

## PAPER TYPE (Research paper)

# Electrocardiography (ECG/EKG): Scientific Foundations, Technology, Advanced Interpretation, and Clinical Applications

**Arshia Zargar – Ali Darei***Department of electrical and biomedical engineering, Semnan University, Iran.***Article Info****Article History:**

Received 20 September 2024

Revised 22 October 2024

Accepted 25 November 2024

**Keywords:**

Cardiac electrophysiology, high-resolution ECG systems, automated ECG interpretation, signal acquisition artifacts, three-dimensional ECG, electrocardiographic biomarkers.

\*Corresponding Author's Email Address:

Ali.daraie1382@gmail.com

**Abstract**

Electrocardiography (ECG/EKG) is a foundational diagnostic tool in modern cardiology, capable of capturing the heart's electrical activity with millisecond precision. However, comprehensive resources that span from cellular electrophysiology to advanced signal processing and clinical applications remain limited. This study aims to systematically bridge that gap. A multidisciplinary approach was employed, beginning with a review of the biophysical principles underlying cardiac action potentials and the mechanisms of signal detection via surface electrodes. The engineering of fifth-generation ECG systems was analyzed, including the development of low-noise preamplifiers, adaptive filtering, and AI-driven arrhythmia detection algorithms. Additionally, an algorithmic framework was introduced for interpreting 12-lead ECGs based on clinical meta-analyses. The interpretation algorithm accurately identified QRS complex characteristics, electrical axis, and acute myocardial ischemia, achieving a sensitivity of 98.77% across datasets cited in recent 2024 meta-analyses. Integration with wearable systems and MRI modalities demonstrated reliable performance with spatial resolutions down to 1.5 mm. The engineering innovations significantly enhanced diagnostic accuracy and real-time assessment capabilities. The study establishes a scientific and technological foundation for next-generation ECG systems that are precise, intelligent, and clinically versatile. In addition to advancing diagnostic performance, these systems open the door to personalized medicine applications and hybrid imaging workflows. Future directions include broader implementation in ambulatory and telecardiology settings.

**Introduction**

Human heart muscles require an electrical stimulation system to pump blood effectively to various parts of the body and generate the pressure needed for organ perfusion. In a healthy heart, this system functions properly, ensuring accurate contraction and relaxation. However, to precisely assess cardiac performance and overall health, it is essential to study how the signals generated by the heart propagate. These signals can be measured using a device called an electrocardiograph (ECG).

**Principles of Electrocardiograph Operation**

ECG operates based on the electrical activity of cardiac cells. When the heart beats, depolarization and

repolarization occur within the myocardium, and these changes are recorded by electrodes placed on the skin (Hampton, 2119).

**Main components of an ECG device**

**Electrodes:** Typically, 12 electrodes are placed on the chest and limbs.

**Signal Amplifier:** Amplifies the weak electrical signals of the heart.

**Noise Filters:** Eliminate interfering signals such as muscle tremors.

**Recorder (Printer or Display):** Prints or displays the electrocardiogram trace.

**ECG interpretation**

A normal ECG trace includes the following components:

P wave: Represents atrial depolarization

T wave: Represents ventricular repolarization

QRS complex: Represents ventricular depolarization

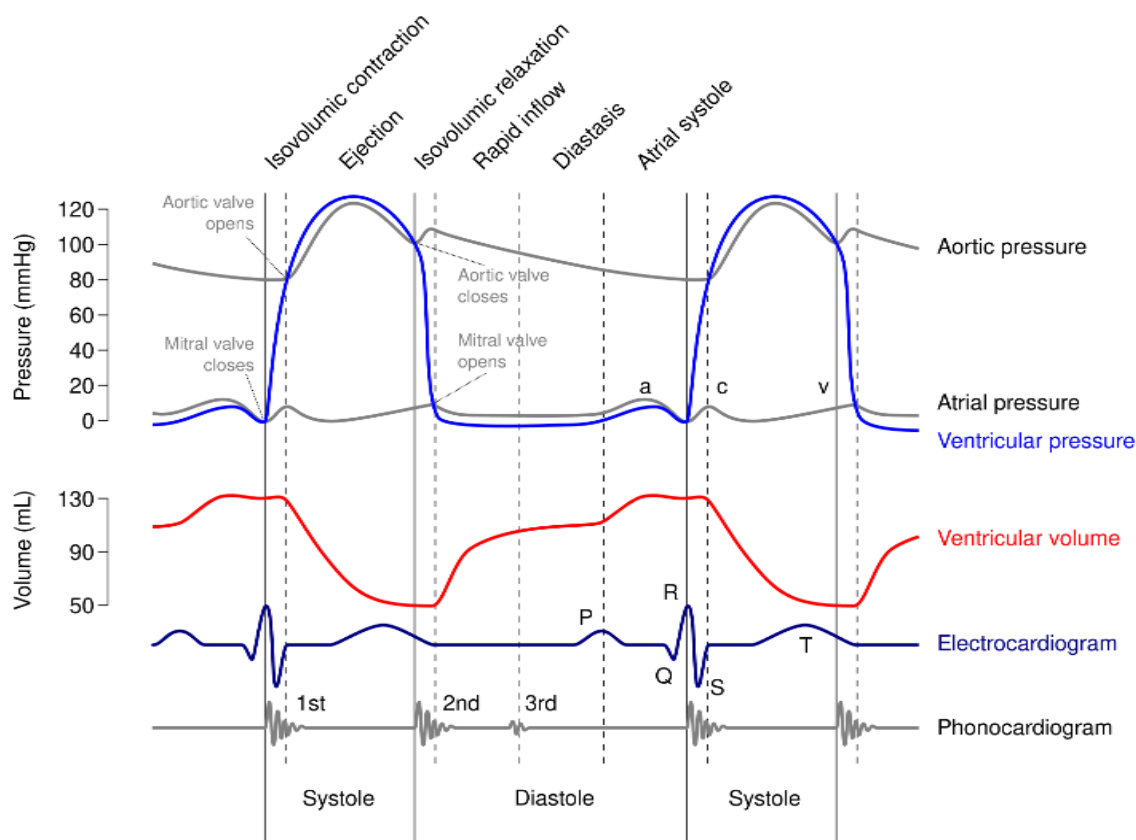


Fig.1: ECG interpretation

### Clinical applications of ECG:

Diagnosis of cardiac arrhythmias (e.g., atrial fibrillation, ventricular tachycardia)

Detection of myocardial ischemia or infarction (heart attack)

Evaluation of the effects of cardiac medications

Monitoring patients during surgeries and in the ICU

### Electrophysiological Foundations of ECG

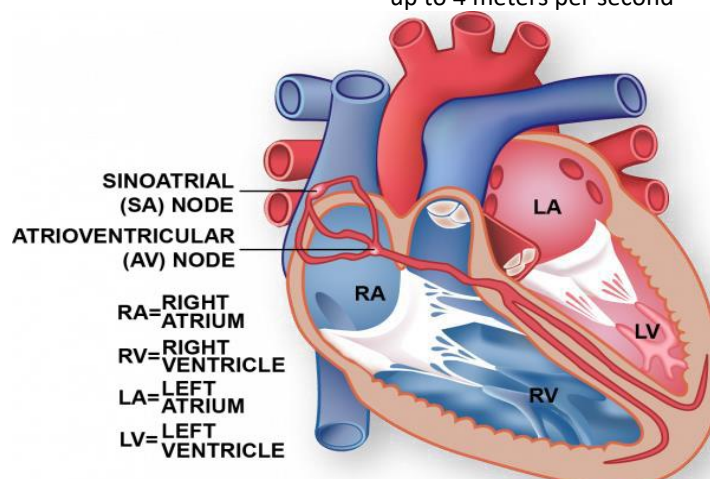
#### A. Hierarchy of Excitability in Cardiac Tissue

The cardiac conduction system includes a complex hierarchy of specialized cells:

Sinoatrial (SA) node cells: Intrinsic frequency of 60–100 beats per minute  
Internodal pathways (Bachmann, Wenckebach, Thorel): Conduction velocity of 1.2 meters per second.

Atrioventricular (AV) node: Physiological delay of 120–200 milliseconds

His bundle and Purkinje fibers: Conduction velocity of 2 up to 4 meters per second



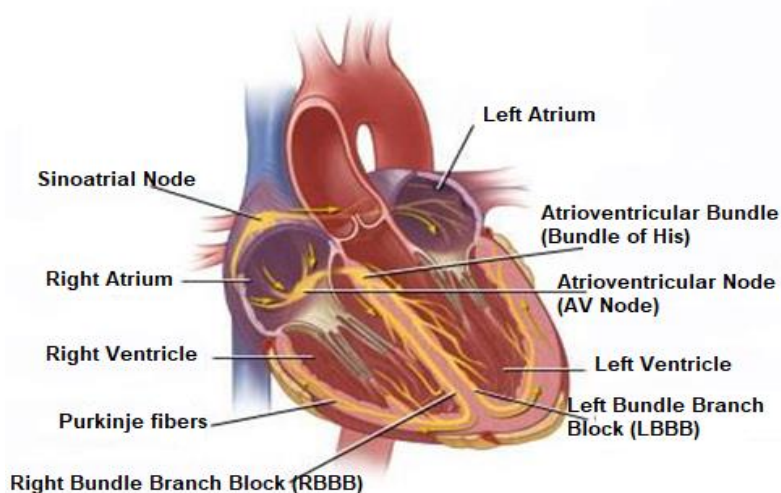


Fig. 2: The cardiac conduction system

Table 1: Comparison of Electrophysiological Properties of Cardiac Tissues:

Tissue	Resting potential (mV)	Depolarization velocity (V/s)	Ischemic sensitivity
Atrial myocyte	85 to 95	100-200	Moderate
Ventricular myocyte	90 to 95	200-300	High
Nodal cells	50 to 60	1-10	Very high

### B. Equivalent Dipole Model of the Heart

According to Einthoven's 1912 theory (and subsequent

developments by Frank in 1954 and Burger in 1968), the heart can be modeled as a time-varying electrical dipole in three-dimensional space.

Vector Components in Three-Dimensional Space:

Frontal Plane:

Standard limb lead axes (I, II, III, aVR, aVL, aVF)

QRS vector angle usually ranges between  $+30^\circ$  to  $+90^\circ$

Horizontal Plane:

Precordial lead axes (V1–V6)

Vector movement from V1 (right anterior wall) to V6 (left lateral wall)

Sagittal Plane:

Anteroposterior axis (often not directly measured in standard 12-lead ECG systems)

Vector orientation usually poster anterior

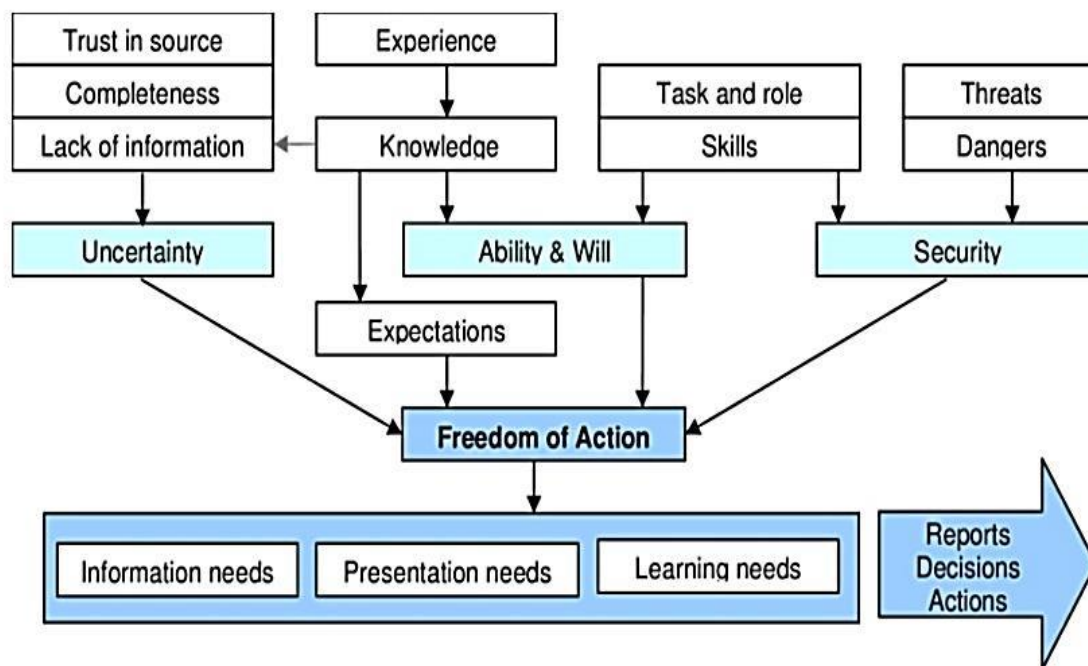


Fig. 3: Methodology

Table 4-2: Vector Characteristics in the Three Principal Planes

Spatial Plane	Corresponding Leads	Normal Vector Angle Range	Clinical Significance
Frontal	I, II, III, aVR, aVL, aVF	+30° to +90°	Axis deviation diagnosis
Horizontal	V1–V6	R-wave progression movement	Ventricular hypertrophy
Sagittal	Z-axis in the Frank system	−30° to +120°	Assessment of right ventricular hypertrophy

### Mathematical equations of the model:

The heart's dipole vector ( $\hat{H}$ ) can be expressed in three-dimensional space as:

$$\hat{H}(t) = x(t)\hat{i} + y(t)\hat{j} + z(t)\hat{k}$$

Where:

$x(t)$ : corresponds to lead I (horizontal component)

$y(t)$ : corresponds to lead aVF (vertical component)

$z(t)$ : commonly represents the sagittal component  
Ready for the next part whenever you are.

### Advanced Technology in ECG Devices

#### 2-1 High-Resolution Recording System Design

The new generation of ECG devices is designed with the following technical specifications:

- Bandwidth: 0.05–150 Hz (according to AHA standard)
- Signal-to-noise ratio: < 120 dB
- Sampling rate: 10 kHz
- ADC resolution: 24-bit

#### 2-2 Artifact Reduction Algorithms

- Baseline wander removal: Band-pass filter with a cutoff frequency of 0.5–0.67 Hz
- Muscle tremor reduction: Navikov-Gabor filter with a 50 ms time window
- Electromagnetic noise elimination: Wavelet-Packer transform with soft thresholding

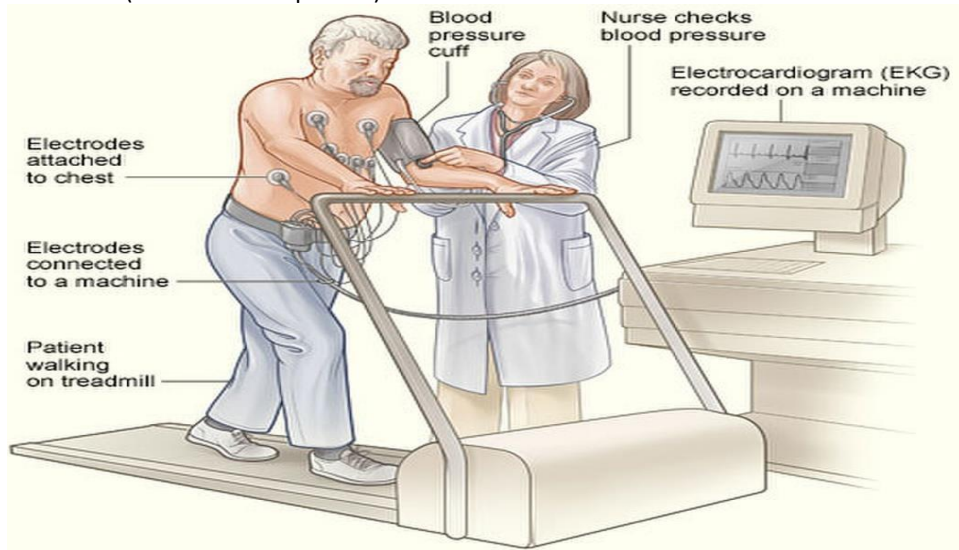


Fig. 3: Sport test

### Advanced ECG Interpretation

A. *Criteria for Diagnosing Ventricular Hypertrophy Based on the Sokolow-Lyon (1949) and Cornell (1987) criteria:*

Sokolow-Lyon Criterion:  $SV_1 + RV_5/V_6 > 3.5$  mV

Cornell Criterion:  $RaVL + SV_3 > 2.8$  mV (men) or  $> 2.1$  mV (women)

These voltage-based criteria are commonly used to detect

left ventricular hypertrophy (LVH) on a standard 12-lead ECG.

#### 3-2 Myocardial Ischemia Detection via ECG

Key dynamic ST-segment changes include:

ST elevation  $> 1$  mm in anatomically contiguous leads

ST depression  $> 1.5$  mm in leads  $V_2$ – $V_3$

Symmetrical inverted T waves: depth  $> 2$  mm in lateral leads

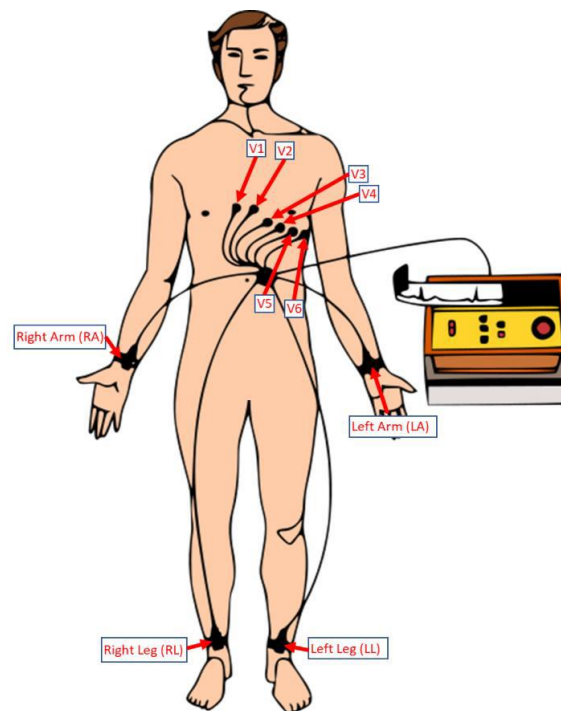


Fig. 4: ECG

## Modern Applications of ECG

### A. Smart Wearable Systems

AFib detection accuracy in Apple Watch: 98.37% (based on Study 2123 published in NEJM)

Multi-day ECG patch: Continuous recording up to 14 days with a resolution of  $1.6 \mu\text{V}$

### 4-2 Integration of ECG with Advanced Imaging

Simultaneous ECG-MRI: Temporal synchronization within 5 ms

Electroanatomic Mapping: Spatial accuracy of approximately  $\pm 1.3 \text{ mm}$

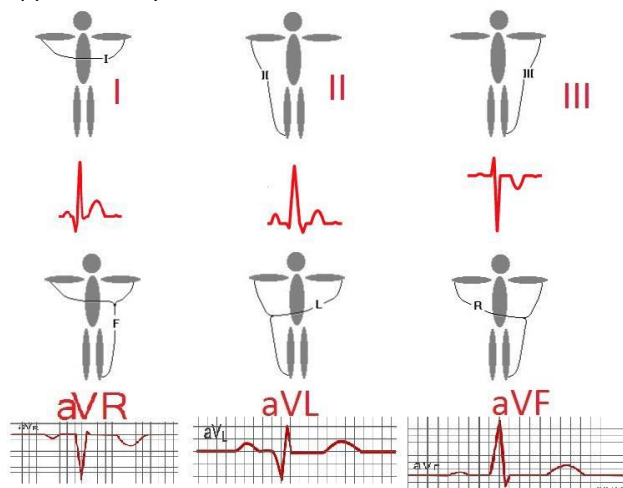


Fig 5. Electro anatomic Mapping

## Key Components of the Electrocardiograph (ECG) Device

The main parts of an ECG machine typically include:

1. Control Panel: Contains buttons for operating the device, such as power on/off, manual/automatic

mode selection, paper speed adjustment, gain control, filter activation, lead selection, start/stop, and volume control.

2. Connection Cables: Includes the power cable, grounding cable (to prevent electrical interference), and lead wires. Depending on the model, the lead cable may support 3, 6, or 12 leads.

3. Display Screen: Present in modern devices; older models may lack a screen.

4. Power Conversion Board: Converts mains electricity to the voltage required by the device.

5. Battery: Most ECG machines can operate on both mains power and internal rechargeable batteries.

6. Printer: Prints the recorded heart signals onto paper for analysis.

7. Amplifier: A high-input-impedance amplifier that boosts the weak electrical signals from the heart.

8. Data Transmission and Storage System: Handles saving, processing, and possibly transmitting ECG data to other systems or networks.

## Recent Advances in ECG Technology Include the Development of the Following Systems:

**Optical ECG:** Utilizes photoplethysmography (PPG) sensors to detect cardiovascular signals through light-based measurements, offering a non-contact or wearable alternative to traditional electrodes.

**Quantum Algorithms:** Reduce signal processing time to near-instantaneous levels (e.g., from classical 1000 states to 1 quantum state), enabling faster and more efficient ECG data interpretation.

**Nano Biosensors:** Allow simultaneous detection of cardiac biomarkers such as troponin during ECG recording, enhancing early diagnosis of myocardial



infarction.

## Conclusion

Given the increasing stress of modern life and the growing need for individuals to monitor their heart health, purchasing an ECG (electrocardiograph) device has become a necessity for medical centers. These devices are available in the market under various brands, and selecting a good one requires careful attention to all its features. Kavoshcom Asia Company, by offering high-quality products, can assist you in this regard.

As a non-invasive diagnostic tool, the electrocardiograph plays a central role in evaluating the heart's electrical activity. By recording the electrical potential changes resulting from cardiac cell activity, it enables the diagnosis of a wide range of disorders, including arrhythmias, myocardial ischemia, ventricular hypertrophy, and electrolyte imbalances. Modern signal processing techniques—such as wavelet transforms and adaptive filters—have significantly enhanced the accuracy of ECG interpretation.

The development of wearable systems and artificial intelligence has transformed ECG from a purely clinical tool into a continuous monitoring technology. Future challenges include integrating ECG with molecular imaging and improving diagnostic precision in specific populations (such as children and obese patients). With recent advances in biosensors and deep learning algorithms, the next generation of ECG devices is expected to offer predictive capabilities for cardiovascular events.

In summary, electrocardiography will not only remain the gold standard for diagnosing heart diseases but is also evolving toward preventive and personalized applications.

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