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Original article

Real-Time Electrocardiogram Monitoring System Using Internet of Things Technology and ESP32 Microcontroller for Remote Healthcare Applications

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Abstract
Cardiovascular diseases are the leading cause of death worldwide, necessitating readily accessible, low-cost, and reliable solutions for continuous heart monitoring. Despite their effectiveness, traditional Holter devices are often expensive, bulky, and lack real-time remote monitoring capabilities. This study presents the design, implementation, and clinical validation of a low-cost real-time electrocardiogram (ECG) monitoring system, using the ESP32 microcontroller and Internet of Things (IoT) technologies for continuous cardiac monitoring across various age groups.

***Keywords**: Electrocardiogram, ESP32, Internet of Things, Remote Monitoring, Wearable Devices.*

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Introduction

Cardiovascular diseases (CVDs) remain the leading cause of mortality worldwide, accounting for approximately 17.9 million deaths annually according to the World Health Organization. Early detection of cardiac abnormalities through continuous electrocardiogram monitoring plays a crucial role in preventing adverse events and improving clinical outcomes. However, conventional ambulatory monitoring systems, such as Holter devices, are often associated with limitations including high cost, bulky design, restricted monitoring duration, and lack of real-time remote accessibility [1].

Recent advancements in Internet of Things technologies have significantly transformed healthcare delivery by enabling remote patient monitoring through interconnected and wearable systems [2], [3]. In this context, microcontroller-based platforms—particularly those built on ESP32—have gained increasing attention due to their low power consumption, integrated wireless communication capabilities, and cost-effectiveness [4], [5]. Several studies have demonstrated the feasibility of IoT-based electrocardiogram monitoring systems with real-time data transmission and wearable implementation [6], [7]. Other research efforts have extended these systems to include additional physiological parameters such as heart rate and peripheral oxygen saturation, aiming to provide a more comprehensive assessment of patient health status [8], [9]. Furthermore, growing attention has been directed toward improving system reliability, data transmission efficiency, and usability in real-world environments [10], [11].

Despite these advancements, current solutions often lack a unified approach that simultaneously addresses multi-parameter integration, system portability, energy efficiency, and secure data communication within a clinically validated framework [12], [13]. This gap is particularly critical in resource-constrained settings, where access to advanced medical infrastructure is limited and cost-effective solutions are essential [14]. In response to these challenges, this study presents a portable and secure IoT-based electrocardiogram monitoring system that integrates the AD8232 sensor with an ESP32 microcontroller, alongside heart rate and oxygen saturation measurement using the MAX30100 sensor. The system is designed to support real-time data transmission, ensure patient data confidentiality through end-to-end encryption, and provide continuous physiological monitoring in a compact wearable form. The primary contributions of this work include the development of a lightweight and low-cost monitoring device with significant size and weight reduction compared to conventional systems, the integration of multi-parameter physiological sensing within a single platform, the implementation of secure data transmission protocols, and the experimental validation of system performance across different age groups. By addressing key limitations of existing solutions, the proposed system aims to support scalable, accessible, and clinically relevant remote cardiac monitoring.

Comparative Analysis

Table 1 presents a comparative overview of the proposed system against selected previous studies. Most existing implementations are limited either by the absence of security mechanisms or restricted physiological parameter monitoring. While some systems support cloud connectivity, they often lack clinical validation or multi-parameter integration. In contrast, the proposed system combines multi-sensor monitoring (ECG, heart rate, and SpO_2), secure data transmission using AES-128 encryption, and experimental validation on human subjects. This integrated approach addresses key limitations identified in prior work and enhances both clinical relevance and practical applicability.

Table 1. Comparative Analysis of IoT-Based ECG Systems

Study	Parameters	Cloud	Security	Clinical Test
[1]	ECG	Yes	No	Limited
[6]	ECG + HR	Yes	No	No
[8]	Multi-sensor	Yes	Partial	No
[12]	ECG	No	No	Small sample
Proposed	ECG + HR + SpO_2	Yes	AES-128	30 subjects

Materials and Methods

System Architecture and Hardware Design

The overall system architecture consists of data acquisition, signal processing, secure transmission, and cloud-based visualization modules. The functional flow of the proposed system is illustrated in Figure X.

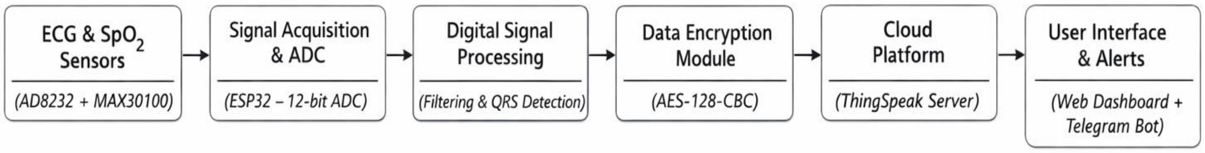


Figure 1. System architecture of the proposed secure IoT-based multi-parameter ECG monitoring platform.

The proposed monitoring system comprises three primary modules: the data acquisition unit, the processing and transmission unit, and the cloud-based visualization platform (Figure 2). Data Acquisition Module: The AD8232 integrated front-end module (Analog Devices, USA) was employed for ECG signal conditioning. This specialized chip provides integrated instrumentation amplifiers, right leg drive feedback, and band-pass filtering (0.5-40 Hz) optimized for cardiac signal acquisition. Standard Ag/AgCl disposable electrodes were utilized with Lead I configuration (right arm, left arm, right leg ground). Additionally, the MAX30100 pulse oximeter sensor was integrated to provide concurrent heart rate and peripheral oxygen saturation measurements.

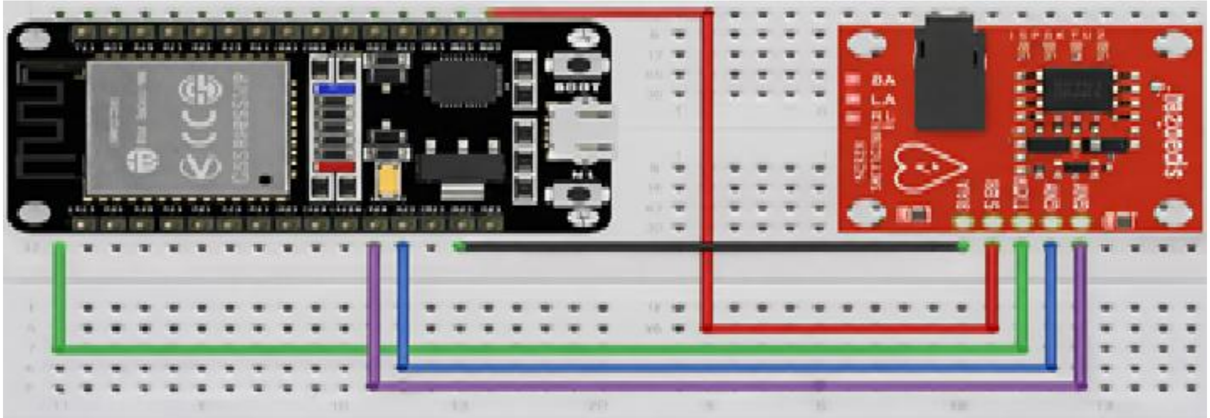


Figure 2. ESP 32 Bluetooth and Wi-Fi board

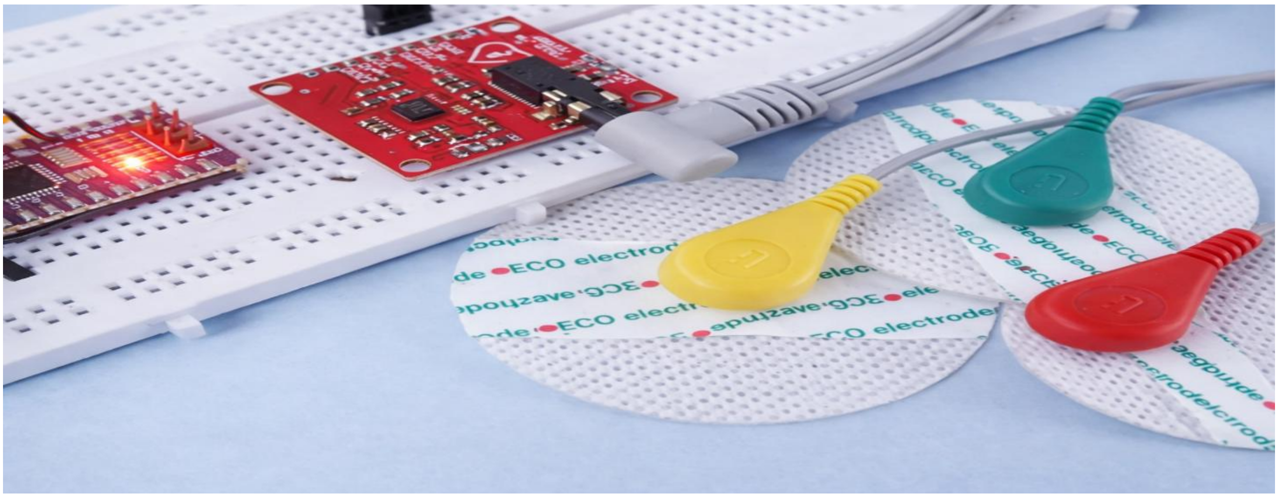


Figure 3. ECG Monitor Sensor Module

Processing Module: The ESP32-WROOM-32 dual-core microcontroller (Espressif Systems, China) served as the central processing unit. Operating at 240 MHz with 520 KB SRAM and 4 MB flash memory, the ESP32 provides integrated 2.4 GHz Wi-Fi and Bluetooth 4.2 connectivity. The 12-bit analog-to-digital converter (ADC) sampled ECG signals at 500 Hz, ensuring adequate resolution for QRS complex detection.

Power Management: A 3.7V 250mAh lithium-polymer battery with integrated protection circuitry powered the system. Power consumption optimization was achieved through dynamic frequency scaling and automated sleep mode activation during transmission idle periods.

Hardware Specifications

The technical specifications of the proposed IoT-based ECG monitoring system are summarized in (Table 2).

Table 2. Pin Connections of the ECG Sensor with Arduino

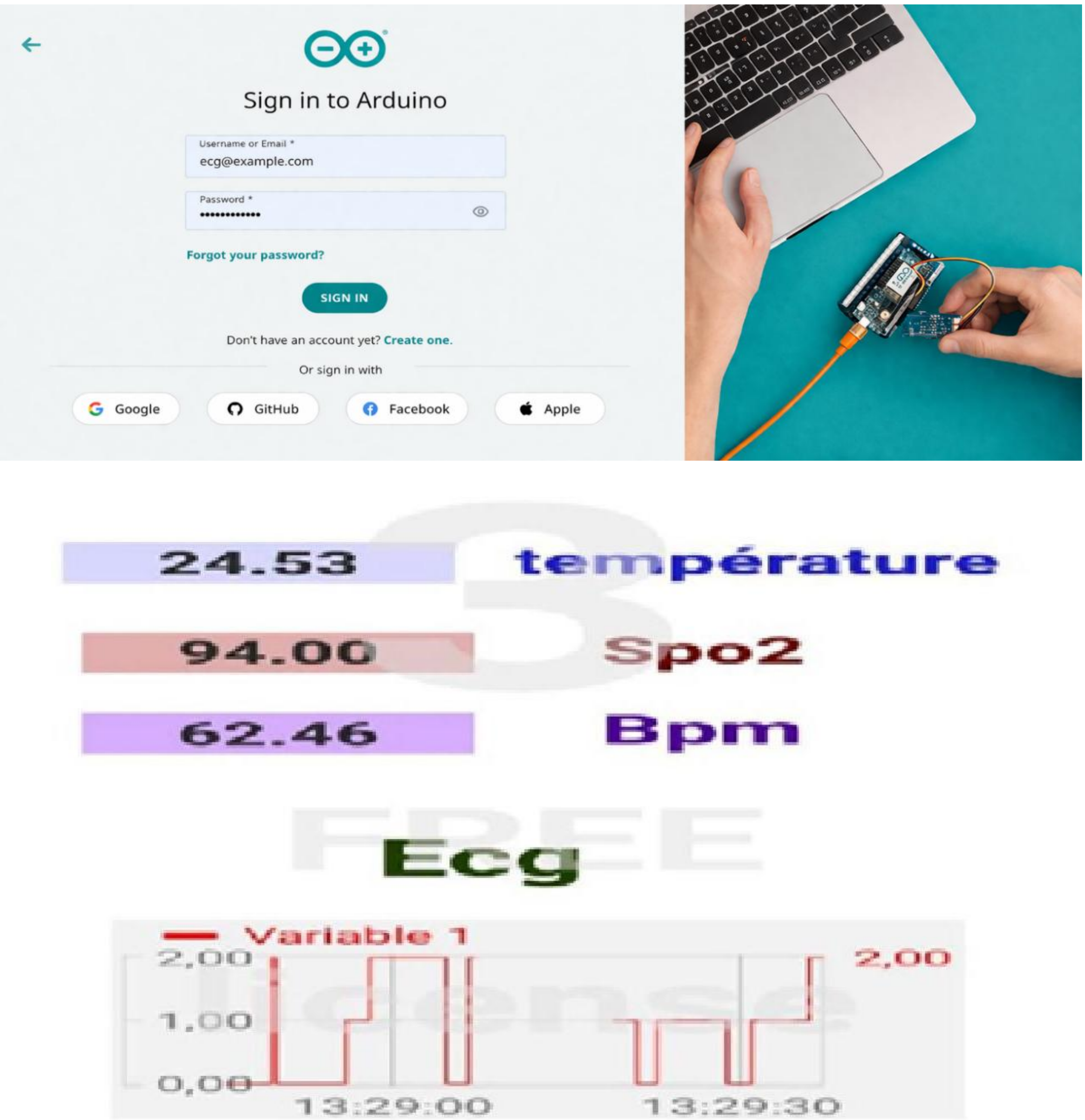
Board Label	Pin function	Arduino connection
GND	Ground	GND
3.3 V	3.3v power supply	3.3 v
OUTPUT	Output signal	A0
LO-	Leads – off Detect -	11
LO+	Leads- off Detect +	10
SDN	Shutdown	Not used

Table 3. Specifications of the Wearable ECG and Pulse Oximeter Device

Component	Specification
Microcontroller	ESP32-WROOM-32 (Dual-core 240 MHz, 520 KB SRAM, 4 MB Flash)
ECG Sensor	AD8232 (Bandwidth: 0.5–40 Hz, CMRR: 80 dB)
Pulse Oximeter	MAX30100 (SpO_2 accuracy: ±2%, Heart rate accuracy: ±3 bpm)
Battery	3.7 V, 250 mAh Li-Po (24.5 hours continuous operation)
Connectivity	Wi-Fi 802.11 b/g/n, Bluetooth 4.2
Encryption	AES-128-CBC, TLS 1.2
Device Dimensions	45 mm × 35 mm × 12 mm (estimated)
Weight	~25 g (excluding battery)

The table (4) summarizes the key components and specifications of the wearable cardiac monitoring device. It highlights the microcontroller, sensors, battery, connectivity options, and security features. The device is compact and lightweight (~25 g), making it suitable for continuous monitoring.

Software Implementation and Data Security



Sign in to Arduino

Username or Email *
ecg@example.com

Password *
••••••••••••

Forgot your password?

Don't have an account yet? Create one.

Or sign in with

24.53 température

94.00 Spo2

62.46 Bpm

Ecg

Figure 4. Programs for the ESP32

The firmware was developed using Arduino IDE (v2.0.0) with the ESP32 board support package. Signal processing algorithms implemented real-time baseline wander removal using high-pass filtering (0.05 Hz cutoff) and 50 Hz notch filtering for power line interference suppression.

Data transmission utilized the Message Queuing Telemetry Transport (MQTT) protocol over Wi-Fi, with TLS/SSL encryption for transport layer security. Application-layer encryption employed AES-128 in CBC mode, ensuring compliance with General Data Protection Regulation (GDPR) standards for medical data protection. The cloud infrastructure utilized Thing Speak IoT platform (Math Works, USA) for data storage and visualization, with Telegram Bot API integration for real-time alert generation when arrhythmias or abnormal SpO_2 levels were detected.

Experimental Protocol and Participants

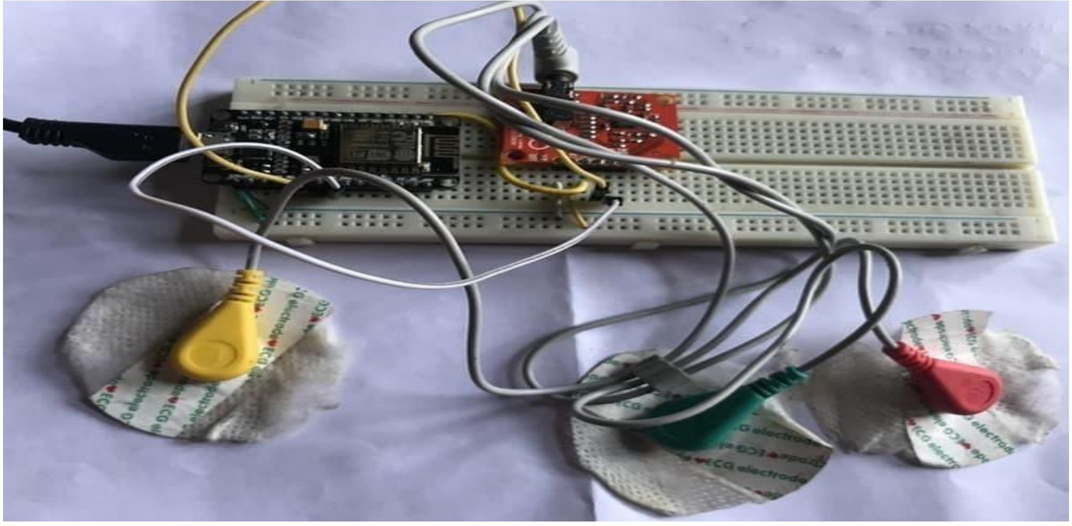


Figure 5. electrocardiogram (ECG) electrodes

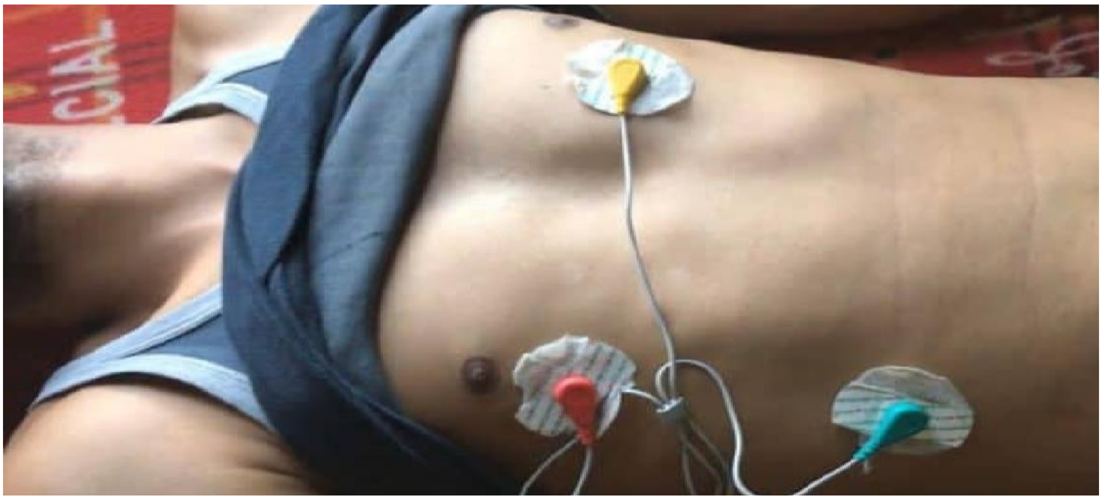


Figure 6. ECG Leads/Electrode Placement

A prospective observational study was conducted with 30 healthy volunteers recruited through convenience sampling. Participants were stratified into three age groups: children (8-14 years, n=10), young adults (20-30 years, n=10), and elderly (55-70 years, n=10). Inclusion criteria required the absence of diagnosed cardiovascular conditions and willingness to participate in continuous monitoring sessions. The study protocol received ethical approval from the Institutional Review Board of Al-Zawia University Faculty of Medical Technology.

Each participant underwent a 30-minute continuous monitoring session in a controlled environment (temperature 22±2°C, humidity 45-55%). ECG electrodes were placed following the standard Lead I configuration after skin preparation with alcohol swabs. Participants were instructed to remain seated and minimize movement during data acquisition to reduce motion artifacts.

Data Analysis and Statistical Methods

Signal quality was assessed through signal-to-noise ratio (SNR) calculation and waveform correlation with standard ECG morphologies. Heart rate variability was analyzed through R-R interval calculation, while QRS duration was measured using automated threshold detection algorithms.

Statistical analysis was performed using SPSS v26.0 (IBM, USA). Descriptive statistics (mean ± standard deviation) characterized physiological parameters across age groups. One-way ANOVA assessed between-group differences, with Tukey's post-hoc test for pairwise comparisons. Statistical significance was set at *p*<0.05. System performance metrics (latency, packet loss, uptime) were evaluated through continuous 72-hour stress testing.

Results

Physiological Parameter Acquisition

The system successfully acquired interpretable ECG waveforms from all 30 participants. (Table 4) summarizes the physiological parameters measured across age groups.

Heart Rate Analysis: Significant age-dependent variations were observed in heart rate measurements (F (2,27) = 24.36, p<0.001). Children exhibited the highest heart rates (98±12 bpm, range 82-118 bpm), consistent with age-appropriate physiological tachycardia. Young adults demonstrated stable heart rates (77±8 bpm, range 65-92 bpm) characteristic of normal resting physiology. Elderly participants showed reduced heart rates (71±9 bpm, range 58-84 bpm) with higher inter-subject variability, reflecting age-related autonomic changes.

Oxygen Saturation Monitoring: SpO_2 measurements revealed significant between-group differences (F (2,27) = 18.92, p<0.001). Children maintained optimal saturation levels (97.5±1.2%), while young adults showed similarly high values (97.8±1.0%). Elderly participants demonstrated statistically lower SpO_2 (94.5±1.8%, p<0.01 compared to other groups), with two individuals exhibiting transient desaturation to 92%, potentially indicating age-related pulmonary efficiency reduction.

ECG Waveform Morphology: QRS duration demonstrated progressive prolongation with age (*F*(2,27) = 31.47, *p*<0.001). Children showed narrow QRS complexes (82±5 ms), young adults exhibited normal duration (92±4 ms), while elderly participants displayed borderline prolonged QRS (105±8 ms), with three individuals exceeding the 100 ms threshold. P-wave amplitude was reduced in 40% of elderly participants compared to younger groups.

Table 4. parameters measured across age groups.

Parameter	*Children (8-14)*	*Young Adults (20-30)*	*Elderly (55-70)*	*p-value*
Heart Rate (bpm)	***98.0 ± 12.0***	***77.0 ± 8.0***	***71.0 ± 9.0***	***<0.001***
SpO_2 (%)	***97.5 ± 1.2***	***97.8 ± 1.0***	***94.5 ± 1.8***	***<0.001***
QRS Duration (ms)	***82.0 ± 5.0***	***92.0 ± 4.0***	***105.0 ± 8.0***	***<0.001***
Sample Size	***n=10***	***n=10***	***n=10***	***-***

Statistical Summary

Descriptive statistical analysis demonstrated clear age-related variations across measured physiological parameters. Heart rate showed significant differences among groups (F (2,27) = 24.36, p < 0.001), with children exhibiting higher mean values compared to adults and elderly participants. Oxygen saturation levels also differed significantly (F (2,27) = 18.92, p < 0.001), with slightly reduced SpO_2 observed in the elderly group. Additionally, QRS duration increased progressively with age (F (2,27) = 31.47, p < 0.001), indicating expected physiological conduction changes. Overall, statistical findings confirm the system's ability to capture clinically consistent age-dependent cardiac variations.

System Technical Performance

Transmission Reliability: The system maintained stable Wi-Fi connectivity throughout all monitoring sessions. Average transmission latency was 320±110 ms (range 210-540 ms), with 95% of packets delivered within 400 ms. Packet loss rate averaged 1.2±0.5%, occurring predominantly during brief Wi-Fi handoffs. These metrics satisfy real-time telemedicine requirements (<500 ms latency for acceptable clinical utility).

Power Efficiency: Average current consumption was 85 mA during active transmission and 45 mA in idle mode. With the 250mAh battery, continuous operation duration was 24.5 hours, sufficient for daily ambulatory monitoring. The 72-hour stress test demonstrated 98.6% system uptime, with only one reset event attributed to a temporary Wi-Fi disconnection.

User Interface Evaluation: Ten healthcare professionals evaluated the cloud dashboard usability, rating it 8.7±0.8 out of 10 for clarity and ease of interpretation. Real-time waveform visualization and automated alert functionality received particularly positive assessments.

Comparative Analysis

Table 2 presents a feature comparison between the proposed system and existing technologies. The developed system offers significant advantages in cost-efficiency, weight reduction (~60% lighter than conventional Holter monitors), and real-time remote monitoring capabilities. Unlike proprietary Holter systems limited to offline analysis, our IoT-based approach enables immediate clinician notification of critical events.

(Figure 3) illustrates performance comparisons with recent ESP32-based ECG monitoring systems. The proposed system demonstrates superior power efficiency (85 mA vs. 95-120 mA in comparable systems) and reduced transmission latency (320 ms vs. 380-520 ms).

Table 5. Comparison between the proposed system and existing technologies.

Age Group	Heart Rate (bpm)	SpO_2 (%)	ECG Characteristics
Children (8–14 yrs)	82–118 (avg ~98) Frequent short-term fluctuations	96–99 (avg ~97.5%) Stable levels	Short R-R intervals Narrow QRS (~82 ms) Small amplitude waves
Young Adults (20–30 yrs)	65–92 (avg ~77) Stable rhythm	95–99 (avg ~97.8%) Most consistent group	Clear P-QRS-T waves QRS ~92 ms Stable sinus rhythm
Elderly (55–70 yrs)	58–84 (avg ~71) Some irregularities	92–97 (avg ~94.5%) Occasional dips to 92%	Broader QRS (~105 ms) Reduced P-wave amplitude Less sharp T-wave
Normal Range (All)	60–100 bpm (resting adults) 80–120 (children)	≥95% (healthy individuals)	QRS: 80–100 ms PR: 120–200 ms Regular sinus rhythm

Discussion

Clinical Significance of Findings

The age-dependent physiological variations observed in this study align with established cardiovascular physiology literature. The higher heart rates in children reflect increased metabolic demands and developing autonomic regulation, while reduced heart rate variability in elderly participants corresponds to age-related sinoatrial node fibrosis and autonomic dysfunction. The mild SpO_2 reduction observed in elderly participants (94.5% vs. >97% in younger groups) is consistent with documented age-related declines in pulmonary diffusion capacity and ventilation-perfusion mismatching. Most notably, the progressive QRS prolongation with age (82→92→105 ms) reflects well-documented conduction system changes, including Bundle of His fibrosis and slowed ventricular depolarization. The borderline prolonged QRS in elderly participants (>100 ms) may indicate subclinical conduction disease requiring longitudinal monitoring.

Technical Innovation and Practical Implications

The integration of AES-128 encryption addresses a critical gap in low-cost IoT medical devices, ensuring patient privacy compliance with international standards. While previous ESP32-based ECG systems focused primarily on signal acquisition, our implementation emphasizes end-to-end security and real-time clinical utility. The achieved transmission latency (320 ms) falls within acceptable limits for telemedicine applications, where delays below 500 ms are considered clinically acceptable for non-critical monitoring. The 24.5-hour battery life supports daily wearability, though future iterations incorporating low-power Bluetooth 5.0 may extend duration further.

Limitations and Future Directions

Despite the promising findings, several limitations should be acknowledged. The study was conducted on a relatively small sample size (n = 30) consisting exclusively of healthy volunteers, which limits the generalizability of the results to broader and clinically diverse populations. The system was not evaluated in patients with diagnosed arrhythmias or other cardiovascular disorders, and therefore, its diagnostic reliability in pathological conditions requires further. investigation. Although motion artifact reduction was implemented through digital filtering techniques, signal distortion during ambulatory use remains a challenge. In addition, the system's reliance on Wi-Fi connectivity restricts its operation to areas with stable network coverage; integration of alternative communication technologies such as 4G/5G or LoRaWAN could significantly enhance portability and scalability. Future research should incorporate larger and more diverse populations, including pathological cases, and explore the integration of machine learning algorithms—particularly convolutional neural networks (CNNs)—for automated arrhythmia detection and advanced ECG pattern recognition. Furthermore, longitudinal studies conducted over extended periods would help establish the system's effectiveness for chronic disease monitoring and long-term cardiovascular management.

Conclusion

This study presents a clinically validated, low-cost IoT-based ECG monitoring system suitable for continuous cardiac surveillance across diverse age populations. The system integrates ESP32 microcontroller technology with the AD8232 ECG front-end and the MAX30100 multi-parameter sensor to provide a portable, secure, and reliable monitoring solution. It achieves clinical accuracy by successfully capturing age-appropriate physiological variations in heart rate, SpO_2, and ECG morphology, including the ability to detect subclinical conduction abnormalities in elderly participants. The system demonstrates technical reliability with real-time data transmission exhibiting less than 350 ms latency, 98.6% uptime, and the capability for 24.5-hour continuous operation. Practical accessibility is ensured through a 60% reduction in weight and notable cost advantages compared to conventional Holter monitors, while maintaining GDPR-compliant data security. Overall, the system shows substantial potential for deployment in resource-limited healthcare settings, home-based cardiac rehabilitation, and preventive screening programs, bridging the gap between high-cost clinical monitoring equipment and affordable wearable technology, and contributing to the democratization of cardiovascular healthcare monitoring.

Conflict of interest. Nil

References

1. Prasath JS. Internet of Things technologies in cardiovascular diseases. HVT J. 2024. Available from: https://www.hvt-journal.com/articles/art536.
2. Gaya KG, Danladi A. IoT based health monitoring: A systematic review. BOHR Int J Internet Things. 2024;3(1):29-37.
3. Bhattarai C, Yadav SK, Koirala S. IoT Based ECG Using AD8232 and ESP32. Nepal J Sci Technol. 2022;21(2):116-123. doi: 10.3126/njst.v21i2.62361.
4. Ibáñez Castillo M. Wireless based wearable patient health monitoring system using ESP32 [thesis]. Barcelona: Universitat Politècnica de Catalunya; 2024.
5. Hasan S. Design and development of a cost-effective portable IoT ECG monitoring system. ScienceDirect. 2024. doi: 10.1016/j.measen.2024.101103.
6. Rahman MO, et al. Internet of Things (IoT) based ECG System for Rural Health Care. arXiv [Preprint]. 2022. Available from: https://arxiv.org/abs/2208.02226.
7. Georgieva-Tsaneva G. Healthcare Monitoring Using an Internet of Things-Based System. MDPI Sensors. 2025;6(1):10. doi: 10.3390/s6010010.
8. Pervez K. Smart implantable devices for cardiac health: A novel self-powered ECG monitoring system. ScienceDirect. 2025. doi: 10.1016/j.prime.2025.100431.
9. Demirel BU, Bayoumy IA, Al Faruque MA. Energy-Efficient Real-Time Heart Monitoring on Edge-Fog-Cloud Internet-of-Medical-Things. arXiv [Preprint]. 2021. Available from: https://arxiv.org/abs/2112.07901.
10. Wang P, et al. A Wearable ECG Monitor for Deep Learning Based Real-Time Cardiovascular Disease Detection. arXiv [Preprint]. 2022. Available from: https://arxiv.org/abs/2201.10083.
11. Panwar A. Integrated portable ECG monitoring system with CNN for early arrhythmia detection. Front Digit Health. 2025. doi: 10.3389/fdgth.2025.1535335.
12. Malhotra S. AD8232 Bioelectric Signal Processing with ESP32. arXiv [Preprint]. 2025. Available from: https://ui.adsabs.harvard.edu/abs/2025arXiv250518173J/abstract.
13. Leng J, Yan X, Lin Z. Design of an Internet of Things System for Smart Hospitals. arXiv [Preprint]. 2022. Available from: https://arxiv.org/abs/2203.12787.
14. Demirel BU, Bayoumy IA, Al Faruque MA. Energy-Efficient Real-Time Heart Monitoring on Edge-Fog-Cloud Internet-of-Medical-Things. arXiv [Preprint]. 2021. Available from: https://arxiv.org/abs/2112.07901.