 60	The assistant. Steps in when the manager goes quiet.
Ventricles (His-Purkinje)	20 to 40	Night shift. Takes over only when all above are silent.

Why Rhythms Go Wrong

Four mechanisms produce dysrhythmias: **enhanced automaticity**, **escape** (a lower site takes over because a higher one failed), **re-entry** (an impulse finds a circular path and keeps re-exciting tissue), and **conduction block**. The rhythm is the symptom and the cause is what you treat, so carry the checklist: **ischemia and hypoxia**, **electrolyte disturbance** (potassium, magnesium, calcium), **drugs and stimulants**, **autonomic tone**, **chamber stretch**, **acid-base disturbance**, **hypothermia**, **scar**.

Electrodes, Leads, and the Camera Analogy

An electrode is a sticker. A lead is a view, specifically the **voltage difference measured between two points**, so a lead is a calculation rather than a wire. **The camera analogy:** picture the positive electrode as a camera aimed at

the heart, pointing along the line toward the negative electrode. That one image explains why moving the camera changes the picture without changing the heart, and why leads see different walls: a camera at the left leg looking up sees the inferior wall, one on the left chest looking across sees the lateral wall.

Common Trap

You place ten electrodes and the machine prints twelve leads. Where do the other two come from?

Nowhere physical. This is the single highest-yield unstuck fact in the chapter. **A lead is the voltage difference between two points, and some of those points are calculated averages rather than physical electrodes.**

- **I, II, III** are bipolar: one physical positive electrode against one physical negative electrode.
- **aVR, aVL, aVF** are augmented: one physical positive electrode against the *calculated average* of the other limb electrodes. No new sticker required.
- **V1 through V6** measure one physical chest electrode against that same calculated central reference.

And the fourth limb electrode, the right leg, is a **ground**; it appears in no lead at all. So: 10 stickers, 3 limb electrodes doing real work, 1 grounding, 6 on the chest, 12 views.

Placement and the mnemonics. Limb electrodes go on the fleshy parts of the arms and legs. The classic aids are “**white on right**,” “**clouds over grass**” (white above green, right side), “**smoke over fire**” (black above red, left side), and “**brown in the middle**” for the chest.

Colour code	Right arm	Left arm	Left leg	Right leg	Chest
AHA (United States)	White	Black	Red	Green	Brown
IEC (international)	Red	Yellow	Green	Black	White

★ **Caveat you must carry with the mnemonic.** Those four phrases encode the **AHA (American) code only**. The IEC code is completely different: under IEC a red wire goes on the *right arm*, exactly where AHA puts the left leg wire. On unfamiliar equipment, read the labels rather than trusting the colours.

Chest electrodes. Find the fourth intercostal space by walking down from the sternal angle, not up from the clavicle. V1 just right of the sternum and V2 just left, both fourth intercostal space; V4 fifth intercostal space, midclavicular; V3 midway between V2 and V4; V5 anterior axillary line level with V4; V6 midaxillary line level with V4. The most common placement error is putting V1 and V2 too high, which fakes poor R wave progression and can mimic an anterior infarct on a healthy person.

Lead groups and planes. I, II, III, aVR, aVL and aVF view the **frontal plane**; V1 through V6 view the **horizontal plane**. By wall: **inferior** II, III, aVF; **septal** V1, V2; **anterior** V3, V4; **lateral** I, aVL, V5, V6. aVR watches no wall, which is exactly why it is useful as a check.

★ **The fastest quality check in all of ECG: lead I upright, aVR inverted.** If that is flipped, stop before interpreting anything. The arm electrodes are reversed. Fix them and reacquire.

ECG Paper: Derive It, Do Not Memorize It

ECG paper is graph paper, **time across** and **voltage up**. Know one number, 25 mm/s, and rebuild the rest under pressure:

25 mm passes in 1 second → 1 mm is one twenty-fifth of a second = **0.04 s** → five of those = **0.20 s** (one large box) → five of those = **1 second** → **5 large boxes per second, 30 per six seconds, 300 per minute.**

That last number is not trivia; **300 large boxes per minute is where the 300 rule comes from.** Vertically, gain is 10 mm/mV, so 1 mm is 0.1 mV, one large box is 0.5 mV, and the standardization pulse should be 2 large boxes (10 mm) tall.

Rate method	Use it when	How
300 sequence	Regular rhythms	From an R on a heavy line, count 300, 150, 100, 75, 60, 50

Rate method	Use it when	How
1500 method	Regular, precision needed	1500 divided by small boxes between two R waves
6-second method	Irregular , or very slow	R waves in a 6-second strip, times 10

Common Trap

You have a strip of atrial fibrillation. Can you use the 300 sequence on it?

No. It assumes every R-R interval is the same length, so it is valid on **regular rhythms only**. Run it on an irregular rhythm and it hands you a confident, meaningless number, which is worse than no number. On anything irregular use the 6-second method and report a range: “ventricular rate 70 to 110, irregularly irregular.”

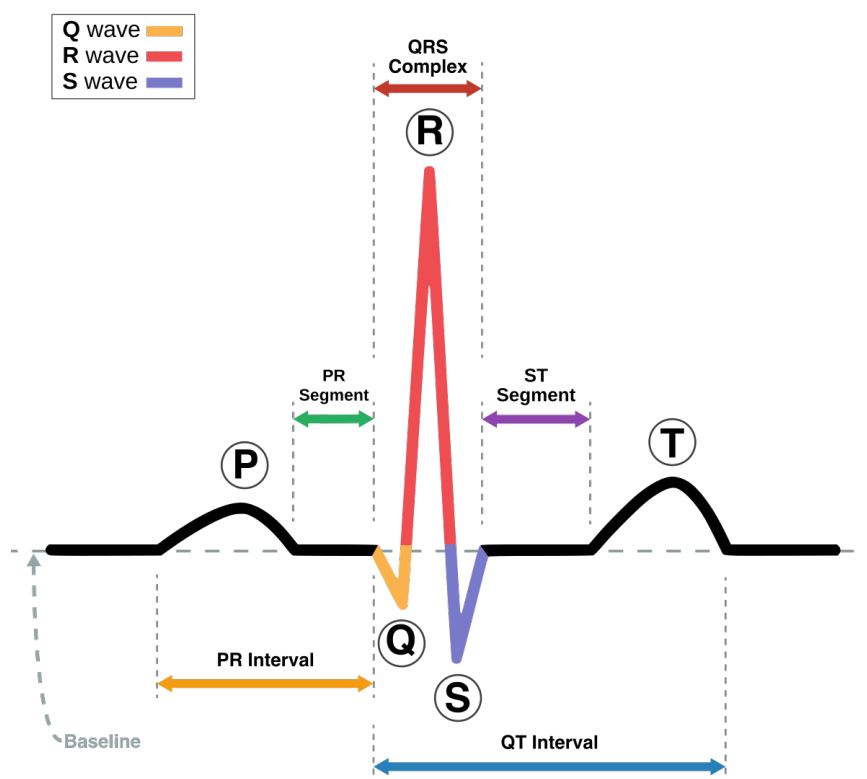
And watch the multiplier. A 6-second strip is multiplied by **10**, a full 10-second 12-lead by **6**; both are right for their own strip length. Instead of two rules, learn one: *multiply by however many of these windows fit into a minute.*

Waveforms, Segments, and Intervals

Three words students use interchangeably and the textbook does not. One rule separates them:

A **waveform** is a deflection away from baseline; it tells you *what happened*. A **segment** is the flat line *between* waveforms; it is *where injury hides*. An **interval** contains at least one waveform *plus* a segment; it tells you *how long something took*.

The corollary you can apply this second: the PR **interval** includes the P wave, the PR **segment** does not, and you will be asked to tell them apart.



The normal complex with waveforms, segments, and intervals labeled. Agateller, Public Domain, via Wikimedia Commons.



Regularity	Regular; the R-R intervals march out evenly
Rate	75; each R falls 20 mm (four large boxes) after the last, and 300 divided by 4 is 75
P waves	One upright P before every QRS, one for one
PR	0.16 s, four small boxes, constant
QRS	0.08 s, two small boxes, narrow

Memory hook Run the Five Questions on this strip until the order is automatic. It is drawn to true scale, so calipers work on this page as on a real tracing.

Fast tell Lead II is your workhorse monitoring lead because normal atrial depolarization travels straight toward its positive electrode at the left leg, which by the deflection rule gives the most reliably upright P wave available.

Where students go wrong Measuring “by eye” and writing “normal.” Write *0.16 s*, not *normal*; a value in seconds is an answer, an adjective is not.

The waveforms. The **P wave** is atrial depolarization, the **QRS** is ventricular depolarization, the **T wave** is ventricular repolarization, and the **U wave**, when present, follows the T and is associated with **hypokalemia**. Naming inside the QRS is not optional: any negative deflection **before** the first positive one is a **Q**, the first positive deflection is the **R** whether or not a Q came first, and a negative deflection **after** an R is an **S**. A complex with no initial negative deflection has no Q wave at all.

Learn both right-hand columns below. Box counts let you measure at a glance; seconds alone force arithmetic on every complex. The QRS is **wide at 0.12 s or more**, which is 3 small boxes, and that threshold separates supraventricular from ventricular in every chapter from here forward.

Measurement	From, to	Normal	Small boxes
P wave duration	Start to end of P	under 0.12 s	fewer than 3
PR interval	Start of P to start of QRS	0.12 to 0.20 s	3 to 5
QRS duration	Start to end of QRS	0.06 to 0.10 s	under 3
QT interval	Start of QRS to end of T	0.44 s or less, rate dependent	about 11 or fewer
ST segment	End of QRS to start of T	Flat, at baseline	

The Two Questions Students Always Ask

Where is the wave for atrial repolarization? It happens; it is simply hidden. The wave is small and occurs at the same moment as ventricular depolarization, so the much larger QRS drowns it out. It is buried, not absent, and it becomes visible in second and third degree AV block, where a P wave arrives with no QRS behind it and nothing large enough to hide behind.

If repolarization is the reverse of depolarization, why is the T wave upright? Because two opposites cancel. Ventricular repolarization travels **epicardium to endocardium**, the opposite direction from depolarization, and an opposite process travelling in the opposite direction produces the same deflection. Another dividend from the one rule at the top of this guide.

Artifact, and the Rule That Outranks Everything

Artifact is any deflection that did not come from the heart. Four to recognize: **wandering baseline** (loose electrode, dried gel, respiration, movement), **muscle tremor** (shivering, talking, a cold or anxious patient), **60-cycle interference** (fine, perfectly regular fuzz from nearby equipment or an ungrounded cable), and **a broken or disconnected lead wire**, which prints a flat line that looks exactly like asystole in one lead while every other lead

looks fine. **A loose electrode can print asystole, and a shivering patient can print something that looks like ventricular fibrillation.** Both are lethal rhythms on paper and neither is happening in the chest.

Never treat the monitor. Look at the patient.

Assess the patient, then the equipment, then reacquire, and confirm a lethal rhythm in more than one lead before acting. If the patient is sitting up talking to you, they are not in ventricular fibrillation, whatever the screen says.

The reverse error is just as dangerous, and it is the seed the ventricular rhythms chapter harvests. **Depolarization is an electrical event and it does not prove that any muscle squeezed.** The monitor shows you the wiring, not the plumbing; it is the key turning in the ignition, not the car moving. Textbook complexes can march across the screen with no pulse at all, which is **pulseless electrical activity**, and it is exactly why we check a pulse instead of trusting a waveform.

Before You Move On

You should now be able to:

- run the Five-Question Method in order on any strip, without looking it up
- state the deflection rule and use it to predict why aVR is inverted and why R waves grow across the chest leads
- derive every paper value from 25 mm per second rather than memorizing the table
- measure a PR interval and a QRS in both small boxes and seconds
- say which of a waveform, a segment and an interval you are looking at, and why the PR interval and the PR segment are different

The next chapter puts the Five-Question Method to work on the sinus mechanisms, where every answer comes back normal except one.

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