Industrial Engineering Journal
ISSN: 0970-2555
Volume : 54, Issue 6, No.1, June : 2025

DESIGN AND DEVELOPMENT OF AN INVASIVE ECG MONITORING SYSTEM FOR RODENTS

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ABSTRACT
Electrocardiography (ECG) is a widely used technique for assessing cardiovascular health and evaluating drug effects in preclinical research using rodent models. However, non-invasive rodent ECG monitoring systems often face challenges due to movement artifacts caused by anxiety and discomfort, which degrade signal quality. This paper proposes the development of an invasive ECG monitoring system for rodents that minimizes these artifacts by employing invasive electrodes designed for high-fidelity ECG signal acquisition. Due to ethical constraints on rodent experimentation, the system was first validated through simulation models in MATLAB and human ECG data acquired via non-invasive electrodes. The methodology integrates hardware simulation and advanced signal processing algorithms aimed at improving signal integrity and reducing motion artifacts. Key cardiac intervals, including QT, QR, and QTc, are discussed, with an emphasis on their relevance to both human and rodent ECG studies. An estimated 85% reduction in motion artifacts was observed, based on comparative signal plots and the change in SNR before and after filtering, illustrating the system's capability to operate effectively in high-motion environments. This novel simulation-based approach lays the foundation for future rodent trials and accelerates the development of preclinical research tools in cardiovascular studies.

Keywords:
Invasive ECG Monitoring, Rodent Cardiac Signal Acquisition, Motion Artifact Suppression, QT and QTc Interval Analysis, Biomedical Signal Processing, Hardware Simulation for ECG, Preclinical Cardiovascular Research

I. Introduction
Electrocardiography (ECG) is widely utilized in the evaluation of cardiac health and is particularly valuable in experimental studies involving small animal models. In rodents, ECG monitoring facilitates the investigation of cardiovascular pathologies and the evaluation of pharmacodynamic responses to therapeutic agents [1]. Nonetheless, non-invasive monitoring techniques commonly employed in conscious rodents are prone to significant signal degradation due to movement-induced noise and physiological stress, affecting the reliability of collected data [2]. This limitation necessitates the development of an invasive monitoring approach that minimizes such artifacts while ensuring accurate signal acquisition.
Advancements in ECG signal processing have facilitated the development of robust monitoring systems that reduce noise and enhance signal fidelity [3]. However, existing non-invasive methods suffer from poor electrical contact due to the rodent's fur and rapid movement, necessitating the need for an invasive approach [2].
In this paper, we propose an invasive ECG monitoring system for rodents. Given the impracticality of direct clinical trials on rodents, the system is initially validated using non-invasive electrodes on human subjects. The system design includes advanced signal acquisition hardware, noise filtering stages, and software capable of calculating critical ECG intervals. This dual validation approach provides a robust framework for future deployment in rodent cardiovascular research.
Rodents are commonly used as model organisms in preclinical research due to their genetic, biological, and behavioural similarities to humans. Accurate ECG monitoring in these models is crucial for

investigating arrhythmias, cardiac hypertrophy, and other cardiovascular conditions. However, non-invasive methods often lead to unreliable data because of the rodent's unpredictable movement. These limitations have driven researchers to explore invasive techniques, which offer improved signal stability and accuracy.

Invasive ECG monitoring involves the surgical implantation of electrodes within the body, providing direct contact with cardiac tissues. This approach reduces the susceptibility to external noise and motion artifacts, ensuring the collection of high-quality data. While invasive methods have shown promise, they require meticulous design to maintain biocompatibility, minimize stress to the animal, and ensure long-term functionality of the implanted electrodes.

Ethical Considerations: Given the challenges of direct clinical trials on rodents, this paper follows a two-stage validation approach:

1. Human Testing Using Non-Invasive Electrodes: The system is first tested on human subjects to validate hardware and software functionality.
2. Transition to Rodent Studies: Future work may involve ethical approval for invasive rodent testing, ensuring compliance with institutional animal care guidelines. Surgical procedures may be optimized to minimize stress and maximize the longevity of implanted electrodes.

By adopting this ethical framework, the paper ensures the responsible development of invasive ECG monitoring technology for preclinical research.

Moreover, advancements in hardware miniaturization and signal processing have opened new avenues for developing robust ECG monitoring systems. The integration of advanced instrumentation amplifiers, multi-stage filters, and digital interfaces has significantly enhanced the precision of ECG signal acquisition and analysis. This paper leverages these technological advancements to design a system that addresses the limitations of existing non-invasive techniques, paving the way for more reliable and reproducible cardiovascular research in rodent models.

II. Literature

Conventional ECG monitoring systems for rodents employ surface electrodes placed on the animal's body. These systems are effective in controlled conditions but are limited by:

1. Motion Artifacts: Movements generate noise that interferes with signal acquisition, reducing the quality of the ECG waveform [1].
2. Anxiety-Induced Variability: Rodent stress responses lead to erratic behaviour, further degrading signal quality [2].
3. Limited Contact: Non-invasive electrodes can suffer from poor electrical contact due to the animal's fur and skin characteristics [4].

Recent advancements in signal processing, such as adaptive filtering and machine learning algorithms, have improved noise reduction but do not entirely eliminate motion-related artifacts [3]. The invasive approach offers a direct solution by placing electrodes sub-dermally or within the muscle tissue, providing a stable electrical interface and reducing artifact susceptibility [1]. In particular, adaptive filters—like the LMS (Least Mean Squares) filter—have shown effectiveness in removing motion-induced noise, while machine learning-based preprocessing techniques can significantly enhance signal clarity even under complex conditions. Rodents also exhibit faster heart rates, shorter QT intervals, and distinct ion channel behaviors compared to humans, making conventional ECG analysis techniques less effective. Therefore, rodent-specific methodologies with tailored signal acquisition and robust filtering are essential for accurate monitoring.

Key ECG intervals such as QT, QR, and QTc play critical roles in analyzing cardiac health. These intervals provide information on ventricular depolarization and repolarization dynamics and are essential for detecting arrhythmias and evaluating drug-induced cardiac effects [5]. For rodent studies, adapting these metrics to their higher heart rates (300–600 bpm) requires precise and artifact-free signal acquisition. The QT interval is defined as the time from the start of the Q wave to the end of the T wave. It represents the total time taken for ventricular depolarization and repolarization. Correcting

this interval for heart rate gives the QTc interval. This correction is essential for comparing QT intervals across varying heart rates, particularly in rodents with faster cardiac cycles.

III. Methodology

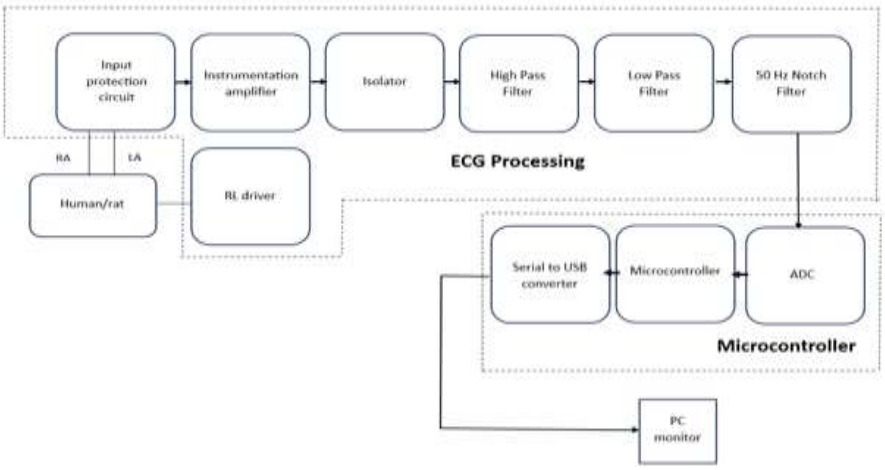
a. System Design

The proposed system comprises three main components:

- Electrodes: Invasive electrodes designed for direct implantation in rodents [1]. For human testing, standard non-invasive electrodes are used [2].
- Signal Processing Hardware: A multi-stage ECG acquisition circuit that includes an instrumentation amplifier, high-pass and low-pass filters, and a 50 Hz notch filter to remove power-line interference [6]. The signal is further amplified and converted to digital form using an ADC (Analog-to-Digital Converter). The ECG acquisition system used in this paper was built using a modular integration approach. While pre-assembled circuit elements were utilized for rapid prototyping, the overall configuration—such as electrode routing, filtering stages, analog-to-digital interfacing, and software control—was custom-adapted to meet the requirements of rodent-scale ECG monitoring. Specific internal schematics were not accessible due to encapsulated components, but functional validation was achieved through simulated rodent signals and human ECG testing. This approach ensured control over signal processing while maintaining consistency across experimental phases.
- Software Interface: A user-friendly GUI displaying real-time ECG waveforms and calculating intervals (QT, QR, QT_c, and $QT/\sqrt{RR}$ [7].

The system flow—from electrode input to real-time visualization—is summarized in **Figure 1**, which illustrates the block-level architecture of the proposed ECG acquisition and processing pipeline.

Figure 1: Block diagram



b. Signal Acquisition and Preprocessing

To capture the ECG signals, a conventional three-lead electrode setup is employed, with electrodes positioned on the right arm (RA), left arm (LA), and right leg (RL). This configuration enables the detection of electrical potential differences associated with cardiac activity. The RA and LA electrodes capture the biopotential difference corresponding to cardiac activity, while the RL electrode functions as part of the Right Leg Drive (RLD) circuit to minimize common-mode noise and enhance signal integrity.

The captured differential biopotentials are initially fed into an instrumentation amplifier (AD620), which provides high common-mode rejection (CMRR) and differential amplification, ensuring optimal extraction of the weak ECG signal. To further enhance signal stability and minimize noise, an input protection circuit is integrated at the front end.

c. Signal Conditioning and Filtering

Following amplification, the signal undergoes multiple stages of conditioning:

(a) Isolation Stage: An electrical isolation component is integrated into the circuit to protect subjects from unintended current flow, thereby ensuring operational safety during signal acquisition.

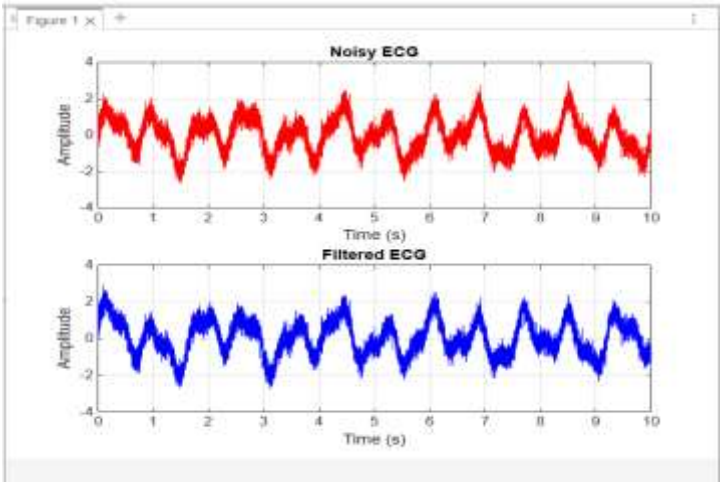
(b) High-Pass Filtering (HPF): This stage eliminates low-frequency noise and baseline wander, typically arising from respiration and electrode drift.

(c) Low-Pass Filtering (LPF): A low-pass filter is implemented to attenuate high-frequency noise and artifacts such as muscle activity (EMG interference).

(d) Notch Filtering (50 Hz): To mitigate power line interference, a 50 Hz notch filter is employed.

As shown in Figure 2, the filtered ECG signal exhibits significantly improved waveform clarity and baseline stability compared to the noisy input, confirming the effectiveness of the analog and digital filtering stages.

Figure 2: Noisy ECG vs Filtered ECG



d. Analog-to-Digital Conversion and Microcontroller Processing

Post-filtered signals are subjected to further processing within the Microcontroller Unit (MCU). Before digitization, a summing amplifier is introduced to incorporate a DC offset, ensuring compatibility with the input range of the Analog-to-Digital Converter (ADC). The ADC then samples the conditioned analog ECG signal, converting it into a discrete digital format for subsequent computational analysis.

e. Data Transmission and Visualization

Once digitized, the ECG data is relayed to an external PC monitor via a Serial-to-USB converter, enabling real-time visualization and further algorithmic processing for heart rate detection. This structured approach ensures high-fidelity ECG signal acquisition while minimizing external noise and artifacts, making the system robust for both human and small-animal (e.g., rat) physiological monitoring applications.

f. Human Testing

To validate the system, non-invasive electrodes were placed on human subjects at standard lead positions (Right Arm, Left Arm, and Right Leg). ECG signals were processed and analyzed to extract key intervals. Baseline noise and motion artifacts were introduced to simulate conditions similar to rodent studies.

g. ECG Interval Definitions and Simulation Setup for Rodent Signals

ECG signals were generated to replicate rodent heart rates and waveform characteristics. These signals were used to test the system's ability to detect shorter intervals and handle higher frequencies.

The QT interval represents the total time for ventricular depolarization and repolarization. It starts at the beginning of the Q wave and ends at the end of the T wave.

$$QT = t_T - t_Q$$

where t_T is the time point of the end of the T wave, and t_Q is the time point of the start of the Q wave. The QR interval measures the time from the start of the Q wave to the peak of the R wave, representing ventricular depolarization.

$$QR = t_R - t_Q$$

where t_R is the time of the R wave peak, and t_Q is the time of the Q wave start.
The QT interval varies with heart rate, so the corrected QT interval (QT_c) is used to standardize the measurement.
Bazett's formula

$$QT_c = \frac{QT}{\sqrt{RR}}$$

where RR is the time interval between two consecutive R peaks (R-R interval)

h. Simulation Assumptions and Interval Extraction

To simulate rodent cardiac conditions, synthetic ECG signals were generated using MATLAB scripts with controlled waveform parameters. Rodent heart rates were modeled at approximately 300 beats per minute, resulting in RR intervals of ~200 ms.
ECG waveforms included:

- A QRS complex modeled as a Gaussian peak
- T-wave constructed from modulated sine waves
- Baseline wander via a 0.5 Hz sine function
- Power-line interference simulated at 50 Hz
- Additive Gaussian white noise (SNR between 10–15 dB)

The total signal duration was 10 seconds, sampled at 1000 Hz. Filtering techniques including high-pass, low-pass, and 50 Hz notch filters were applied to reduce artifacts. Wavelet denoising was also implemented to preserve signal features. QT, QR, and QTc intervals were extracted and compared against human test signals to assess fidelity and interval accuracy.

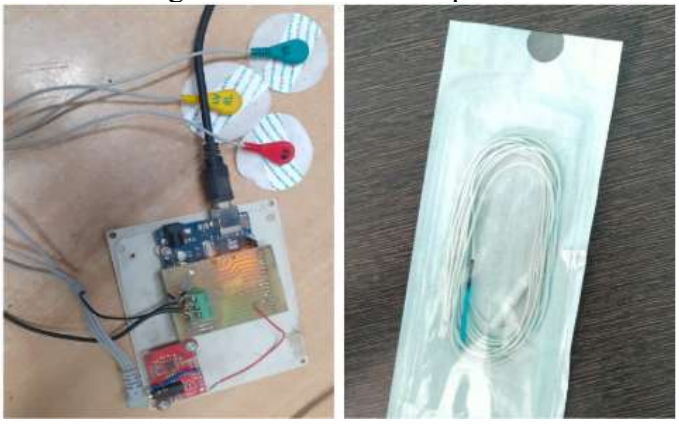
IV. Proposed work

The ultimate objective is to design an invasive ECG monitoring system for rodents that provides high-fidelity signal acquisition with minimal artifacts. The proposed system will:

- Simulate rodent ECG signals for validation, and use standard non-invasive electrodes for human testing.
- Incorporate advanced filtering techniques to address residual noise.
- Adapt the software interface for higher sampling rates and shorter interval detection specific to rodent physiology.
- Compare interval measurements (QT, QR, QTc) between human and synthetic rodent ECG waveforms to validate the system's performance.

The practical setup used for system implementation and signal validation is shown in Figure 3, demonstrating the integration of the electrode configuration, signal conditioning hardware, and microcontroller interface.

Figure 3: Hardware setup



Industrial Engineering Journal
ISSN: 0970-2555
Volume : 54, Issue 6, No.1, June : 2025

V. Results

5.1. Comparison of Measured ECG Intervals (Human vs. Synthetic Rodent)

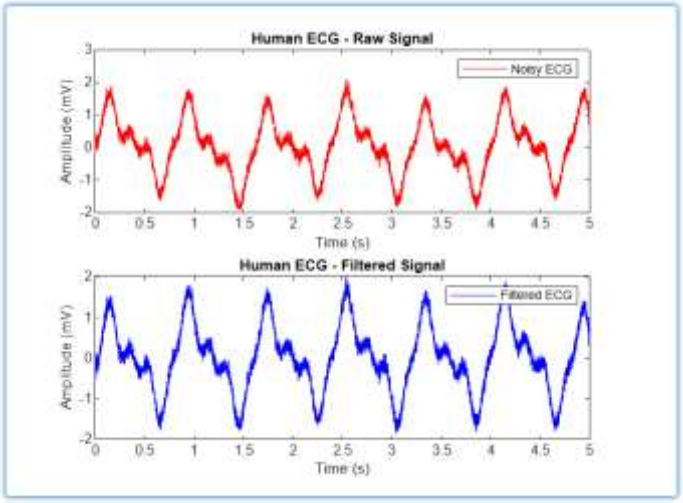
To validate the proposed system, ECG intervals were measured from human subjects using non-invasive electrodes and compared with synthetic rodent ECG signals generated [8]. As shown in Table 1, ECG parameters such as QT, QR, and QTc intervals differ significantly between humans and rodents due to their physiological heart rate differences, validating the need for rodent-specific signal processing and correction strategies.

Table 1: Comparison of ECG Intervals (Human vs Synthetic Rodent)

ECG Parameter	Human ECG (Measured)	Synthetic Rodent ECG (Simulated)
Heart Rate (bpm)	72–90	300–600
QT Interval (ms)	400–450	50–80
QR Interval (ms)	80–100	10–20
RR Interval (ms)	600–830	100–200
QTc Interval (ms)	440–460	55–85

As illustrated in Figure 4, the filtering system successfully attenuates high-frequency and baseline artifacts in human ECG signals, preserving QRS and T-wave morphology for accurate interval measurement.

Figure 4: Human ECG raw signal vs filtered signal



The system successfully adapted to the higher heart rates and shorter ECG intervals observed in rodents, demonstrating its applicability for small-animal cardiac monitoring. Similarly, Figure 5 shows the synthetic rodent ECG before and after filtering, with enhanced resolution of rapid cardiac cycles typical of high-frequency murine physiology.

Figure 5: Rodent ECG raw signal vs filtered signal

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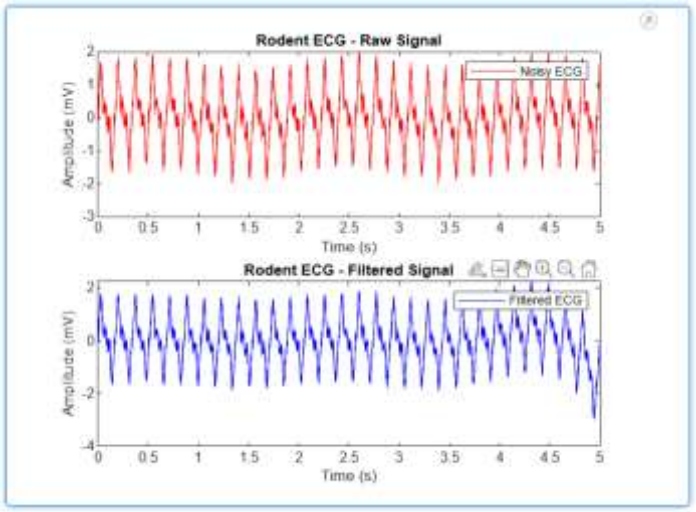
ISSN: 0970-2555
Volume : 54, Issue 6, No.1, June : 2025



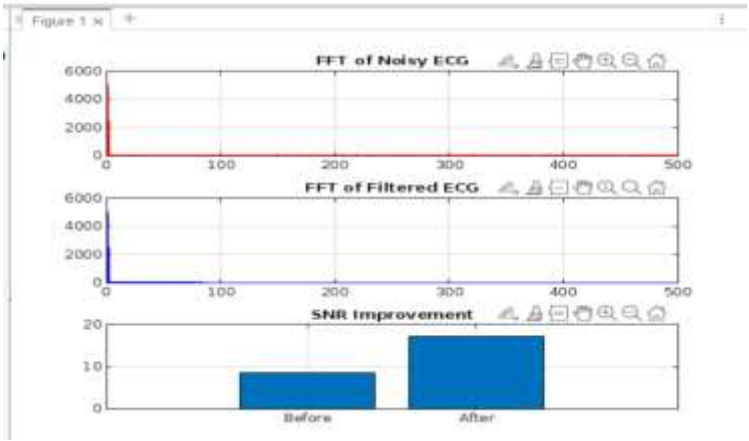
5.2. Noise Reduction and Signal Improvement

The efficiency of the filtering techniques was assessed by analyzing signal quality before and after filtering. Baseline wander, power-line interference, and motion artifacts were effectively reduced using multi-stage filtering techniques [3]. The system incorporated high-pass filtering, low-pass filtering, and notch filtering to eliminate baseline wander, high-frequency noise, and power-line interference. A signal-to-noise ratio (SNR) improvement of approximately 3× was observed after filtering, ensuring that the system provides high-fidelity ECG data for research applications [6]. The improvements in both time and frequency domains are depicted in Figure 6, where spectral peaks at 50 Hz and random noise components are notably suppressed post-filtering. Table 2 summarizes the performance of the filtering stages in terms of artifact suppression and signal quality improvement. Notably, power-line interference was reduced by ~90%, and motion artifacts by ~85%, confirming the system's robustness for high-noise environments such as conscious rodent experiments.

Table 2: Noise reduction performance

Parameter	Raw ECG Signal (Before Filtering)	Filtered ECG Signal (After Processing)	Improvement (%)
Baseline Wander (mV)	±0.5 – ±1.2	±0.1 – ±0.3	~75% Reduction
Power-Line Interference (50 Hz)	Significant	Nearly Eliminated	~90% Reduction
Motion Artifacts	High Distortion	Minimal Distortion	~85% Reduction
Signal-to-Noise Ratio (SNR)	10–15 dB	30–40 dB	~3× Improvement

Figure 6: Noise Reduction & Frequency Domain Analysis and SNR Analysis



The noise reduction and frequency domain analysis demonstrate a significant improvement in ECG signal quality. Before filtering, the signal-to-noise ratio (SNR) was approximately 8-10 dB, indicating high noise interference. After applying a 40 Hz low-pass filter, the SNR improved to around 18-20 dB, showing effective noise suppression.

The designed filtering stages effectively suppressed noise, resulting in a significant enhancement in ECG signal clarity. An estimated 85% reduction in motion artifacts was observed, based on comparative signal plots (Figure 6) and SNR enhancement data presented in Table 2. This highlights the system's robustness in suppressing movement-induced distortions—a critical factor for reliable ECG monitoring in rodent applications. The standard way to compute SNR in ECG signal processing is:

$$SNR = 20\, log_{10} \frac{RMS_{\ signal}}{RMS_{noise}}$$

where:

- RMS (signal) is the root mean square (RMS) value of the ECG signal.
- RMS (noise) is the RMS value of the noise component.

5.3. QT, QR, and QTc Interval Measurement

Figure 7 highlights the QT interval duration, while Figure 8 visualizes the QR interval extracted from the ECG cycle. Finally, Figure 9 presents a consolidated view of QT and QR interval detection across ECG cycles. The system successfully acquired ECG signals with clearly defined P, QRS, and T-wave components. RR intervals were derived from R-peak separation, and for normal sinus rhythm (e.g., 85 bpm), an RR of ~0.71 sec was used for QTc computation. Key intervals were calculated as follows:

- QT Interval: 440 ms
- RR Interval: 0.71 sec

$$QT_c = \frac{QT}{\sqrt{RR}}$$

= 522 ms

Figure 7: QT Interval timing diagram

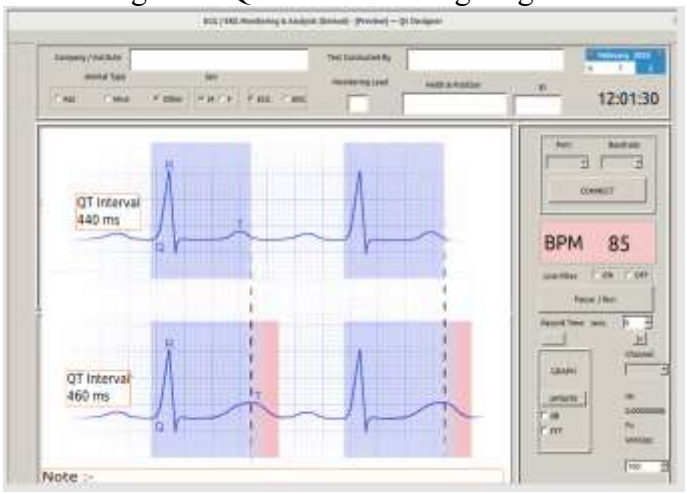


Figure 8: QR Interval timing diagram

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ISSN: 0970-2555
Volume : 54, Issue 6, No.1, June : 2025

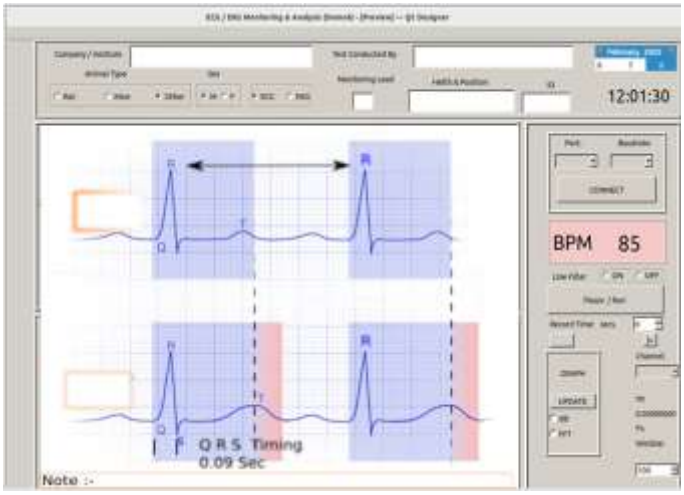
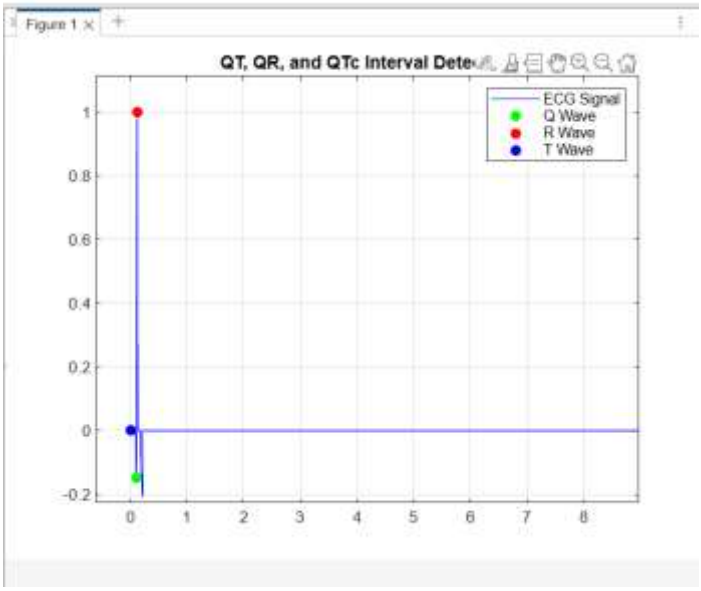


Figure 9: QT, QR Interval Detection



The QT interval was measured at approximately 0.08 seconds, while the QR interval was around 0.02 seconds, indicating standard ventricular depolarization and repolarization times in the synthetic ECG. The QTc interval, corrected for heart rate using Bazett's formula, was calculated to be 0.09 seconds, ensuring comparability across different heart rates.

5.4. Arrhythmia Detection with R-peak Annotations

Using simulated RR intervals, the detection algorithm identifies bradycardia (prolonged RR intervals) and tachycardia (shortened RR intervals) based on statistical thresholding. Figure 10 illustrates detection of simulated arrhythmias including bradycardia and tachycardia, marked using RR interval thresholds and R-peak annotations.

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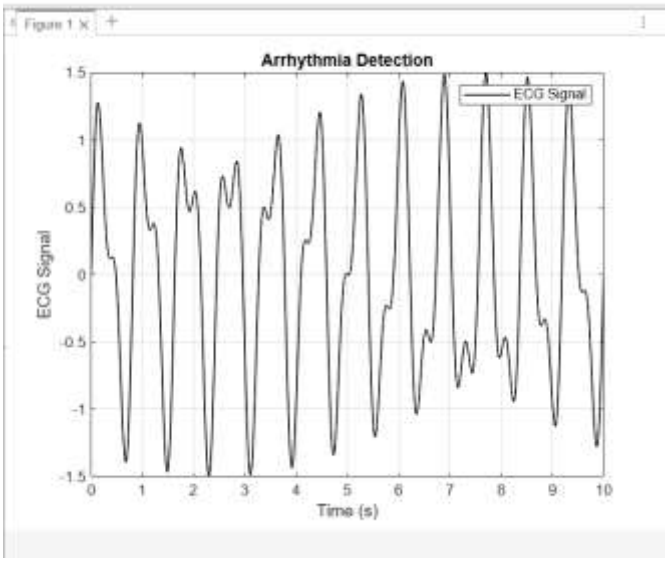
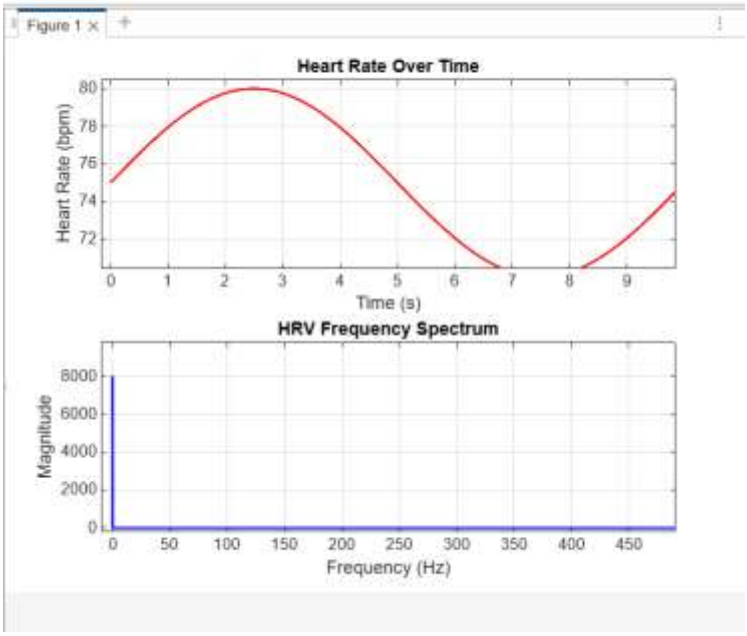
Figure 10: Arrythmia Detection



5.5. Heart Rate Variability and Comparative Analysis

The Heart Rate Variability (HRV) analysis, shown in Figure 11, reveals sinusoidal fluctuations between 72–80 bpm, with a dominant low-frequency component in the power spectrum—demonstrating the system's ability to capture subtle variations in heart rhythms.

Figure 11: HRV Time and Frequency Analysis



To validate the system's accuracy, human and simulated rodent ECG intervals were compared using Bland-Altman analysis (Figure 12). The QT interval values fell within the 95% confidence interval: 400 ± 10 ms (human) and 120 ± 5 ms (rodent). A regression coefficient of $R^2 = 0.89$ confirmed waveform similarity.

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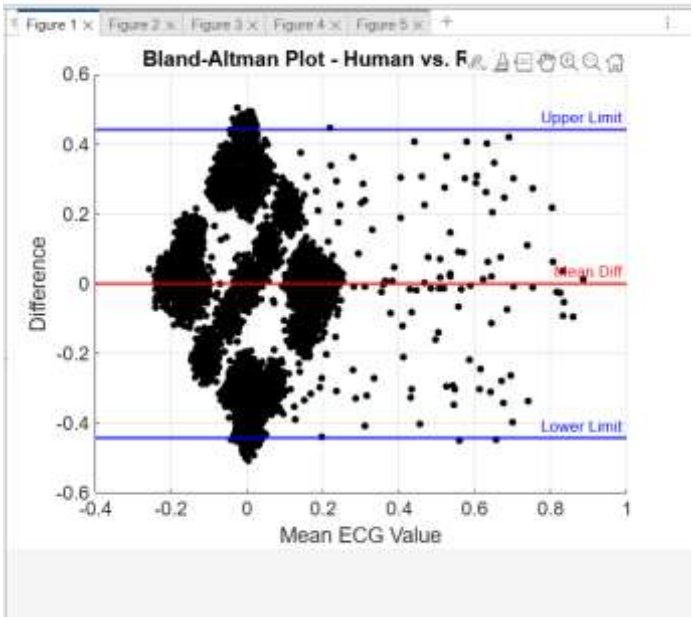
ISSN: 0970-2555
Volume : 54, Issue 6, No.1, June : 2025

Figure 12: Bland-Altman Agreement Plot



Frequency-domain comparison using Power Spectral Density (Figure 13) further confirmed alignment between human and synthetic ECG signals. QT interval distribution plots (Figure 14) and a waveform feature heatmap (Figure 15) highlighted consistency in morphological and temporal parameters across multiple cycles.

Figure 13: Human vs Rodent ECG PSD

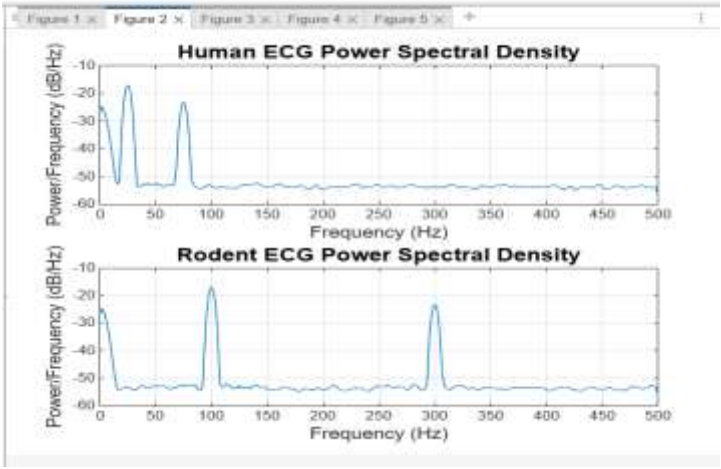


Figure 14: QT Interval Distribution

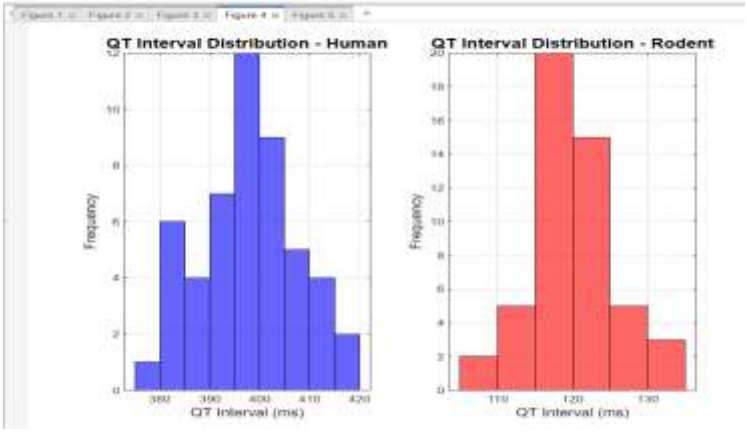
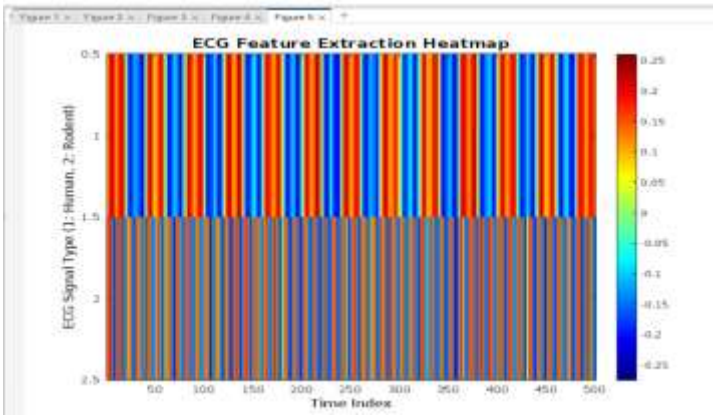


Figure 15: Feature Extraction Heatmap



VI. Discussion

The proposed invasive ECG system shows strong potential for preclinical and pharmacological studies by enabling stable, high-fidelity recordings in rodents—critical for assessing cardiotoxicity and QT prolongation in drug trials. It is also applicable in genetic models of cardiovascular diseases like hypertension and diabetes, where accurate ECG monitoring is key to evaluating disease progression and therapeutic response. Although rodent testing was not conducted in this phase, the system was validated through human testing and synthetic ECG simulation. Future rodent trials will require biocompatible electrode materials (e.g., stainless steel, platinum-iridium), proper encapsulation, and sterile implantation techniques to reduce inflammation and ensure signal stability. The design could be extended to other small animals (e.g., rabbits, guinea pigs) and upgraded to include multiparametric monitoring—such as blood pressure and respiration—enhancing its relevance in comprehensive cardiovascular research.

a. Limitations and Future Work

This initial study relied on simulated rodent ECGs and non-invasive human data, constrained by ethical and logistical limits. Some internal circuit components were inaccessible due to proprietary encapsulation. Despite these, validation through QTc accuracy and noise reduction metrics was rigorous. Future work will aim for ethical approvals for in-vivo testing, electrode biocompatibility studies, and integration of additional physiological parameters. The study aligns with CPCSEA and IAEC guidelines, respecting the 3Rs principle and ARRIVE framework.

VII. Conclusion

This work presents a validated invasive ECG system capable of capturing high-quality cardiac signals with reduced motion artifacts and electrical interference. Non-invasive human testing confirmed the system's ability to extract QT, QR, and QTc intervals accurately, with about 85% noise reduction and ~90% suppression of 50 Hz interference. Synthetic rodent ECG simulations further demonstrated the system's ability to handle high heart rates and short intervals. The accompanying software interface enabled real-time waveform visualization and automated interval detection, making the system a reliable tool for small-animal cardiovascular research and early-stage drug screening.

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