Birzeit University

Faculty of Engineering & Technology

Department of Electrical & Computer Engineering

ENCS5200

Introduction To Graduation Project

"HeartGuard Project"

Report #1

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Abstract

Cardiovascular diseases remain the leading cause of death worldwide, with early detection being critical to prevent fatal outcomes. The HeartGuard Project proposes an AI-powered system that automatically analyzes ECG (electrocardiogram) signals to classify them as normal or abnormal and prioritizes emergency cases. Using machine learning models such as Convolutional Neural Networks (CNNs), the system identifies patterns in ECG data to detect arrhythmias and other heart conditions. It includes a decision-support layer that flags high-risk cases for immediate medical attention, potentially reducing delays in critical diagnosis. The project also features a user-friendly interface tailored for healthcare professionals, ensuring efficient interaction with AI-generated insights. By combining clinical data preprocessing, intelligent modeling, and real-time prioritization, HeartGuard aims to enhance the speed, accuracy, and accessibility of cardiac diagnostics in both clinical and portable settings.

المستخلص

تُعدّ أمراض القلب من الأسباب الرئيسية للوفيات عالميًا، ويُعدّ الاكتشاف المبكر لها ضروريًا لتفادي العواقب الخطيرة. يهدف مشروع "HeartGuard"إلى تطوير نظام ذكي قائم على الذكاء الاصطناعي لتحليل إشارات تخطيط القلب الكهربائي (ECG) وتصنيفها إلى طبيعية أو غير طبيعية، مع التركيز على تحديد الحالات الطارئة أولاً. يعتمد النظام على نماذج تعلم آلي مثل الشبكات العصبية الالتفافية (CNNs)لاكتشاف أنماط غير طبيعية قد تدل على اضطرابات في نظم القلب. ويتضمن طبقة دعم اتخاذ قرار تقوم بتمييز الحالات عالية الخطورة وإبرازها للأطباء لتلقي الرعاية بشكل أسرع. كما يتميز المشروع بواجهة استخدام بسيطة وفعّالة مخصصة للعاملين في المجال الصحي. ومن خلال دمج معالجة البيانات الطبية والنمذجة الذكية وآلية ترتيب الأولويات في الوقت الفعلي، يسعى HeartGuard إلى تحسين سرعة ودقة وتوفّر تشخيص أمراض القلب في البيئات السريرية والمحمولة.

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1.1 Motivation

Heart disease is one of the leading causes of death around the world. Detecting heart problems early is very important to prevent serious outcomes like heart attacks. Doctors use ECG (electrocardiogram) signals to check heart activity, but reading and understanding these signals takes time and expertise. In busy hospitals, it can be hard for doctors to quickly identify which patients need urgent care, especially when ECGs are checked in the order patients arrive, not based on how serious their condition is.

The Heart Guard Project aims to solve this problem by using artificial intelligence to read and analyze ECG signals. The system can detect if a heart signal is normal or if there may be a problem. It can also help doctors by highlighting emergency cases first, so they can give faster care to patients who are in danger.

This AI-based tool can save time, reduce mistakes, and support doctors in making better decisions. With the rise of portable ECG devices and smart health technology, Heart Guard can make heart monitoring easier, faster, and more available to everyone.

1.2 Problem Statement

In many hospitals and clinics, doctors review ECG results in the order patients arrive, without knowing which cases are urgent. This can delay treatment for patients who are experiencing serious heart issues, putting their lives at risk. Additionally, analyzing ECG signals requires medical expertise, and the process can be time-consuming—especially in busy or under-resourced healthcare environments.

There is a need for an intelligent system that can automatically analyze ECG signals, detect abnormalities, and highlight critical cases for immediate attention. Such a system would support doctors in making faster and more accurate decisions, reduce the chances of missed emergencies, and improve patient outcomes. The lack of such a tool represents a major gap in current healthcare support systems, especially as heart disease continues to be a leading cause of death worldwide.

1.3 Methodology

The Heart Guard Project follows a structured approach to design and develop an AI-based system capable of analyzing ECG signals and detecting potential heart abnormalities. The methodology consists of the following key stages:

1.3.1 Data Collection

We begin by gathering a large dataset of ECG signals from publicly available medical databases. These datasets include signals labeled as normal or representing specific heart conditions (such as arrhythmias). Proper data preprocessing is performed to clean the signals and ensure consistency.

1.3.2 Signal Processing

The collected ECG signals are filtered and normalized to remove noise and irrelevant variations. This step ensures that the AI model receives clear and meaningful inputs. Key features such as heart rate, QRS complex, and P and T waves are extracted from the signals.

1.3.3 AI Model Development

A machine learning model—such as a Convolutional Neural Network (CNN)—is trained on the preprocessed ECG data. The model learns to classify ECG patterns as either normal or abnormal, and may also identify the type of heart condition present. Various models may be tested to compare performance and accuracy.

1.3.4 Emergency Detection and Prioritization

The system includes a decision-making layer that ranks ECG inputs based on severity. If the model detects a potentially dangerous abnormality, it flags the case as high-priority. This helps doctors quickly identify patients who need urgent medical attention.

1.3.5 System Testing and Evaluation

The AI model is tested using unseen ECG data to evaluate accuracy, precision, recall, and overall performance. The system is fine-tuned to minimize false positives and false negatives. Feedback from medical professionals may also be used to improve results.

1.3.6 User Interface Development

A simple and intuitive user interface is developed for healthcare professionals. The interface displays analyzed ECG results, highlights emergency cases, and allows doctors to view signal patterns and AI-based suggestions.

1.4 Contribution

The Heart Guard Project contributes to the field of healthcare technology by proposing an intelligent system that uses artificial intelligence to analyze ECG signals and support early detection of heart conditions. The main contributions of this project include:

- Developing a machine learning model capable of distinguishing between normal and abnormal ECG signals.
- Designing a system that automatically flags high-risk or emergency cases to help doctors prioritize urgent patients.
- Creating a user-friendly interface that allows healthcare professionals to quickly interpret AI-generated results.
- Reducing the time and effort required for manual ECG analysis, especially in high-pressure or resource-limited environments.
- Supporting the broader goal of making cardiac diagnostics more accessible, accurate, and responsive through AI integration.

This contribution sets the foundation for future work, including integration with real-time wearable devices and expanding the model to detect a wider range of heart conditions.

1.5 Report Outline

This report is organized into several chapters, each addressing a key aspect of the Heart Guard Project:

- **Chapter 1 – Introduction:** Provides the background, motivation, problem statement, project contribution, and an overview of the report structure.
- **Chapter 2 – Medical Background:**

Chapter 2 Medical Background

Cardiovascular Physiology and ECG Fundamentals.

2.1 Understanding Heart Function and Circulation

2.1.1 Differences Between Arteries, Veins, and Capillaries

The human circulatory system consists of three main types of blood vessels: arteries, veins, and capillaries, each playing a distinct role in blood transport and exchange.

- **Arteries (الشرايين):**
  - Carry oxygen-rich blood away from the heart to body tissues (except the pulmonary artery).
  - Located deeper in the body and not visible through the skin.
  - Have thick muscular walls to withstand high pressure.
  - Produce a palpable pulse.

- **Veins (الأوردة):**
  - Carry oxygen-poor blood back to the heart (except the pulmonary veins).
  - Often visible under the skin.
  - Have thinner walls and valves to prevent backflow due to lower pressure.
  - Do not produce a pulse.

- **Capillaries (الشعيرات الدموية):**
  - The smallest blood vessels, forming networks between arteries and veins.
  - Consist of a single thin layer of endothelial cells.
  - Allow for exchange of oxygen, nutrients, and waste between blood and tissues.
  - Visible under the skin in some areas as red or purple lines.

Note: The p**ulmonary artery** carries deoxygenated blood, and the **pulmonary veins** carry oxygenated blood, which is the opposite of the systemic circulation.

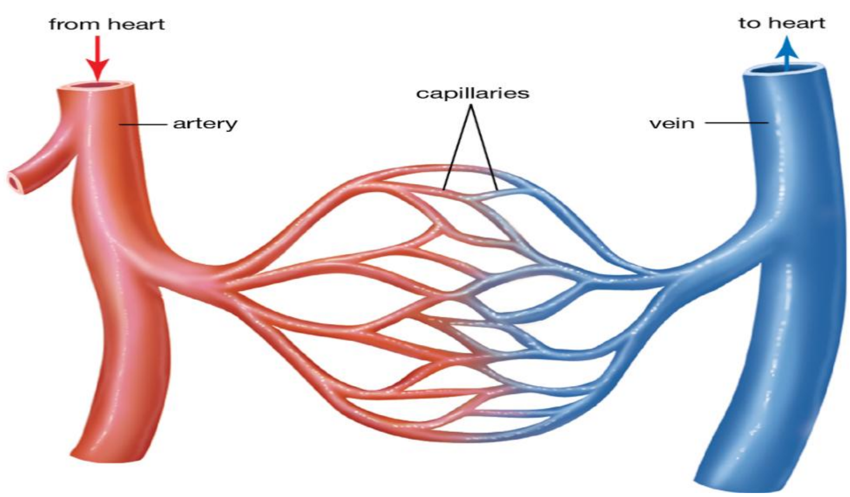


Figure 1: Visual comparison between arteries, veins, and capillaries

2.1.2 Anatomy of the Heart

The heart is a muscular organ responsible for pumping blood throughout the body via the circulatory system. It consists of four main chambers and several valves that regulate blood flow:

- **Right Atrium (الأذين الأيمن):** Receives deoxygenated blood from the body via the superior and inferior vena cava.
- **Right Ventricle (البطين الأيمن):** Pumps deoxygenated blood to the lungs via the pulmonary artery.
- **Left Atrium (الأذين الأيسر):** Receives oxygenated blood from the lungs via the pulmonary veins.
- **Left Ventricle (البطين الأيسر):** Pumps oxygenated blood to the rest of the body through the aorta.

🩺 Valves regulate unidirectional blood flow:

- **Tricuspid Valve (الصمام ثلاثي الشرفات):** Between right atrium and right ventricle.
- **Mitral Valve (الصمام المترالي):** Between left atrium and left ventricle.

🫀 Major vessels:

- **Aorta (الشريان الأورطي):** The main artery carrying oxygenated blood to the body.
- **Pulmonary Artery (الشريان الرئوي):** Carries deoxygenated blood to the lungs.
- **Pulmonary Veins (الأوردة الرئوية):** Bring oxygenated blood back to the heart.
- **Superior & Inferior Vena Cava (الوريد الأجوف العلوي والسفلي):** Bring deoxygenated blood from the body back to the heart.

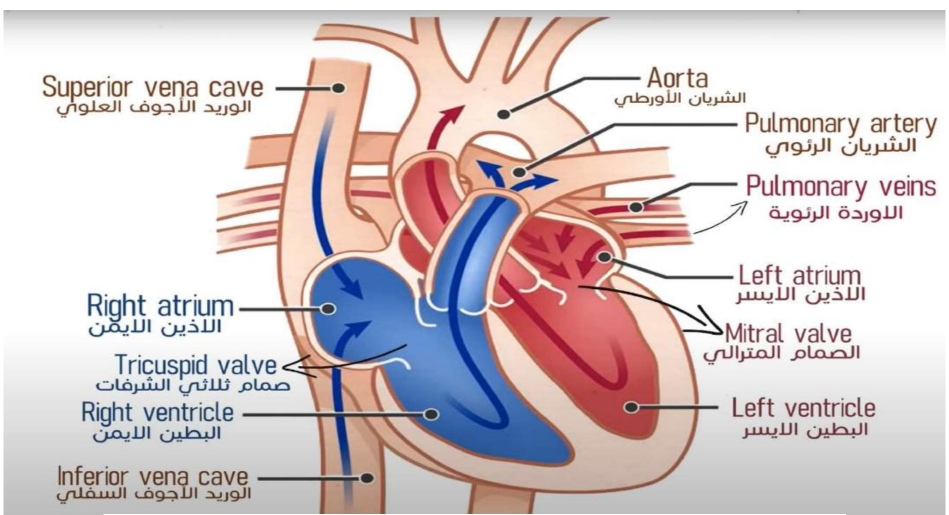


Figure 2: Diagram showing the anatomical structure of the human

2.1.3 How the Heart Pumps Blood

The heart functions as a **double pump** that circulates blood through two main circuits**: the pulmonary circulation** (to the lungs) and **the systemic circulation** (to the rest of the body). This process occurs in the following steps:

- **Step 1: Deoxygenated Blood Enters the Heart**

Deoxygenated blood from the body returns to the heart via the superior and inferior vena cava. It enters the right atrium (الأذين الأيمن).

- **Step 2: Blood Moves to the Right Ventricle**

The blood then flows through the tricuspid valve (الصمام ثلاثي الشرفات) into the right ventricle (البطين الأيمن).

- **Step 3: Blood Is Pumped to the Lungs**

When the right ventricle contracts, it pumps the blood through the pulmonary valve into the pulmonary artery (الشريان الرئوي), which carries the blood to the lungs for oxygenation.

- **Step 4: Oxygenated Blood Returns to the Heart**

The oxygen-rich blood from the lungs returns via the pulmonary veins (الأوردة الرئوية) to the left atrium (الأذين الأيسر).

- **Step 5: Blood Moves to the Left Ventricle**

It then passes through the mitral valve (الصمام المترالي) into the left ventricle (البطين الأيسر).

- **Step 6: Blood Is Pumped to the Body**

Finally, the left ventricle pumps the oxygenated blood through the aortic valve into the aorta (الشريان الأورطي), delivering it to the rest of the body.

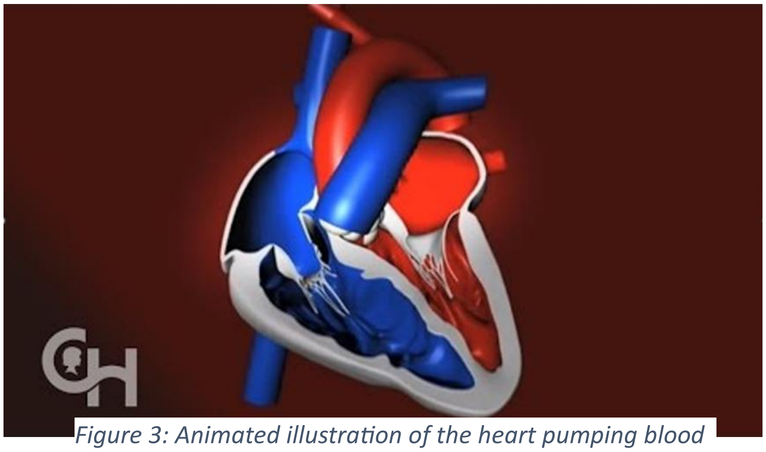


Figure 3: Animated illustration of the heart pumping blood

Watch the full animation here: https://www.youtube.com/watch?v=JA0Wb3gc4mE

2.2 ECG – Electrocardiogram Overview

2.2.1 Introduction to ECG

The Electrocardiogram (ECG) is a non-invasive diagnostic tool used to record the electrical activity of the heart over time. The name is derived from:

- **Electro (كهربة):** Refers to electrical activity.
- **Cardio (قلب):** Refers to the heart.
- **Gram (رسم/تصوير):** Refers to the recording or graphic representation.

ECG machine: A device used to capture and display the heart's electrical signals.

What Does ECG Record?

- ECG records the electrical impulses generated during each heartbeat.
- It reflects the cardiac cycle, specifically the depolarization (contraction) and repolarization (relaxation) of atrial and ventricular muscles.

Electrical vs. Mechanical Activity

- **Electrical Force:**
  - Depolarization = Activation leading to contraction
  - Repolarization = Recovery leading to relaxation
- **Mechanical Force:**
  - Contraction = Muscle tightening (systole)
  - Relaxation = Muscle loosening (diastole)

In ECG terms:

- Atrial depolarization = Atrial contraction
- Ventricular repolarization = Ventricular relaxation

The ECG provides vital information about the rhythm, rate, and electrical orientation of the heart, which can be crucial for diagnosing cardiac abnormalities.

2.2.2 How the Heart Produces Electrical Activity

The heart generates its electrical impulses through a specialized conduction system that controls the timing and rhythm of each heartbeat. This electrical system ensures that the atria and ventricles contract in a coordinated manner. Here's how the process works:

- **Sinoatrial (SA) Node – The Pacemaker**

  - **SA Node (العقدة الجيب أذينية):** is located in the right atrium.
  - It initiates the electrical impulse that spreads across both atria, triggering atrial depolarization, which corresponds to atrial contraction.
  - This action appears on the ECG as the P wave.

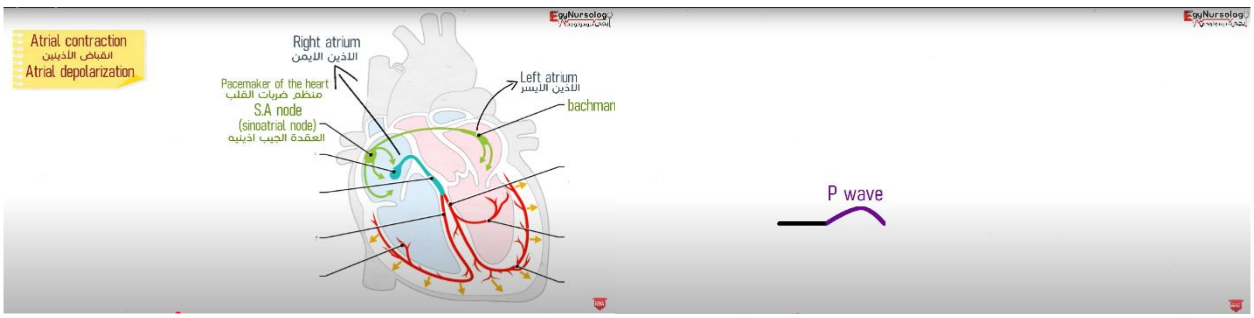


Figure 4: Electrical signal starts at the SA node and spreads to both

- **Bundle of His and Purkinje Fibers – Ventricular Activation**

  - After the AV node, the impulse travels through the **Bundle of His**, then splits into:
    - Right and left bundle branches.
    - Purkinje fibers, which spread the impulse across the ventricles.
  - This results in ventricular depolarization, causing ventricular contraction.
  - Appears on the ECG as the QRS complex.

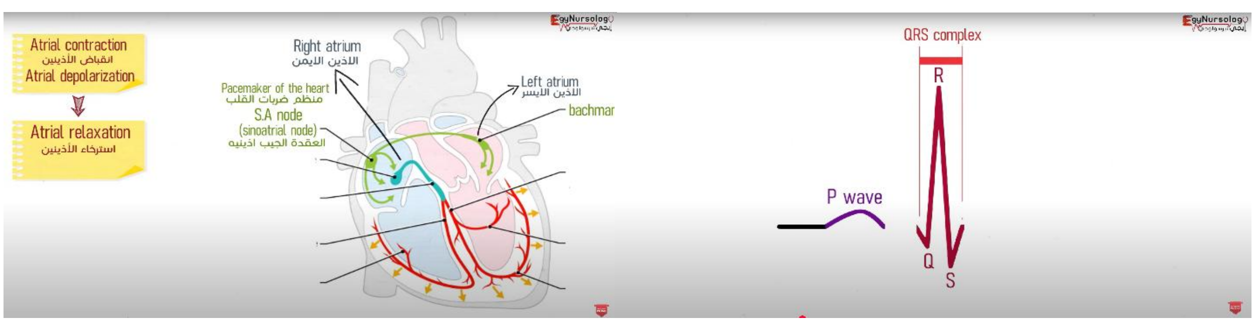


Figure 5: Ventricular depolarization shown by the red QRS complex.

- **Atrioventricular (AV) Node – The Delay Station**
  - The impulse travels to the AV node (العقدة الأذينية البطينية).
  - A short delay allows the ventricles to fill with blood before they contract.
  - This delay is represented on the ECG as the PR interval.

Figure 6: The delay in the AV node shows up as a flat line before the QRS complex.

- **Repolarization – Recovery Phase**

- After contraction, the heart muscle cells recover electrically:
  - Ventricular repolarization = ventricular relaxation → T wave
  - Atrial repolarization is not seen on ECG because it is masked by the QRS.

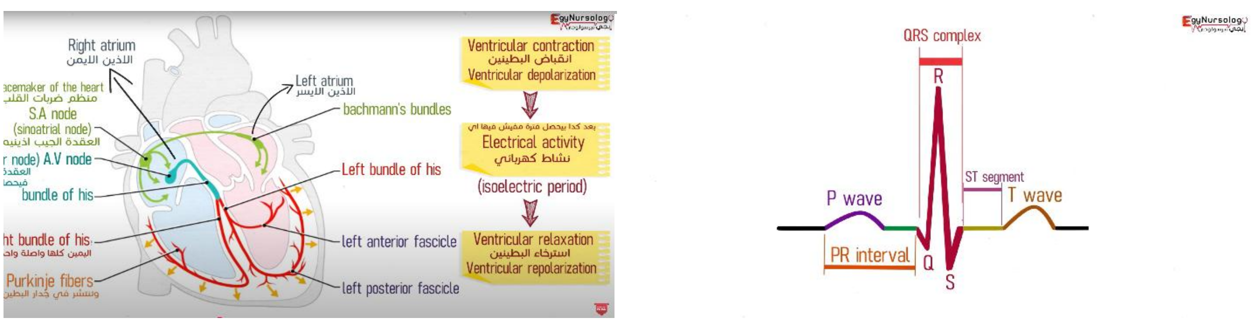


Figure 7: Complete ECG with labeled P wave, QRS complex, and T wave.

Note:

- **The ST segment** represents an electrically silent phase between depolarization and repolarization.
- **The U wave** may appear in some ECGs and is commonly associated with hypokalemia (low potassium levels).

Summary of Electrical Events:

ECG Component	Cardiac Event	Electrical Action	Mechanical Outcome
P wave	Atrial depolarization	SA node fires	Atrial contraction
PR interval	AV node delay	Signal slows down	Ventricles fill
QRS complex	Ventricular depolarization	Rapid signal spread	Ventricular contraction
T wave	Ventricular repolarization	Recovery phase	Ventricular relaxation

Table 1: ECG Components and Their Corresponding Cardiac Events

2.2.3 Basics of Reading an ECG

The ECG (Electrocardiogram) is plotted on a standardized grid paper. Understanding the structure of this paper is essential for measuring time intervals and voltage, which are critical for interpreting heart rhythms and detecting abnormalities.

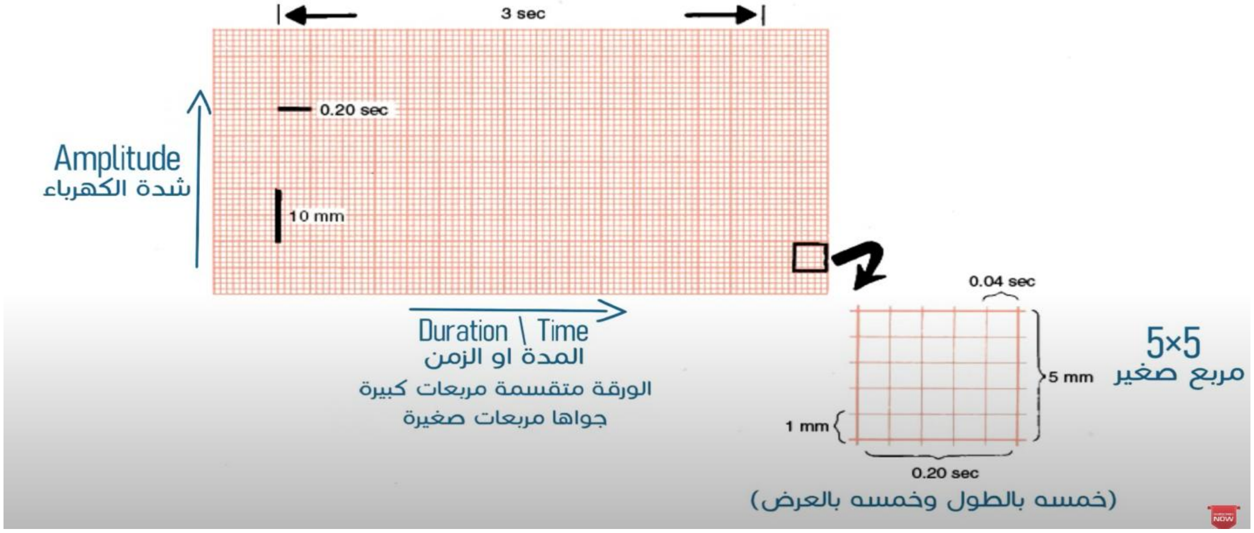


Figure 8: ECG grid showing time and amplitude divisions

ECG Paper Structure:

- Each small square = 0.04 sec (time) / 0.1 mV (voltage)
- Each large square = 0.20 sec = 5 small squares / 0.5 mV
- Horizontal lines = time axis
- Vertical lines = amplitude axis
- Used to measure wave duration and signal strength

Heart Rate Calculation:

- **300 Rule:** Count large squares between two R waves → Heart rate = 300 ÷ squares
- **1500 Rule**: Count small squares between R-R → Heart rate = 1500 ÷ squares
- **6-Second Method:** Count R peaks in 6 seconds (30 large boxes) × 10

Amplitude and Duration:

- Vertical lines = electrical voltage (amplitude)

Horizontal lines = time (duration of wave)

Types of Leads:

- **Bipolar limb leads:** Lead I, II, III → measure between two limbs
- **Unipolar augmented leads:** aVR, aVL, aVF → compare one limb to center
- **Chest leads:** V1 to V6 → provide horizontal view of the heart

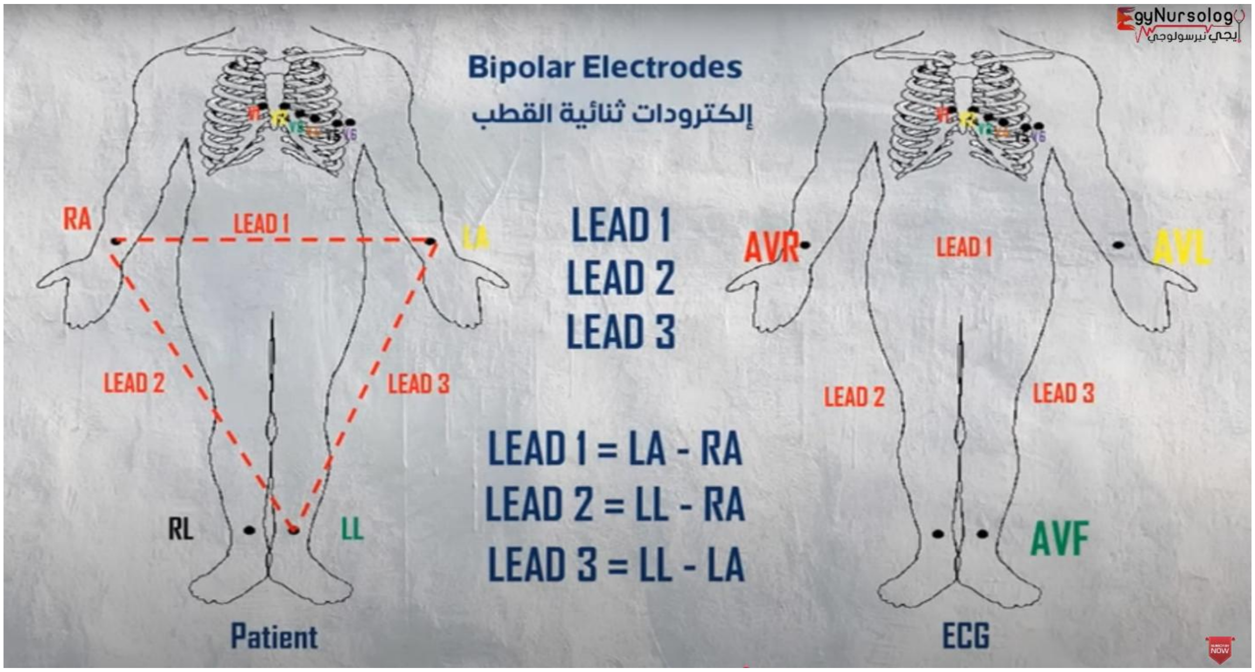


Figure 9: Electrode placement for bipolar and unipolar limb leads

Chest Lead Zones:

- V1–V2: Right ventricle
- V3–V4: Interventricular septum
- V5–V6: Left ventricle

12-Lead ECG System:

- Consists of 12 views.
- Each lead gives a different angle of the heart's electrical activity
- Used to detect ischemia, infarction, conduction blocks, and axis deviation

2.3 Step-by-Step ECG Interpretation

2.3.1 Rhythm – Heartbeat Regularity

One of the first steps in ECG interpretation is evaluating the rhythm, which refers to whether the heartbeats occur at regular or irregular intervals. This is assessed by measuring the distance between similar waves—typically the R-R intervals.

- **Regular Rhythm:**
  - The distance between R waves is consistent.
  - Indicates stable pacemaker activity.

- **Irregular Rhythm:**
  - R-R intervals are uneven.
  - Could be due to:
    - **Atrial Fibrillation:** Irregular, rapid atrial activity without visible P waves.

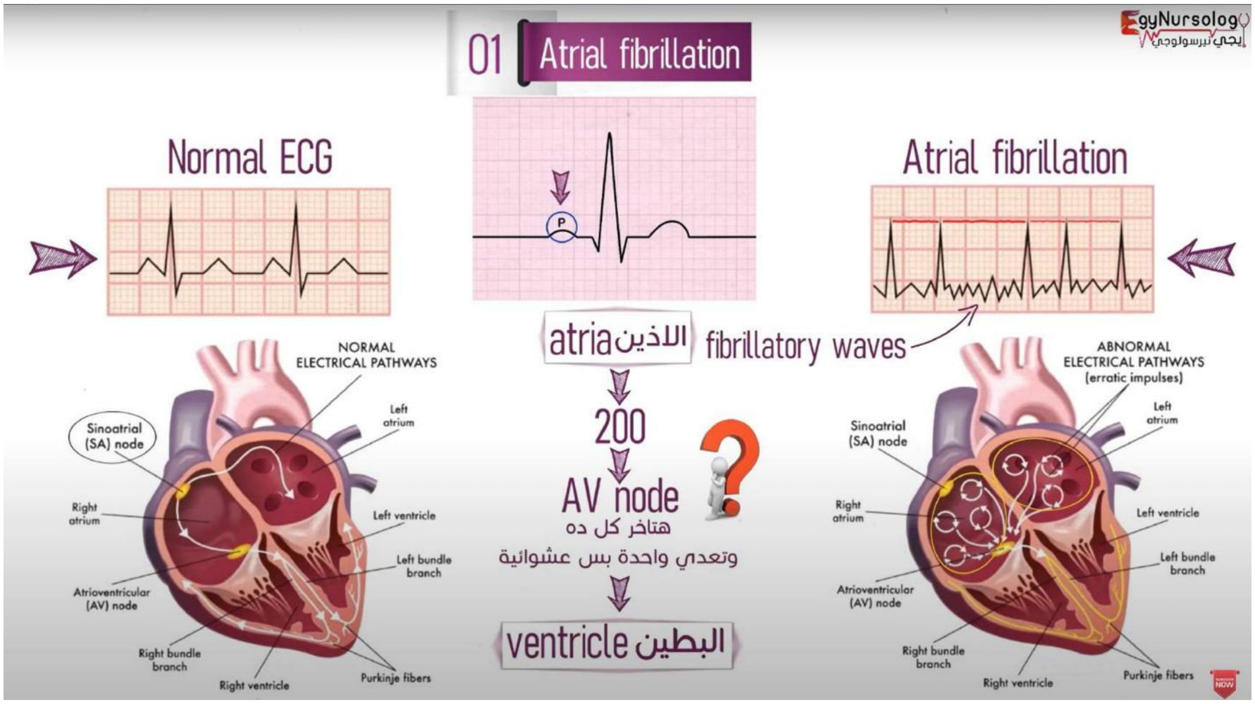


Figure 10: Comparison between Normal ECG and Atrial Fibrillation Rhythm

- **Premature Contractions:** Early beat interrupts the normal rhythm. Can be:
  - **PAC (Premature Atrial Contraction):** Narrow QRS complex.

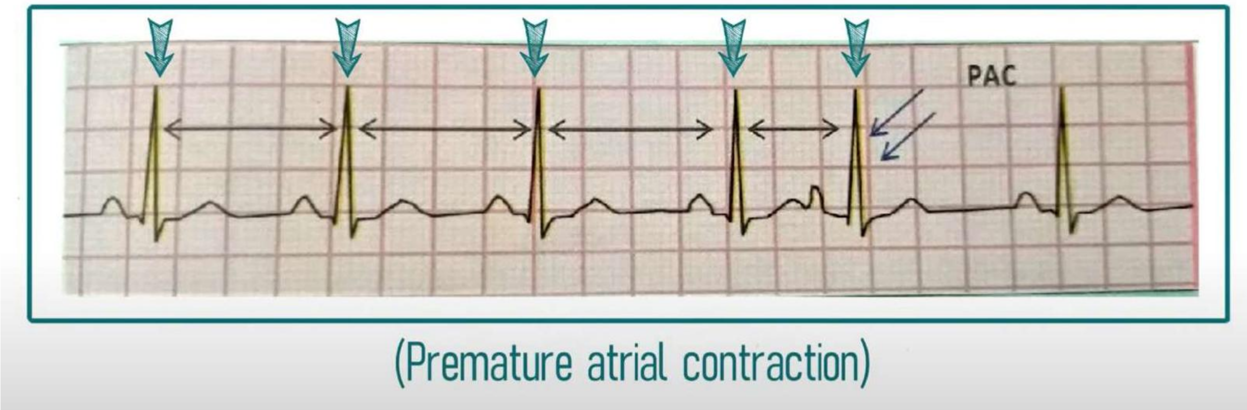


Figure 11: PAC showing early beat with narrow QRS

  - **PVC (Premature Ventricular Contraction):** Wide QRS complex.

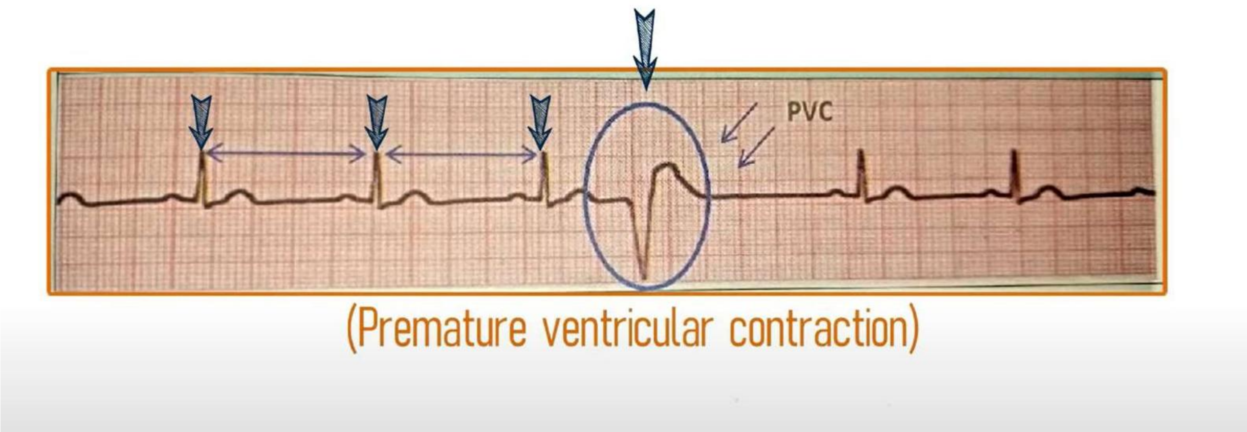


Figure 12: PVC showing early beat with wide QRS

2.3.2 Heart Rate – Calculating Beats Per Minute

Heart rate is the number of beats the heart generates per minute. It can be measured from the ECG by analyzing the R-R intervals using various methods:

➢ **300 Rule:**
- Count the number of large squares between two successive R waves
- Heart Rate = 300 ÷ number of large squares
- Applicable when rhythm is regular

➢ **1500 Rule:**
- Count the number of small squares between two R waves
- Heart Rate = 1500 ÷ number of small squares
- More precise than the 300 rule

➢ **6-Second Rule:**
- Count the number of R waves within 30 large squares (6 seconds)
- Heart Rate = Number of R waves × 10
- Useful when the rhythm is irregular

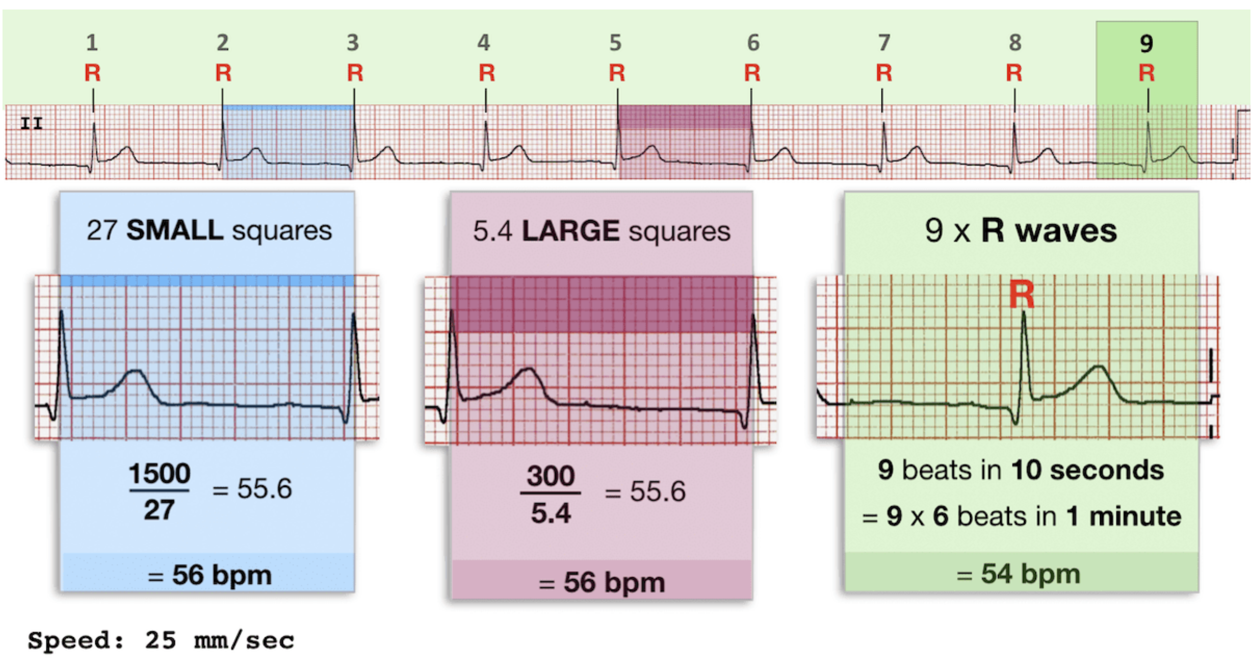


Figure 13: Methods of calculating heart rate using R-R interval spacing on ECG paper

2.3.3 Voltage – Signal Strength

The voltage on an ECG represents the strength of the electrical activity in the heart and is measured on the vertical (Y) axis of the ECG paper.

Each small square vertically = 0.1 mV
Each large square vertically = 0.5 mV (0.1 mV × 5)

🔷 **Normal Voltage Ranges:**

- **P wave:** ≤ 2.5 mm (0.25 mV)
- **QRS complex:** 5–30 mm (0.5–3.0 mV)
- **T wave:** ≤ 10 mm (1.0 mV)

🔻 **Low Voltage:**

- Defined as QRS amplitude < 5 mm in limb leads or < 10 mm in precordial leads
- May indicate: Pericardial effusion, Obesity, Pulmonary disease, Hypothyroidism.

2.3.4 Position of the Heart

The position of the heart within the chest affects the direction of its electrical axis, which is reflected in the ECG. Evaluating this axis can help determine whether the heart is in a normal position or shifted abnormally.

Normal Heart Axis:

- The electrical signals travel downward and to the left.
- Appears as positive (upright) QRS in both Lead I and aVF.
- Axis angle: **–30° to +90°**

Left Axis Deviation (LAD):

- The heart's electrical axis is shifted to the left.
- QRS is positive in Lead I and negative in aVF.
- Possible causes: **Left ventricular hypertrophy**, **left bundle branch block**, or **inferior myocardial infarction**.

Right Axis Deviation (RAD):

- The electrical axis is shifted to the right.
- QRS is negative in Lead I and positive in aVF.

Possible causes: **Right ventricular hypertrophy**, **pulmonary conditions**, or **congenital heart disease**.

2.3.5 Electrical Axis of the Heart

The electrical axis of the heart represents the average direction of ventricular depolarization during the QRS complex. It is a crucial part of ECG interpretation and can indicate normal or pathological conditions based on the axis angle.

🔹 **Normal Axis:**

- QRS is **positive in Lead I** and **positive in Lead aVF**.
- Axis angle is between **–30° to +90°**.
- Indicates normal electrical conduction.

🔻 **Left Axis Deviation (LAD):**

- QRS is **positive in Lead I** and **negative in Lead aVF**.
- Axis angle is between **–30° to –90°**.
- Common causes:
  • Left ventricular hypertrophy
  • Left anterior fascicular block
  • Inferior myocardial infarction

🔻 **Right Axis Deviation (RAD):**

- QRS is **negative in Lead I** and **positive in Lead aVF**.
- Axis angle is between **+90° to +180°**.
- Common causes:
  • Right ventricular hypertrophy
  • Pulmonary hypertension
  • Chronic lung disease

🔻 **Extreme Axis Deviation (Northwest Axis):**

- QRS is **negative in Lead I and negative in Lead aVF**.
- Axis angle is **from –90° to ±180°**.
- May indicate:
  • Ventricular rhythms
  • Severe ventricular hypertrophy
  • Misplaced leads

2.4 Detailed ECG Wave Explanation

2.4.1 P Wave

The **P wave** represents **atrial depolarization**, which is the electrical activation of the atria prior to their contraction.

- **Normal Shape:** Smooth and rounded.
- **Duration:** ≤ 0.12 seconds (3 small squares).
- **Amplitude:** ≤ 2.5 mm (0.25 mV) in limb leads.
- **Location:** Precedes each QRS complex.
- **Clinical Significance:**
    - A normal P wave suggests proper **SA node** activity.
    - Abnormal P waves may indicate:
        - **Right atrial enlargement** → peaked P wave (P pulmonale).
        - **Left atrial enlargement** → notched or widened P wave (P mitrale).
        - **Absent P wave** → may suggest atrial fibrillation or junctional rhythm.

2.4.2 PR Interval

The PR interval represents the time taken for the electrical impulse to travel from the **sinoatrial (SA) node** through the **atria**, **AV node**, and into the **ventricles**. It reflects **atrial depolarization and AV nodal delay**.

◆ **Normal Duration:**

- 0.12 to 0.20 seconds (3–5 small squares on ECG paper)

◆ **Clinical Significance:**

- **Prolonged PR interval (>0.20 sec)** may indicate **first-degree AV block**
- **Short PR interval (<0.12 sec)** can be seen in **pre-excitation syndromes** like Wolff–Parkinson–White (WPW)

◆ **Measured From:**

- The **start of the P wave** to the **start of the QRS complex**

2.4.3 QRS Complex

The **QRS complex** represents **ventricular depolarization**, the process that triggers **ventricular contraction**. It is one of the most important components in ECG analysis due to its role in assessing conduction speed, rhythm, and the electrical health of the ventricles.

- **Structure:**
  - **Q wave**: Initial negative deflection
  - **R wave**: First positive deflection
  - **S wave**: Negative deflection following the R wave

- **Normal Duration:**
  - **0.06 – 0.10 seconds** (1.5 to 2.5 small squares)
  - A QRS duration > **0.12 seconds** is considered prolonged and may suggest **bundle branch block**, **ventricular rhythm**, or **electrolyte disturbances**

- **Clinical Notes:**
  - **Tall R waves** may indicate **ventricular hypertrophy**
  - **Deep Q waves** may suggest **previous myocardial infarction**
  - **Wide QRS** may indicate delayed ventricular conduction

2.4.4 ST Segment

The **ST segment** represents the interval between **ventricular depolarization and repolarization**. It begins at the end of the QRS complex (J point) and ends at the beginning of the T wave.

- **Normal Characteristics:**
  - Usually **isoelectric** (flat, on the baseline)
  - Follows the S wave and precedes the T wave
  - Duration is variable, but **no elevation or depression** is expected in healthy individuals

- **Clinical Significance:**
  - **ST Elevation:**
    • May indicate **acute myocardial infarction (STEMI)**
    • Can also appear in **pericarditis** or **early repolarization**
  - **ST Depression:**
    • Suggests **myocardial ischemia**, **digitalis effect**, or **ventricular strain**

2.4.5 T Wave

The **T wave** represents **ventricular repolarization**, the electrical recovery phase that follows ventricular contraction. It is a crucial marker for electrolyte balance and myocardial health.

◆ **Normal Characteristics:**

- Upright in most leads (especially I, II, V3–V6)
- Smooth, asymmetrical shape (gradual upstroke and steeper downstroke)
- **Amplitude:**
  • Limb leads: ≤ 5 mm
  • Precordial leads: ≤ 10 mm

◆ **Clinical Significance:**

- **Tall/Peaked T waves:**
  • May indicate **hyperkalemia**
- **Inverted T waves:**
  • Suggest **ischemia**, **ventricular hypertrophy**, or **CNS injury**
- **Flattened T waves:**
  • May indicate **hypokalemia**

2.4.6 QT Interval

The **QT interval** represents the total time for **ventricular depolarization and repolarization**. It includes both the **QRS complex** and the **T wave** and varies with heart rate.

◆ **Normal Duration:**

- **Corrected QT (QTc):**
  • Men: ≤ 440 ms
  • Women: ≤ 460 ms
- Measured from the **beginning of QRS** to the **end of T wave**

◆ **Clinical Significance:**

- **Prolonged QT interval:**
  • Risk of **torsades de pointes**, a life-threatening arrhythmia
  • Can be caused by:
    - Medications (antiarrhythmics, antipsychotics)
    - Electrolyte disturbances (low K^+, Mg^{2+}, Ca^{2+})
    - Congenital long QT syndrome
- **Short QT interval:**
  • May indicate **hypercalcemia** or **short QT syndrome**

2.4.7 U Wave

The **U wave** is a small, often subtle deflection that follows the T wave. Its exact origin is uncertain but is believed to represent **late repolarization of the Purkinje fibers**.

- **Normal Characteristics:**
  - **Small and upright**, best seen in **leads V2–V3**
  - Amplitude: ≤ 1.5 mm
  - Follows the T wave, often merging with it when heart rate is fast
- **Clinical Significance:**
  - **Prominent U waves** may be seen in:
    • **Bradycardia**
    • **Hypokalemia**
    • **Hypothermia**
    • **Antiarrhythmic drug use** (e.g., amiodarone)
  - **Inverted U waves** may indicate **ischemia** or **left ventricular overload**
- **Note:**
  - U waves are not always visible and are considered a **normal variant** unless exaggerated or inverted.

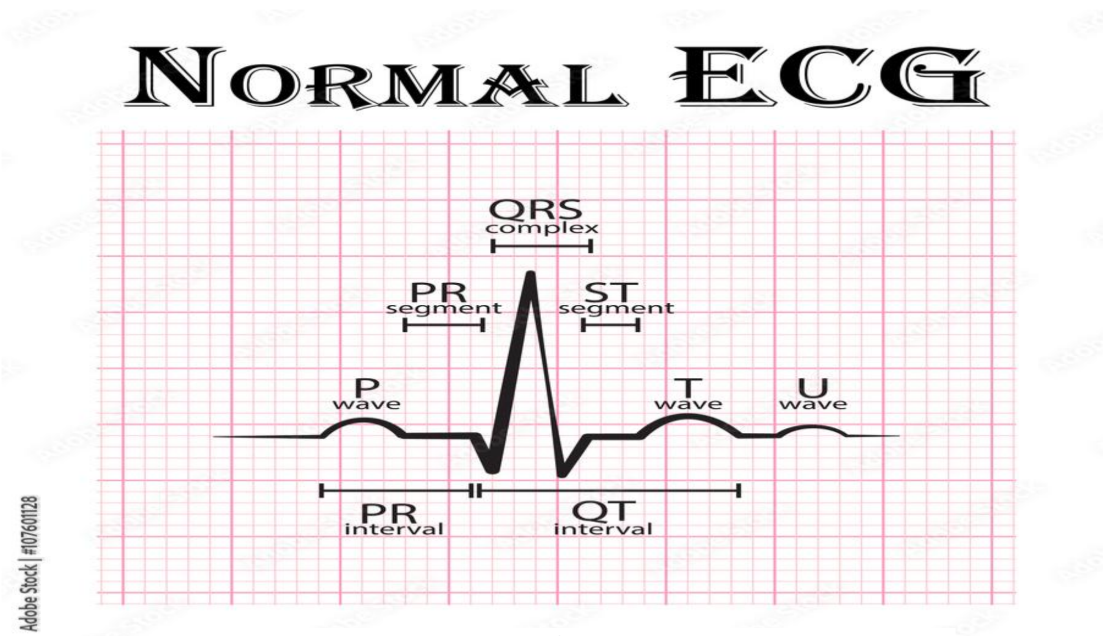


Figure 14: Comprehensive ECG waveform illustrating all key components

Chapter 3 Literature Review

A number of studies and technological advancements in recent years have emphasized the importance of automated ECG interpretation using machine learning techniques. This literature review summarizes key findings from previous research to support the relevance and feasibility of the HeartGuard Project.

3.1 ECG Signal Analysis and Classification

Traditional ECG interpretation is time-consuming and highly dependent on the expertise of cardiologists. Numerous researchers have explored automated methods to improve diagnostic accuracy and efficiency. For instance, **Acharya et al. (2017)** proposed a deep convolutional neural network (CNN) model for classifying ECG beats, achieving high accuracy in detecting arrhythmias. Their work demonstrated the potential of deep learning in capturing complex ECG signal patterns, even in noisy environments.

Another study by **Hannun et al. (2019)** utilized a large dataset of single-lead ECG signals and trained a deep neural network capable of detecting multiple rhythm types, achieving performance comparable to board-certified cardiologists. These findings confirm the viability of AI-assisted ECG interpretation in real clinical settings.

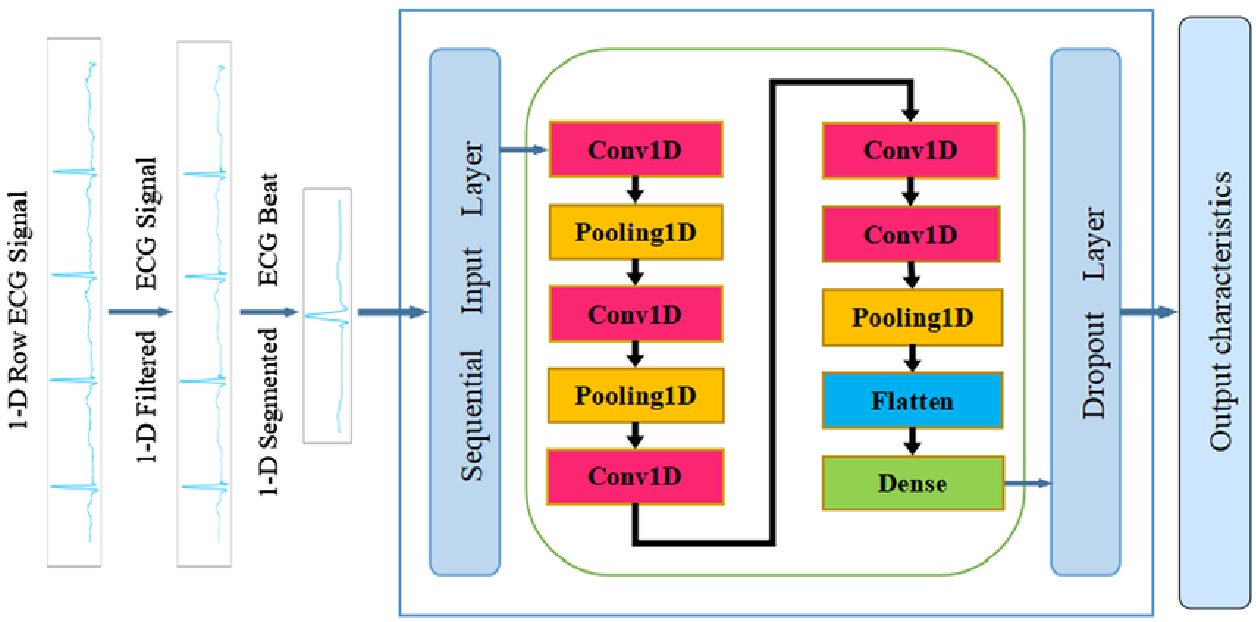


Figure 15: CNN Architecture for ECG Feature Extraction

3.2 Role of AI in Prioritizing Emergency Cases

The integration of AI to prioritize high-risk patients has been explored in several healthcare systems. **Rajpurkar et al. (2018)** developed an AI model called "Cardiologist-Level Arrhythmia Detection with Convolutional Neural Networks," which demonstrated superior performance in detecting atrial fibrillation and other arrhythmias from ambulatory ECG recordings. Their system not only classified rhythms but also flagged critical conditions for immediate attention—aligning closely with the emergency prioritization objectives of the HeartGuard Project.

Moreover, **Nguyen et al. (2020)** emphasized the use of AI triage tools in emergency departments, showing that intelligent systems can reduce patient wait times and improve outcomes when used to identify and prioritize life-threatening cases.

3.3 Publicly Available ECG Datasets

Effective training of AI models requires access to high-quality, labeled ECG datasets. Several publicly available datasets have been instrumental in advancing research in this field. The **MIT-BIH Arrhythmia Database**, developed by the Massachusetts Institute of Technology, remains one of the most widely used datasets for ECG classification tasks. It contains a wide variety of annotated arrhythmias, enabling robust training and testing.

In addition, the **PTB Diagnostic ECG Database**, maintained by PhysioNet, provides 12-lead ECG recordings from healthy individuals and patients with various cardiac diseases. These datasets are valuable for developing models that generalize well across different populations and conditions.

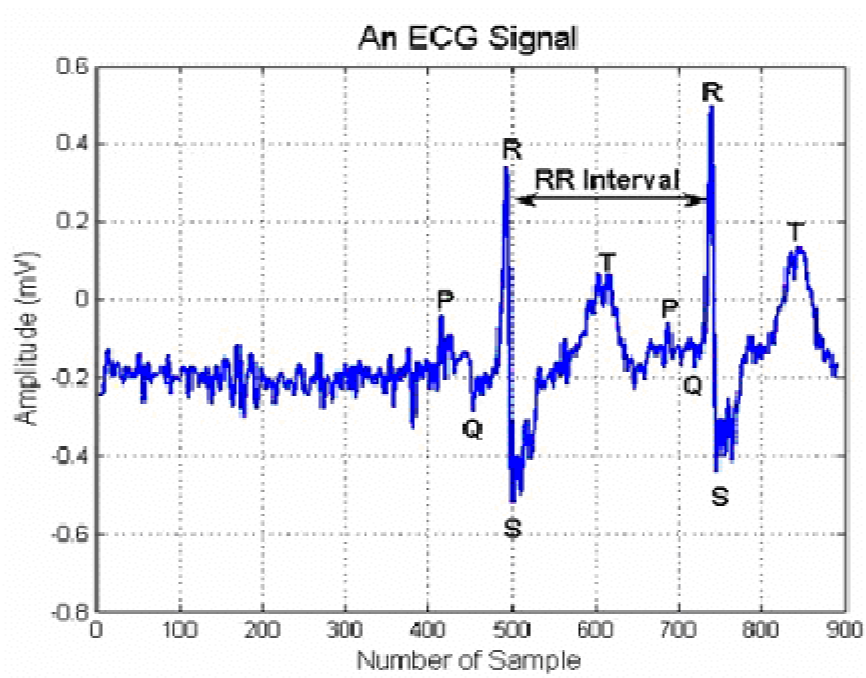


Figure 16: Sample Abnormal ECG Signal from MIT-BIH Database

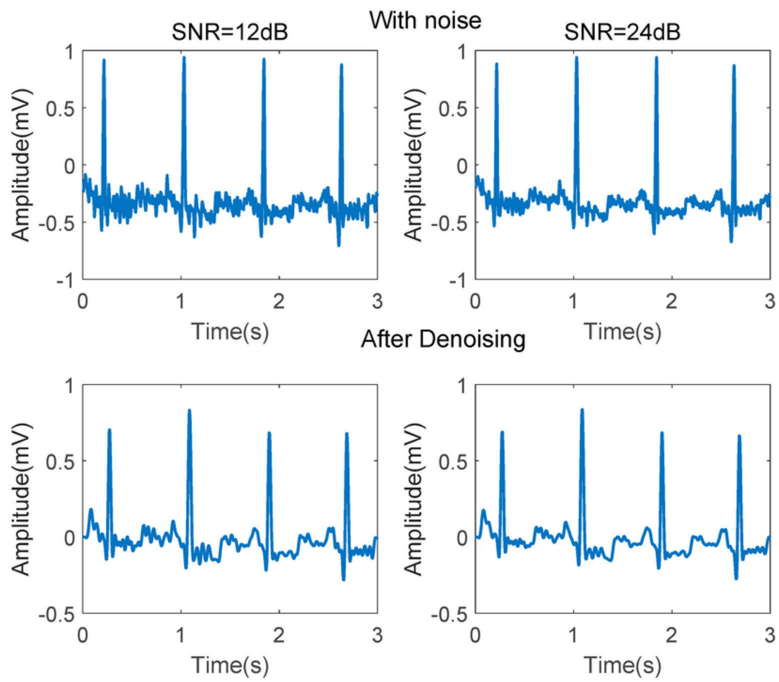
3.4 Challenges in ECG Interpretation

Despite advancements, automated ECG analysis still faces challenges such as signal noise, inter-patient variability, and class imbalance in datasets. **Clifford et al. (2014)** highlighted the difficulty in distinguishing subtle abnormalities, especially in early-stage heart disease. To address this, hybrid approaches combining signal processing techniques (e.g., wavelet transforms) with deep learning have been proposed.

The HeartGuard Project builds on these insights by incorporating both signal preprocessing and machine learning

Figure 15: ECG Signal Before and After Denoising

layers to enhance reliability, reduce false alarms, and ensure accurate prioritization of emergency cases.



3.5 Wearable ECG Devices and Real-Time Monitoring

The growing adoption of **wearable ECG devices** like smartwatches (e.g., Apple Watch, KardiaMobile) has enabled continuous and real-time heart monitoring. These devices can collect massive volumes of data but often lack robust onboard analysis tools. Studies such as **Perez et al. (2019)** showed how smart devices can detect atrial fibrillation but require external tools for deeper analysis.

3.6 Hybrid AI Approaches (e.g., CNN + LSTM)

While CNNs are effective for spatial feature extraction in ECG signals, recent studies have shown that **combining CNNs with LSTMs** (Long Short-Term Memory networks) improves temporal pattern recognition. For example, **Xia et al. (2020)** proposed a CNN-LSTM hybrid model for arrhythmia classification, outperforming traditional CNN-only models.

3.7 Explainability in AI for Healthcare

A major barrier to AI adoption in medicine is the **lack of explainability**—doctors need to understand why the AI flagged a case as dangerous. Studies like **Ghassemi et al. (2021)** emphasize the importance of **interpretable AI** in clinical decision-making. Tools like Grad-CAM, SHAP, and LIME are now used to visualize which parts of the ECG influenced the AI decision.

3.8 Limitations in Current Research

Even the most advanced AI models can suffer from:

- **Dataset bias** (overfitting to one population),
- **Poor generalization** to new hardware or noise types,
- **Lack of FDA approval** for real-world use.

Mentioning these shows awareness of the field's challenges and can support why your system includes robust **evaluation and testing** stages.

Chapter 4 References

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