THE NORMAL ELECTROCARDIOGRAM

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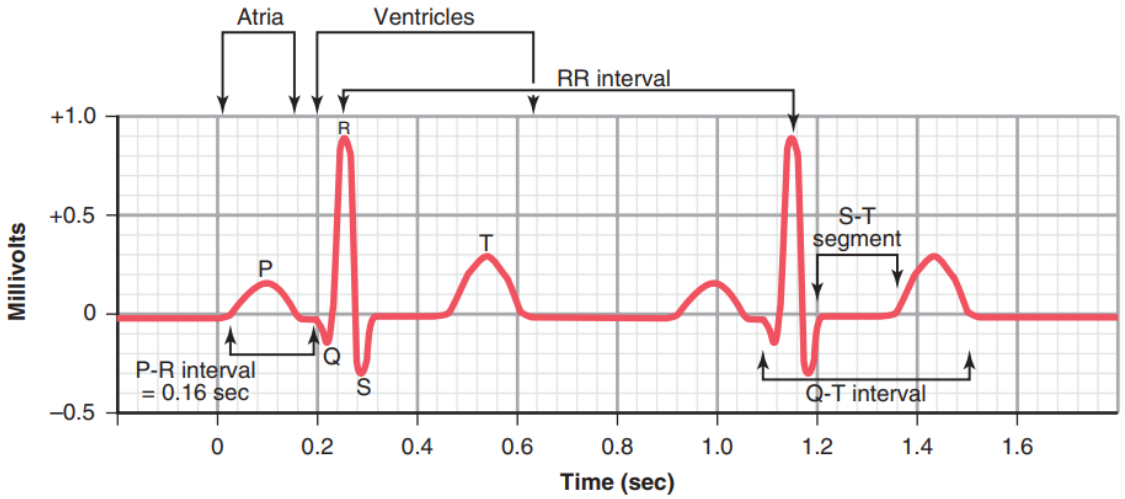


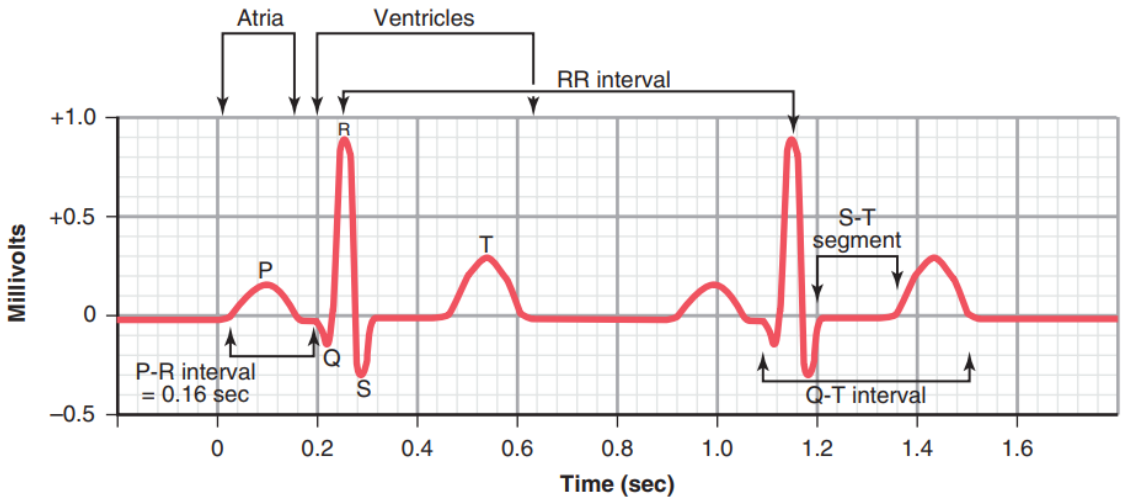
Figure 11-1. Normal electrocardiogram.

OUTLINE

1. Identifying each wave, segment, and interval on a normal ECG.
2. Relating ECG deflections to cardiac action potentials and conduction sequence.
3. Understanding how the 12-lead ECG records activity from different planes.

PRINCIPLE OF THE ECG

- ECG records the potentials from cardiac depolarization and repolarization.
- Body fluids conduct current to surface electrodes.
- Each wave corresponds to a specific phase of the cardiac cycle.



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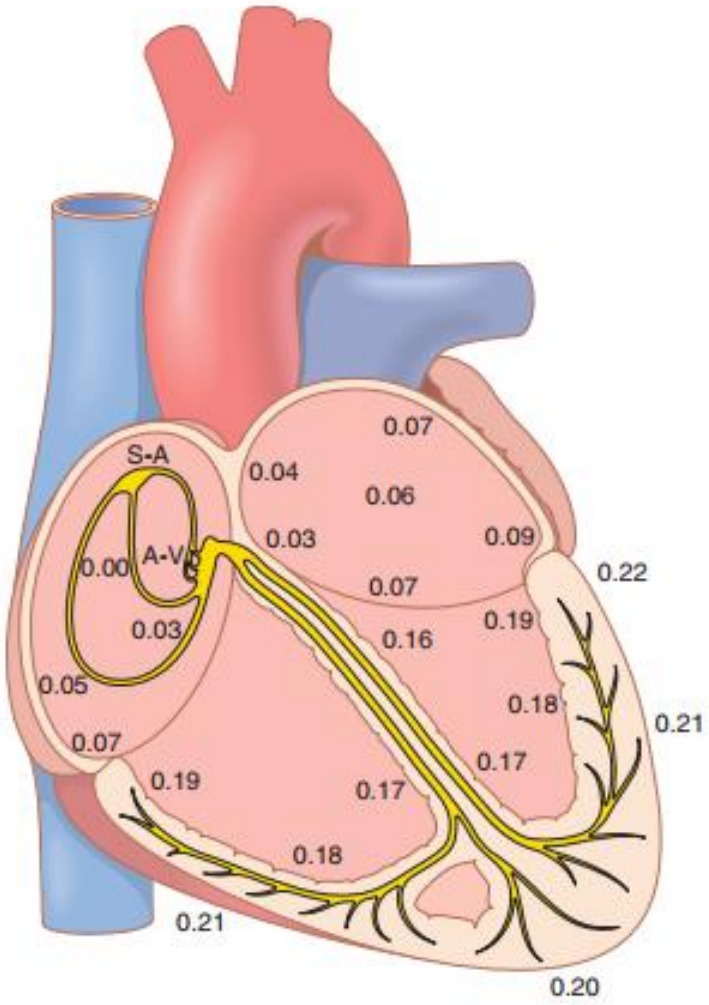
CARDIAC CONDUCTION PATHWAY

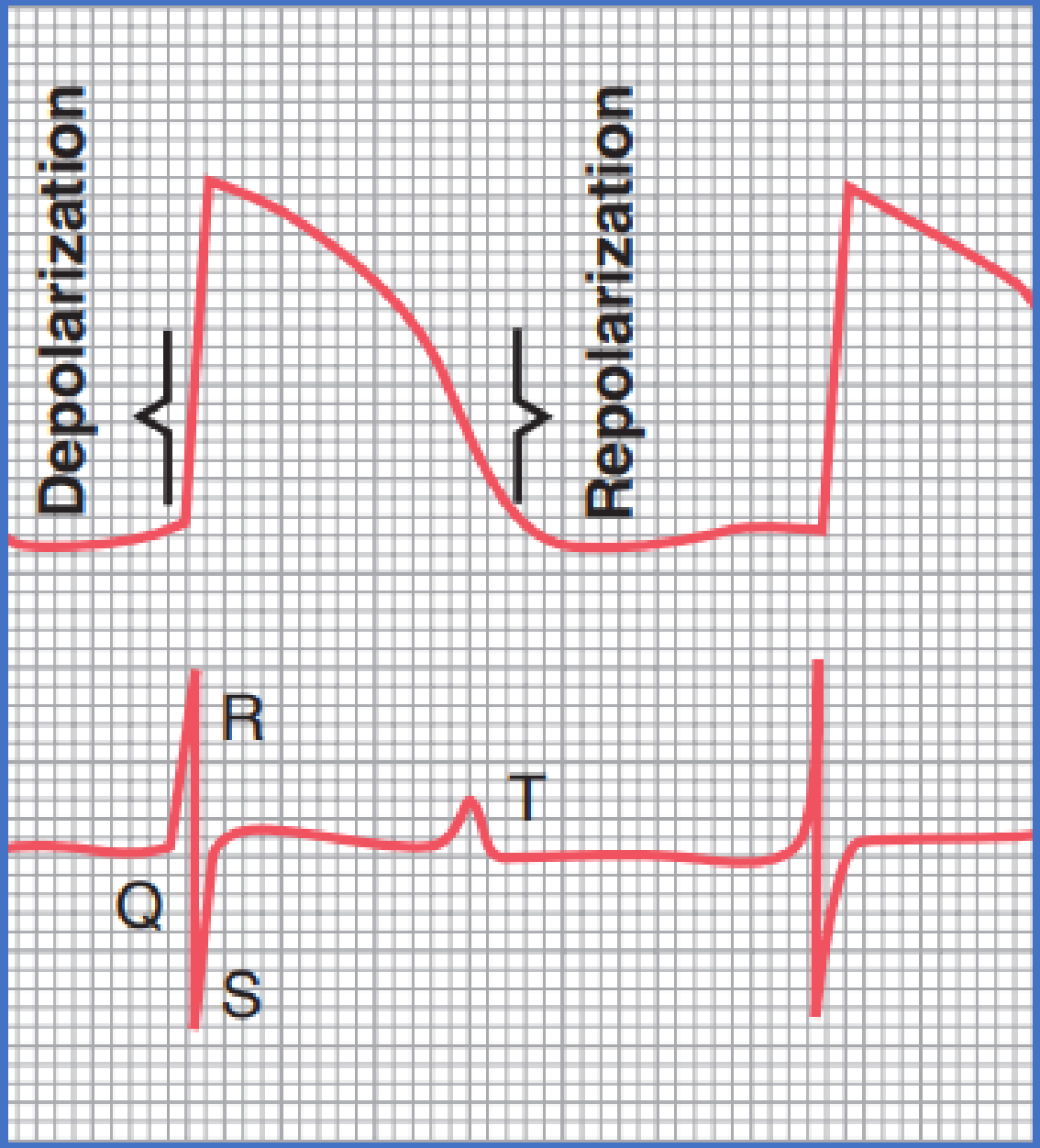
- SA node → Atria → AV node (delay ≈ 0.09 s) → His bundle → Bundle branches → Purkinje fibers → Ventricles.
- Ensures atria contract before ventricles.
- Defines timing of P wave, PR segment, and QRS complex.



VMAP

VS

ECG



P WAVE

- Represents atrial depolarization (SA node → both atria).
- Vector: right → left and downward.
- Corresponds to atrial Phase 0 of atrial MAP (Na^+ influx).
- Duration ≈ 0.08 s, small positive deflection in lead II.

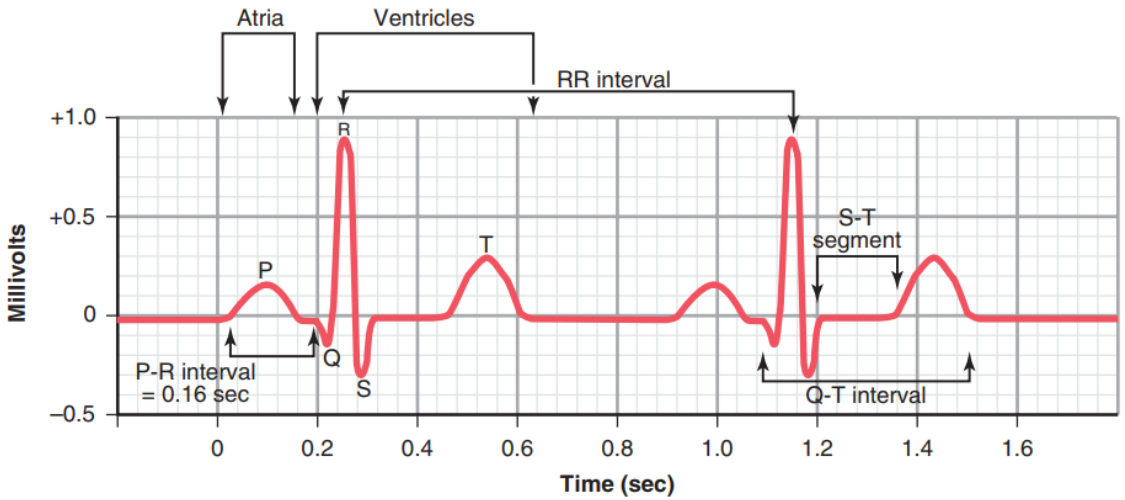


Figure 11-1. Normal electrocardiogram.

PR SEGMENT AND PR INTERVAL

- PR segment: AV nodal delay, no muscle activity → isoelectric line.
- PR interval: P onset → QRS onset (total atrial + AV conduction).
- Normal ≈ 0.16 s; allows ventricular filling before systole.

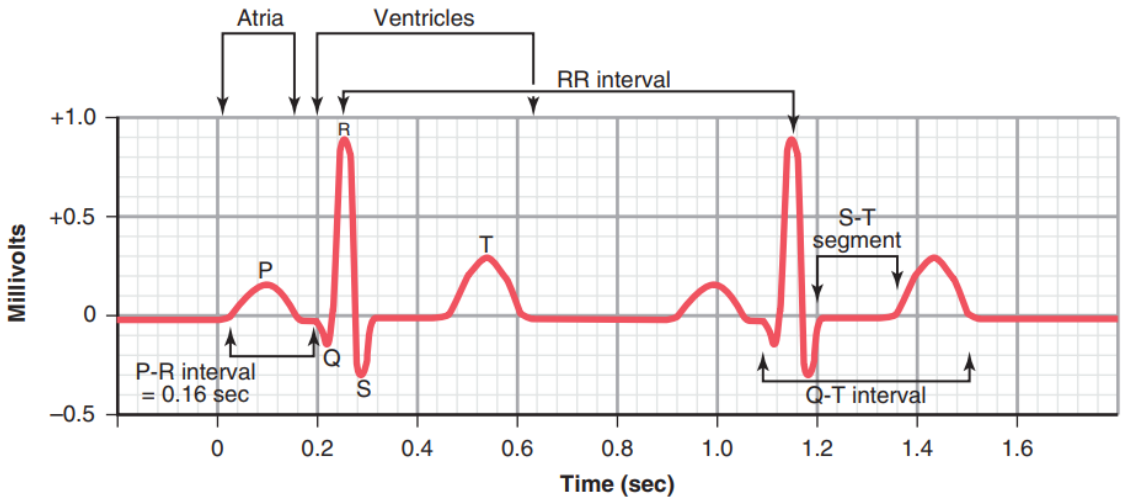


Figure 11-1. Normal electrocardiogram.

QRS COMPLEX

- Q: Septal depolarization (left → right).
- R: Main ventricular mass depolarization (apex-directed).
- S: Basal depolarization (posterior/upward).
- Total < 0.1 s; rapid Purkinje conduction.

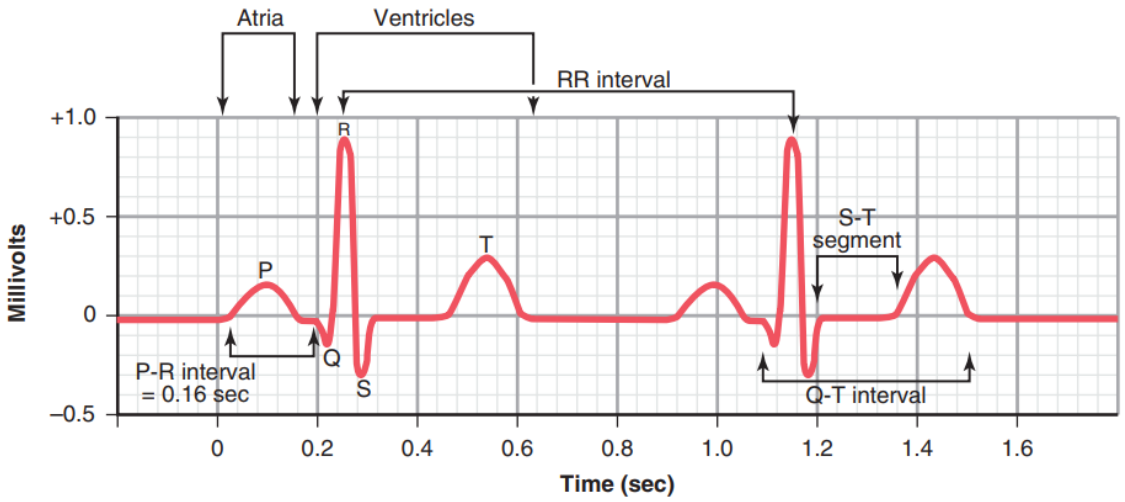


Figure 11-1. Normal electrocardiogram.

ST SEGMENT

- All ventricular cells depolarized → isoelectric line.
- Corresponds to VMAP Plateau (Phase 2).
- Represents electrical systole.

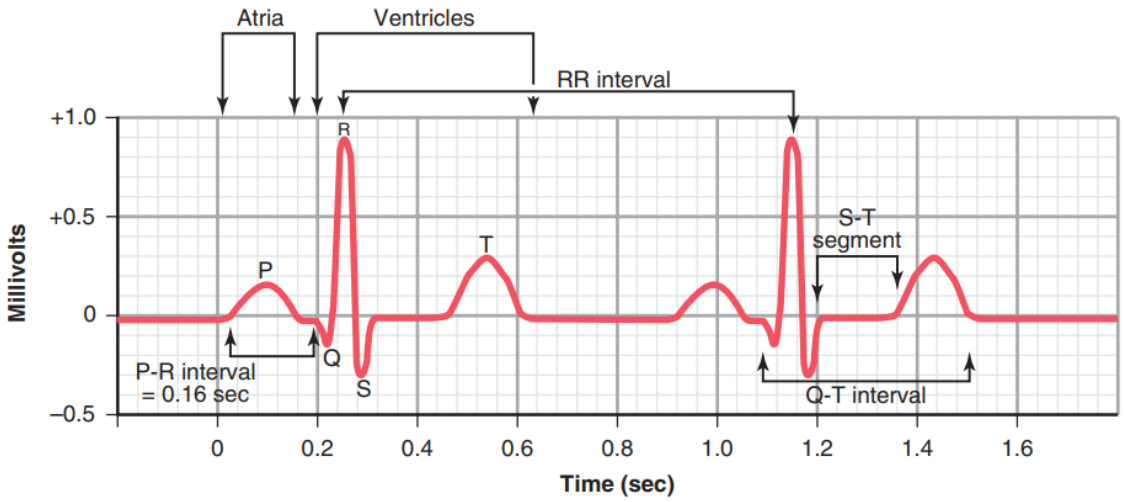


Figure 11-1. Normal electrocardiogram.

T WAVE

- Ventricular repolarization (epicardium → endocardium).
- Opposite direction to depolarization → positive deflection.
- Corresponds to VMAP Phase 3 (K^+ efflux).

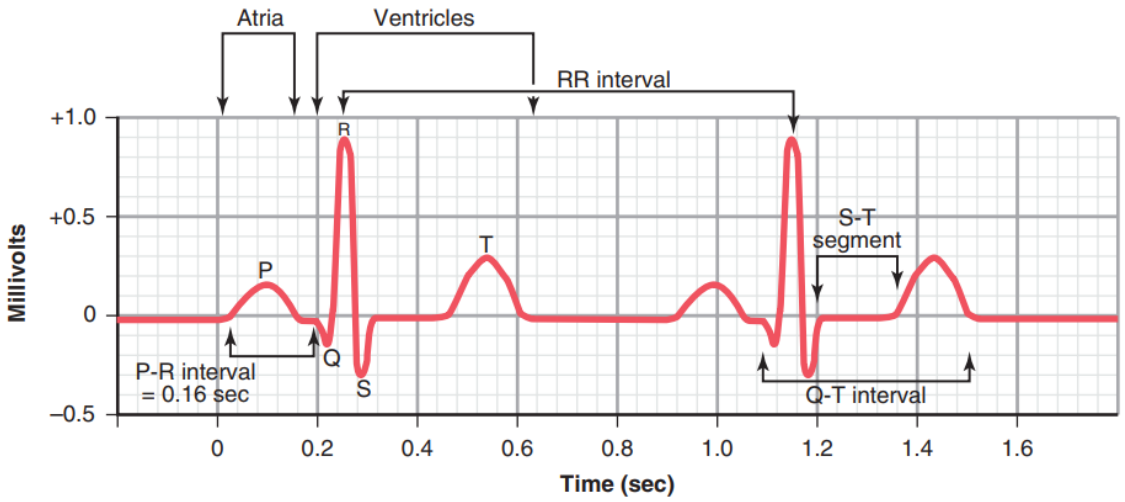


Figure 11-1. Normal electrocardiogram.

QT INTERVAL

- From QRS onset to T wave end.
- Covers total ventricular depolarization + repolarization (Phases 0–3).
- Normal ≈ 0.35 s, varies with heart rate.

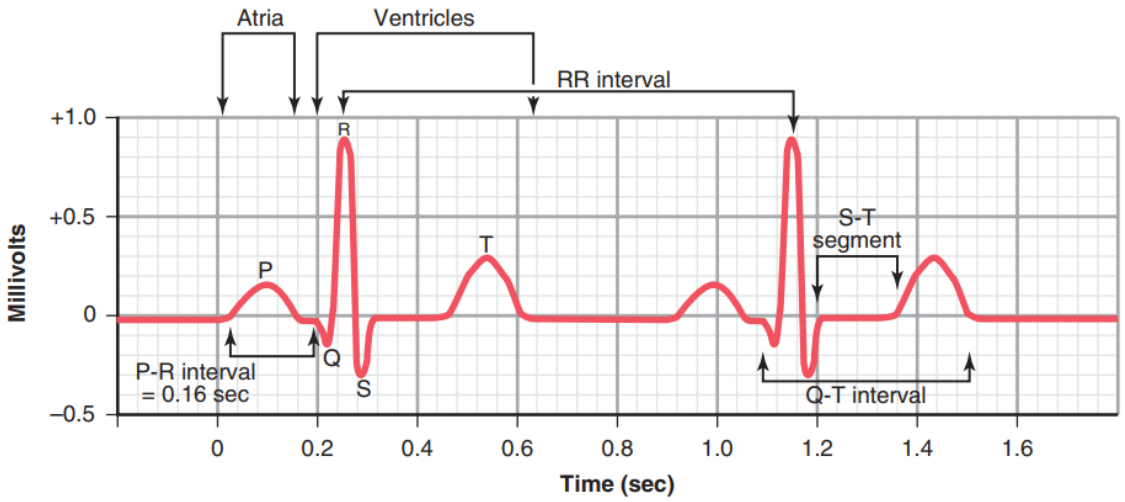
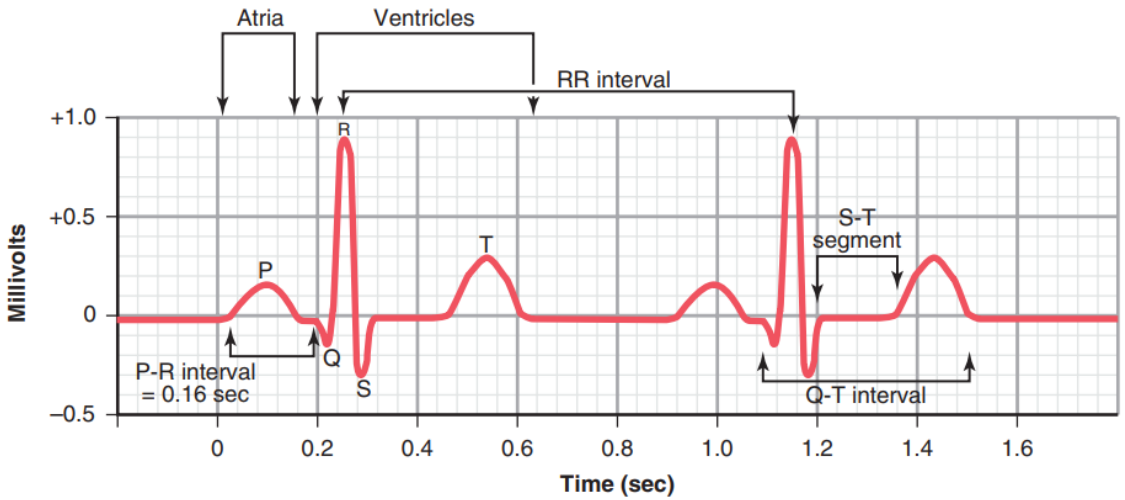


Figure 11-1. Normal electrocardiogram.

TP SEGMENT

- Electrical diastole; all fibers at resting potential (Phase 4).
- Baseline for next cardiac cycle.



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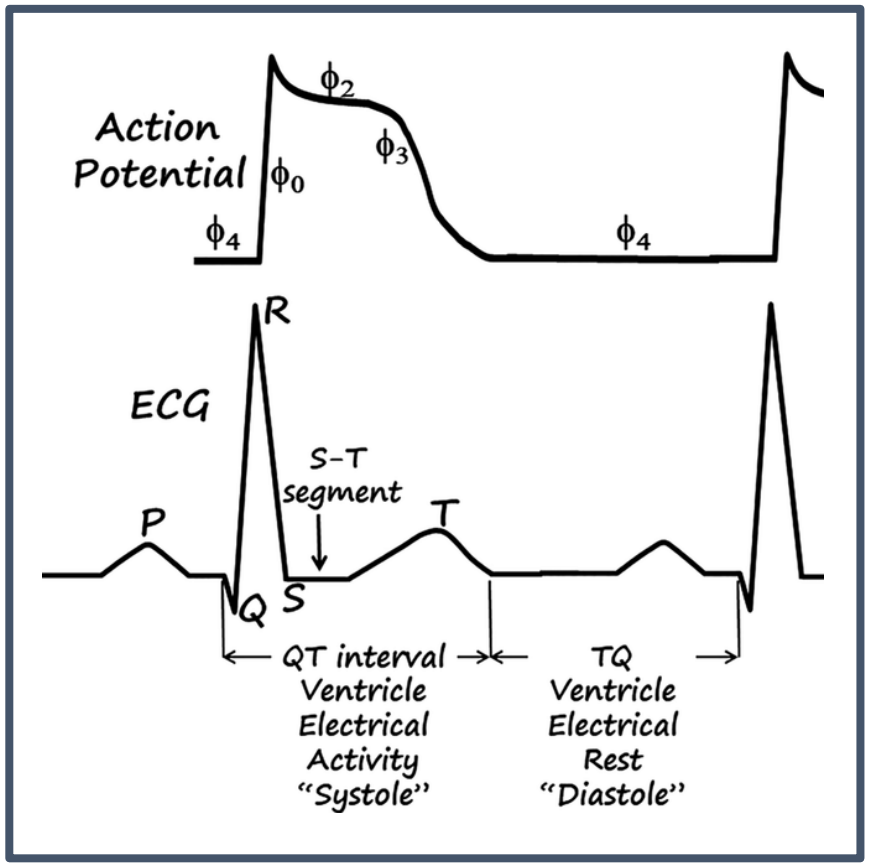
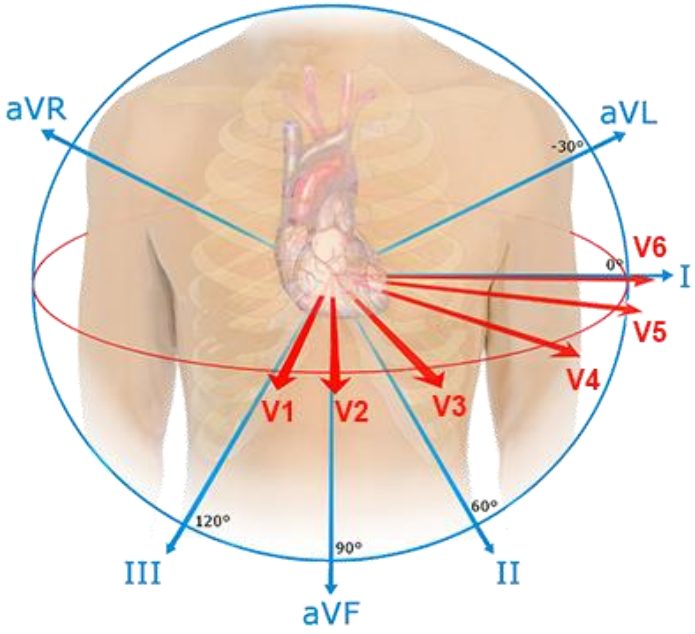
ALIGNMENT: ECG VS. CONDUCTION VS. VMAP

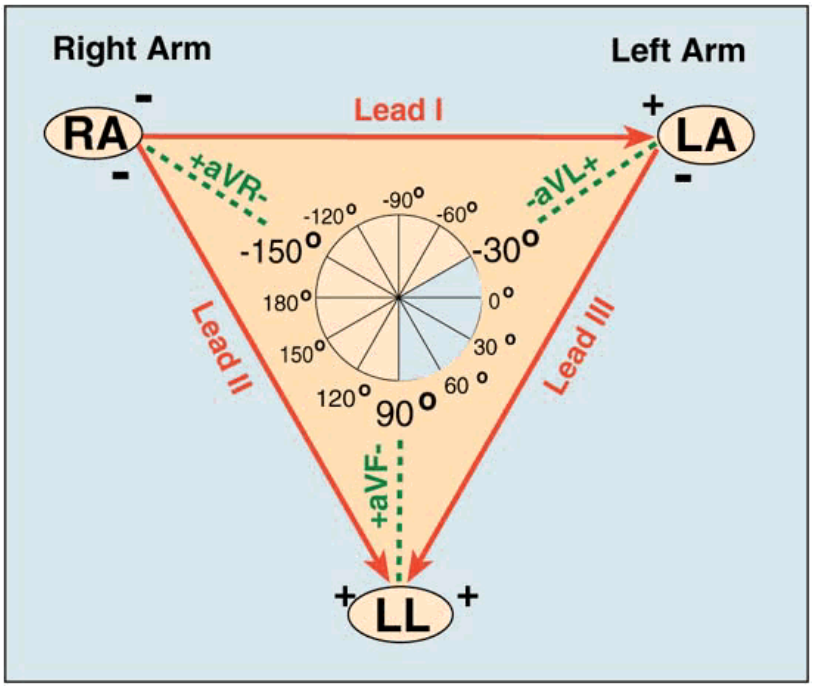


- P wave: Atrial depolarization (SA → atria) – Atrial Phase 0.
- PR segment: AV delay – no muscle depolarization.
- QRS: Ventricular depolarization – Phase 0.
- ST segment: Plateau – Phase 2.
- T wave: Repolarization – Phase 3.
- TP: Diastole – Phase 4.

CONCEPT OF LEADS

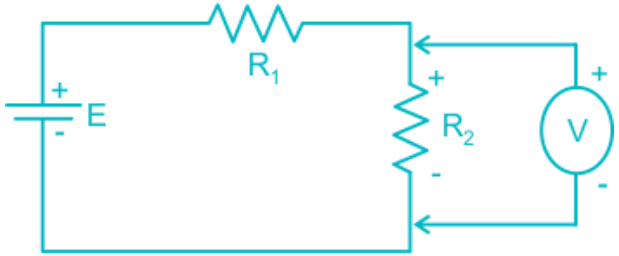
- Each lead views the heart's potential difference from a unique angle.
- 12 leads provide 12 perspectives in space.
- Together, they form a 3D map of cardiac activity.





ELECTRODE VS LEAD

- An electrode is a physical sensor placed on the body to detect electrical signals.
- A lead is the combination of electrodes used to record the potential difference between two points (bipolar) or between a point and a reference (unipolar).



- Lead = a view of the heart:
- Each lead gives a unique angle on the heart's electrical activity.
- For example, Lead I records the difference between the left arm and right arm electrodes; it's called "Lead I" because it's one of the predefined directions used to "look at" the heart's electrical vector.

STANDARD BIPOLAR LIMB LEADS

- Lead I: right arm (−) → left arm (+).
- Lead II: right arm (−) → left leg (+); axis ≈ +60°; largest R wave.
- Lead III: left arm (−) → left leg (+); axis ≈ +120°.

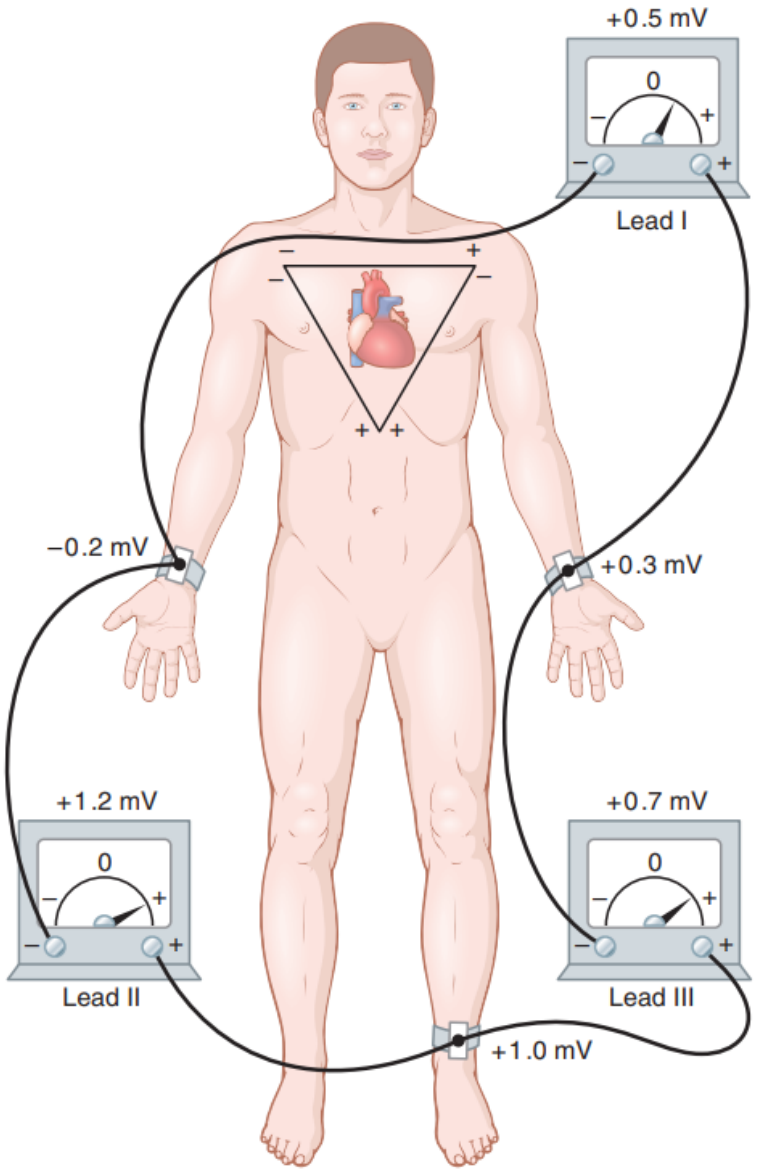


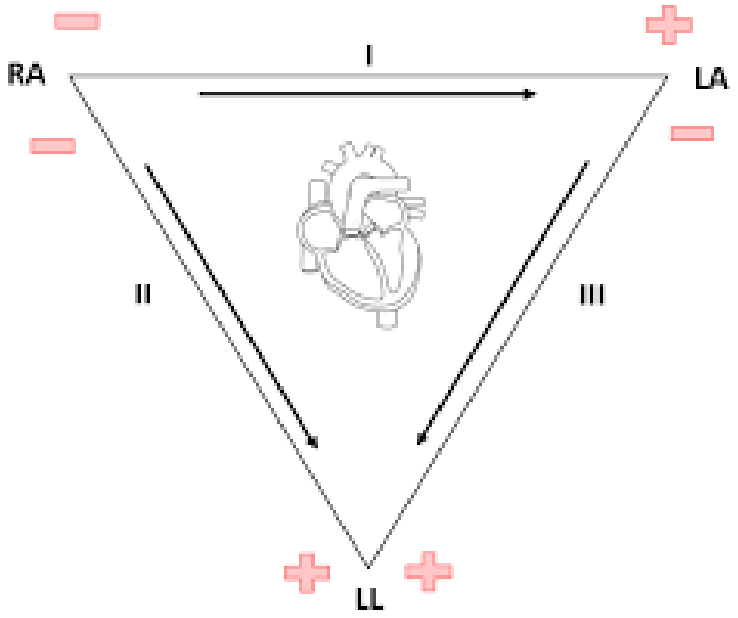
Figure 11-6. Conventional arrangement of electrodes for recording the standard electrocardiographic leads. Einthoven's triangle is superimposed on the chest.

STANDARD BIPOLAR LIMB LEADS

- Lead I: right arm (–) → left arm (+).
- Lead II: right arm (–) → left leg (+); axis ≈ +60°; largest R wave.
- Lead III: left arm (–) → left leg (+); axis ≈ +120°.

- Einthoven's Law:

Lead II = Lead I + Lead III.



CHEST (PRECORDIAL) LEADS

- Unipolar leads (V1–V6) record horizontal plane activity.
- Reference = Wilson's central terminal (average of limb leads).
- V1–V2: right ventricle/septum; negative deflection.
- V3–V4: anterior wall; transition zone.
- V5–V6: left ventricle; tall R waves.

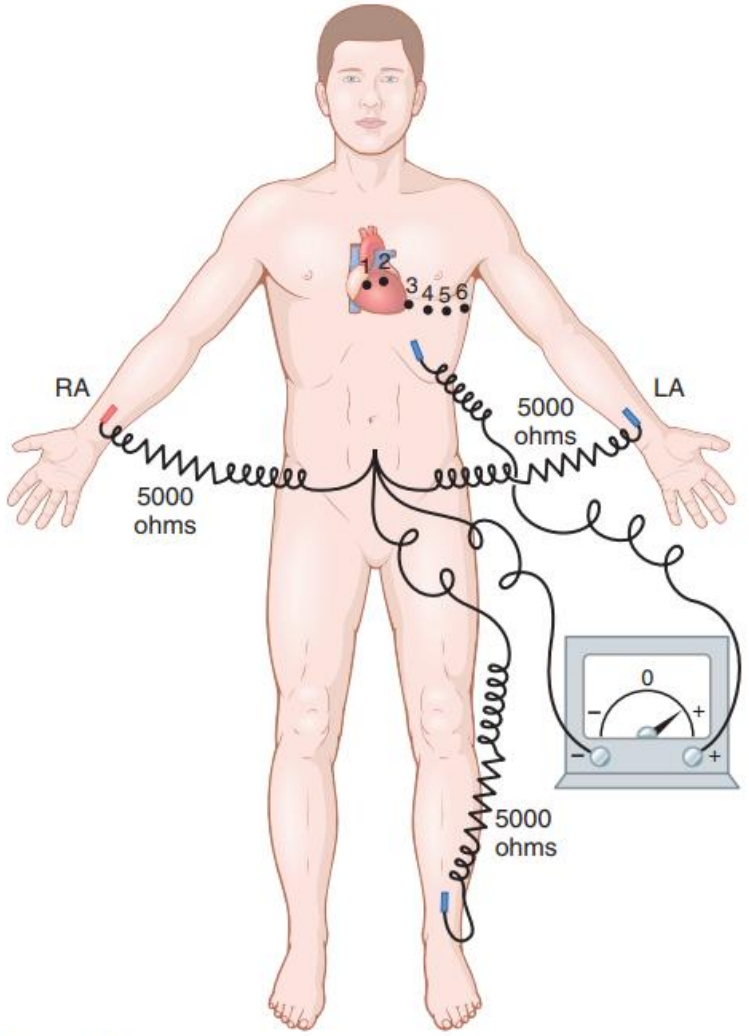
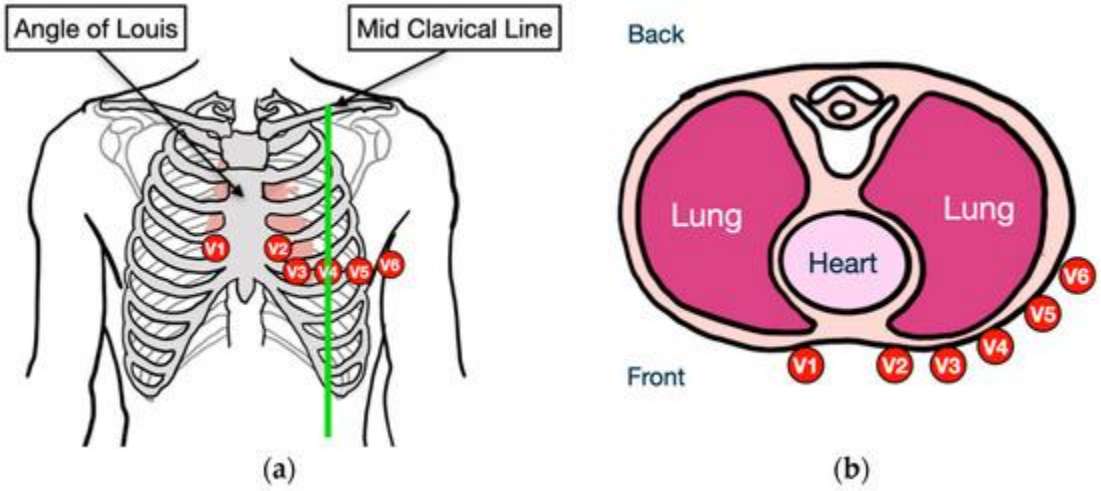


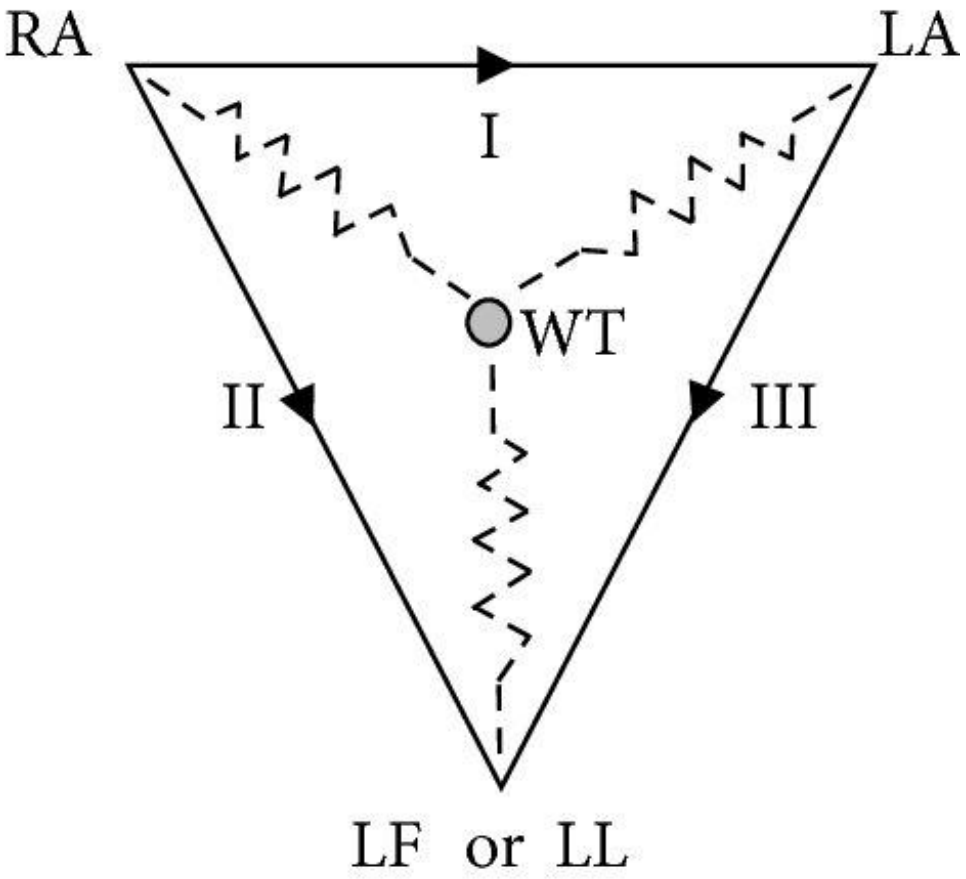
Figure 11-8. Connections of the body with the electrocardiograph for recording chest leads. LA, left arm; RA, right arm.

CHEST (PRECORDIAL) LEADS



Lead	Typical QRS	Placement	Main View
V1	rS	4th intercostal space, **right sternal border**	Septum / RV
V2	rS	4th intercostal space, **left sternal border**	Septum / RV
V3	r ≈ S	Midway between **V2 and V4**	Transition zone
V4	Rs	5th intercostal space, **midclavicular line**	Anterior LV
V5	R (dominant)	Same horizontal level as V4, **anterior axillary line**	Lateral LV
V6	R (dominant)	Same horizontal level as V4, **midaxillary line**	Lateral LV

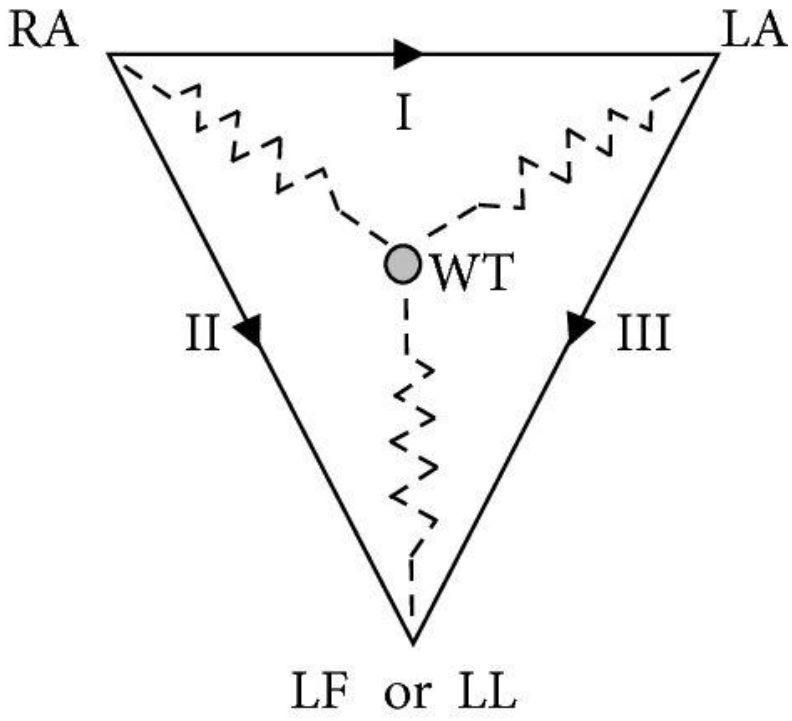
WILSON'S CENTRAL TERMINAL



AUGMENTED UNIPOLAR LIMB LEADS

- aVR: right shoulder → heart; negative waves.
- aVL: left shoulder view; small positive R wave.
- aVF: inferior view (foot); positive deflection.

- Average of only 2 electrodes is used as a reference for the 3rd.



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- aVR: right shoulder → heart; negative waves.
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- aVF: inferior view (foot); positive deflection.

- Average of only 2 electrodes is used as a reference for the 3rd.

aVR (Right Arm)

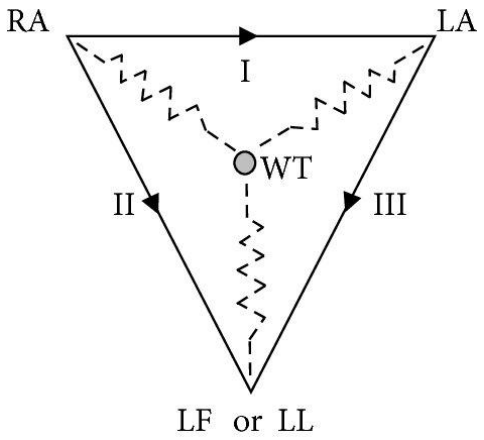
$$\text{aVR} = V_{RA} - \frac{V_{LA} + V_{LL}}{2}$$

aVL (Left Arm)

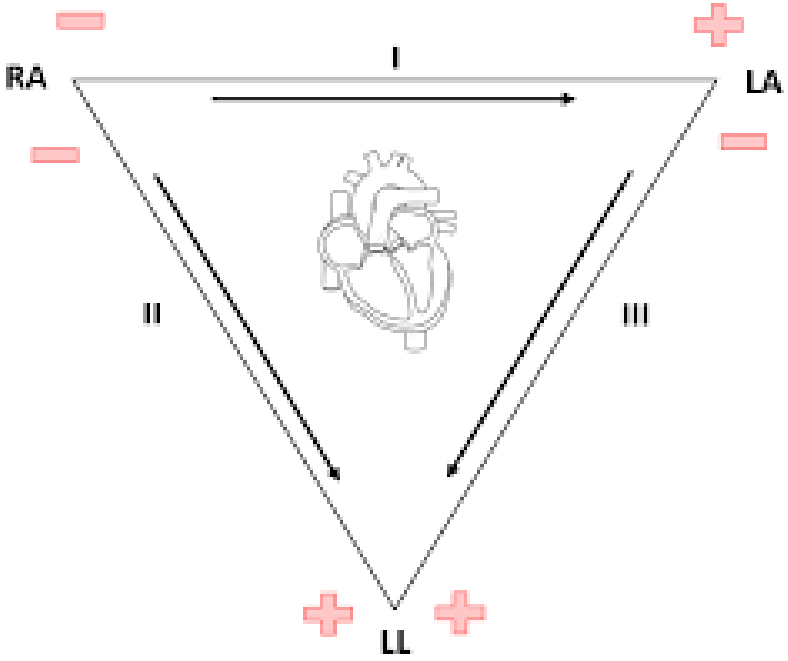
$$\text{aVL} = V_{LA} - \frac{V_{RA} + V_{LL}}{2}$$

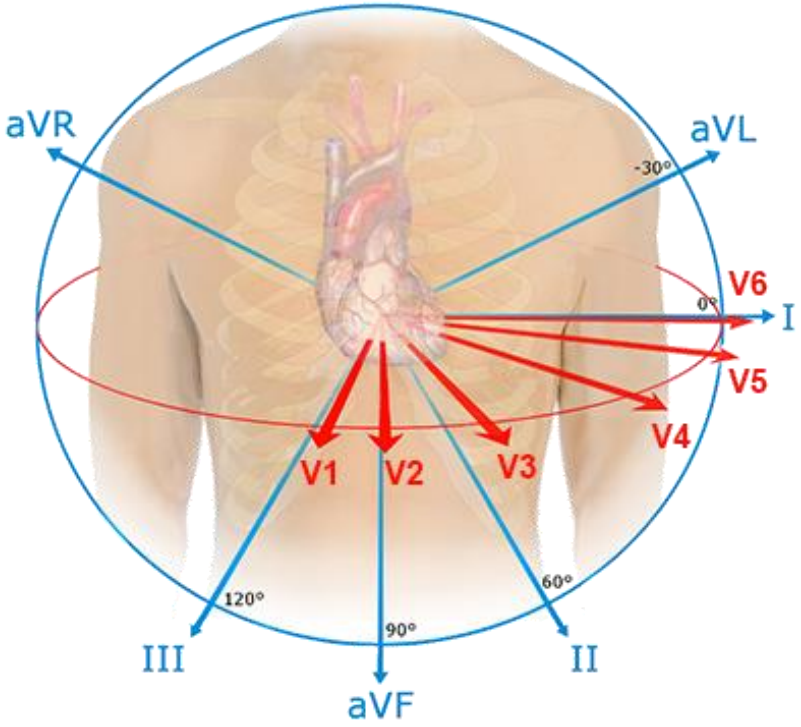
aVF (Left Leg / Foot)

$$\text{aVF} = V_{LL} - \frac{V_{RA} + V_{LA}}{2}$$



ALL 12 LEADS IN ONE SHOT





LEAD SUMMARY

- I, II, III – frontal plane: general cardiac axis (Einthoven's triangle).
- aVR, aVL, aVF – frontal plane: right, left, inferior views.
- V1–V6 – horizontal plane: septal, anterior, lateral walls.

MEAN ELECTRICAL AXIS (QRS AXIS) – I

- Definition:

Let the **mean QRS vector** in the frontal plane be:

$$\vec{QRS} = |\vec{QRS}| \text{ at angle } \theta$$

Where:

- $|\vec{QRS}|$ = magnitude of vector
- θ = mean QRS axis (angle from Lead I, horizontal)

MEAN ELECTRICAL AXIS (QRS AXIS) – II

- Lead orientations (the 6 frontal leads):

Lead	CW Angle from x^+
I	0°
II	+60°
III	+120°
aVR	−150°
aVL	−30°
aVF	+90°

For any lead at angle θ_{lead}:

$$V_{\text{lead}} = |Q\vec{R}S| \cos(\theta - \theta_{\text{lead}})$$

1. **Lead I (0°)**

$$V_I = |Q\vec{R}S| \cos(\theta - 0^\circ) = |Q\vec{R}S| \cos\theta$$

2. **Lead II (+60°)**

$$V_{II} = |Q\vec{R}S| \cos(\theta - 60^\circ) = |Q\vec{R}S|(\cos\theta \cos 60^\circ + \sin\theta \sin 60^\circ)$$

$$\cos 60^\circ = 0.5, \quad \sin 60^\circ = 0.866$$

$$\Rightarrow V_{II} = |Q\vec{R}S|(0.5\cos\theta + 0.866\sin\theta)$$

3. **Lead III (+120°)**

$$V_{III} = |Q\vec{R}S| \cos(\theta - 120^\circ) = |Q\vec{R}S|(\cos\theta \cos 120^\circ + \sin\theta \sin 120^\circ)$$

$$\cos 120^\circ = -0.5, \quad \sin 120^\circ = 0.866$$

$$\Rightarrow V_{III} = |Q\vec{R}S|(-0.5\cos\theta + 0.866\sin\theta)$$

MEAN ELECTRICAL AXIS (QRS AXIS) – III

- Lead orientations (the 6 frontal leads):

Lead	CW Angle from x^+
I	0°
II	+60°
III	+120°
aVR	−150°
aVL	−30°
aVF	+90°

For any lead at angle θ_{lead}:

$$V_{\text{lead}} = |\vec{QRS}| \cos(\theta - \theta_{\text{lead}})$$

4. aVR (−150°)

$$V_{aVR} = |\vec{QRS}| \cos(\theta - (-150^\circ)) = |\vec{QRS}| \cos(\theta + 150^\circ)$$

$$\cos 150^\circ = -0.866, \quad \sin 150^\circ = 0.5$$

$$\Rightarrow V_{aVR} = |\vec{QRS}|(-0.866 \cos\theta + 0.5 \sin\theta)$$

5. aVL (−30°)

$$V_{aVL} = |\vec{QRS}| \cos(\theta - (-30^\circ)) = |\vec{QRS}| \cos(\theta + 30^\circ)$$

$$\cos 30^\circ = 0.866, \quad \sin 30^\circ = 0.5$$

$$\Rightarrow V_{aVL} = |\vec{QRS}|(0.866 \cos\theta + 0.5 \sin\theta)$$

6. aVF (+90°)

$$V_{aVF} = |\vec{QRS}| \cos(\theta - 90^\circ) = |\vec{QRS}|(\cos\theta \cdot 0 + \sin\theta \cdot 1) = |\vec{QRS}| \sin\theta$$

MEAN ELECTRICAL AXIS (QRS AXIS) – IV

- Example: find the QRS vector given leads I (+0.5 mV) and II (+0.7 mV)

$$\begin{cases} V_I = |\vec{QRS}| \cos(\theta - 0^\circ) = |\vec{QRS}| \cos\theta \\ V_{II} = |\vec{QRS}| \cos(\theta - 60^\circ) = |\vec{QRS}| \left(\cos\theta \cos 60^\circ + \sin\theta \sin 60^\circ \right) \end{cases}$$

- **Substitute cos60° = 0.5, sin60° = √3/2 ≈ 0.866:**

$$V_{II} = |\vec{QRS}| \left(0.5 \cos\theta + 0.866 \sin\theta \right)$$

- Solve for **θ**:

$$\frac{V_{II}}{V_I} = \frac{0.5 \cos\theta + 0.866 \sin\theta}{\cos\theta} = 0.5 + 0.866 \tan\theta$$

$$\Rightarrow \tan\theta = \frac{V_{II}/V_I - 0.5}{0.866}$$

MEAN ELECTRICAL AXIS (QRS AXIS) – V

- Example: find the QRS vector given leads I (+0.5 mV) and II (+0.7 mV)

  [Angle calculation]

Formula using Leads I & II:

$$\tan\theta = \frac{V_{II}/V_I - 0.5}{0.866}$$

Substitute numbers:

$$\tan\theta = \frac{0.7/0.5 - 0.5}{0.866} = \frac{1.4 - 0.5}{0.866} = \frac{0.9}{0.866} \approx 1.039$$

$$\theta = \arctan(1.039) \approx 46.0^\circ$$

Which quadrant?

Since both leads are positive, we are in the 4th quadrant (x^+, y^-), so keep the angle.

MEAN ELECTRICAL AXIS (QRS AXIS) – VI

- Example: find the QRS vector given leads I (+0.5 mV) and II (+0.7 mV)

  [Magnitude calculation using lead I; lead II can be used for confirmation]

$$|\vec{QRS}| = \frac{V_I}{\cos\theta}$$

$$\cos 46^\circ \approx 0.694$$

$$|\vec{QRS}| = \frac{0.5}{0.694} \approx 0.720 \text{ mV}$$

So, the QRS vector is 0.72 mV, 46 degrees CW from the positive x-axis.

CLOSING QUOTE

"The ECG is the language of the heart's electricity — to read it well, we must think in both time and space (4D)."

REFERENCES

- Guyton and Hall Textbook of Medical Physiology, 13th Ed., Chapter 11
- Dr. Faisal's lectures
- Kaewrat, C., Anopas, D., Aung, S. T., & Punsawad, Y. (2024). Application of Augmented Reality Technology for Chest ECG Electrode Placement Practice. *Informatics*, *11*(1), Article 5.

  https://doi.org/10.3390/informatics11010005