AI-Driven ECG Signal Analysis and Arrhythmia Classification System Using Deep Learning

# Abstract

Electrocardiograms (ECGs) are vital for diagnosing cardiac arrhythmias, yet manual interpretation is time-consuming and prone to human error. This paper presents an AI-driven ECG analysis system that automates the detection of arrhythmias using deep learning. The system incorporates signal preprocessing, QRS complex detection, and classification using a convolutional neural network (CNN). It also supports image-based ECG interpretation and real-time visualization. The solution aims to assist clinicians by providing fast, reliable, and accessible cardiac analysis tools.

# 1. Introduction

Cardiovascular diseases (CVDs) are the leading cause of death globally, responsible for approximately 17.9 million deaths annually. ECGs are a fundamental diagnostic tool for detecting heart abnormalities, especially arrhythmias. However, accurate interpretation of ECG signals requires expert knowledge, which may not be available in all healthcare settings. This motivates the development of an AI-powered ECG analysis system that can enhance diagnostic efficiency and accuracy.

This paper proposes an integrated system combining traditional signal processing and state-of-the-art deep learning to deliver a scalable, real-time, and multi-input analysis tool.

# 2. Related Work

Several researchers have explored automated ECG analysis using ML and DL. Traditional ML models, such as support vector machines (SVMs) and decision trees, have shown promise but require manual feature extraction. More recently, CNNs have gained popularity due to their ability to learn complex patterns directly from raw or minimally processed data. The MIT-BIH Arrhythmia Database has been widely used as a benchmark for training and evaluating such models. Our work builds upon these foundations and incorporates multimodal inputs, including signal waveforms and ECG images.

# 3. Methodology

3.1 Data Collection

We utilized datasets from PhysioNet, particularly the MIT-BIH Arrhythmia Database. The dataset includes over 48 half-hour excerpts of two-channel ambulatory ECG recordings, sampled at 360 Hz. Data was used in both waveform (.csv) and image (.png) formats.

3.2 Preprocessing

Signal preprocessing was essential to eliminate noise and improve feature extraction accuracy. The following steps were applied:

- Bandpass Filtering: Removed baseline wander and high-frequency noise.

- Baseline Correction: Applied polynomial detrending.

- QRS Detection: Implemented Pan-Tompkins algorithm.

3.3 Model Architecture

Two models were trained:

- A 1D CNN for signal input

- A 2D CNN (ResNet-inspired) for image input

Both were trained on preprocessed and normalized datasets with augmentation applied to image inputs.

3.4 Real-Time System Design

A Flask-based backend received user-uploaded ECGs in various formats and returned predictions from the trained models. The frontend was built using React to display results visually along with charts and patient history tracking.

# 4. Results and Evaluation

4.1 Performance Metrics

The models were evaluated using accuracy, precision, recall, F1-score, and confusion matrix analysis. The image-based CNN achieved:

- Accuracy: 94.3%

- Precision: 92.5%

- Recall: 93.7%

- F1-Score: 93.1%

The signal-based model achieved slightly lower metrics but showed faster inference time.

4.2 Real-Time Testing

The real-time system was tested using external ECG files. The predictions were returned within 3–5 seconds per file. Visualization and summary generation were successfully rendered using the React frontend.

# 5. Applications

The system has potential applications in:

- Rural or underserved healthcare centers

- Emergency remote monitoring

- Educational tools for biomedical students

- Preliminary cardiac screening by non-experts

# 6. Future Work

Future improvements will include:

- Support for DICOM and PDF inputs

- Voice-controlled summary generation using LLMs

- Deployment to cloud servers (e.g., Render, Railway)

- Patient history and anomaly type tracking

# 7. Conclusion

This paper presented a comprehensive AI-powered ECG analysis system capable of classifying arrhythmias from signal and image inputs. With robust accuracy and a real-time dashboard, the system can significantly aid clinicians in rapid cardiac screening and monitoring.

# Keywords

ECG, Deep Learning, Biomedical AI, Arrhythmia Detection, Signal Processing, CNN