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Design and Construction of an ECG Simulator with Bipolar Leads Based on the Arduino Nano Microcontroller

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Abstract

Electrocardiogram (ECG) devices require periodic testing and calibration to ensure diagnostic accuracy, especially in clinical settings where reliable patient monitoring is critical. However, commercially available ECG simulators remain relatively expensive and difficult to access in low-resource environments, creating a gap in the availability of affordable calibration tools. This study aims to design an economical and practical ECG simulator based on the Arduino Nano microcontroller using PWM pins to generate bipolar lead signals. The simulator features an LED indicator that mimics the human heartbeat and provides four operating modes: Mode I (Normal sinus rhythm) 80 BPM, Mode II (Bradycardia) 40 BPM, Mode III (Normal sinus rhythm) 120 BPM, and Mode IV (Tachycardia) 120 BPM. Testing was conducted by collecting data 10 times for each mode across Lead I, Lead II, and Lead III to verify BPM readings and PQRST waveform outputs on both ECG and patient monitor devices. The results demonstrated average accuracies of 98.70% on the ECG and 99.37% on the patient monitor, with deviations of 1.3% and 0.63%, respectively—well within the tolerance limits of the ECRI 410-20010301 standard (±5%). These findings indicate that the proposed simulator offers a reliable, low-cost alternative for internal calibration of patient monitors with bipolar leads, providing a practical and accessible solution for healthcare facilities with limited resources.

Keywords: Arduino Nano, Bipolar, Electrocardiogram

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1. Introduction

The heart is a vital organ that pumps blood and maintains body health. However, heart disease has become a leading cause of death globally, including in Indonesia, with a significant increase in prevalence. Globally, deaths from cardiovascular disease reach 9.4 million per year, with 45% (4.23 million) caused by coronary heart disease. Based on projections, this figure is expected to increase sharply to 23.3 million by 2030 [1]. This situation emphasizes the importance of more aggressive public health interventions. One of these is through regular heart examinations. An electrocardiogram (ECG) is a fundamental non-invasive diagnostic method in detecting the heart's electrical activity and potential rhythm abnormalities, as well as disturbed cardiac conduction [2]. The accuracy of an ECG is highly dependent on calibration and routine testing [3]. This is because uncalibrated diagnostic devices can produce irrelevant findings, trigger unnecessary further tests, and even harm patients [4].

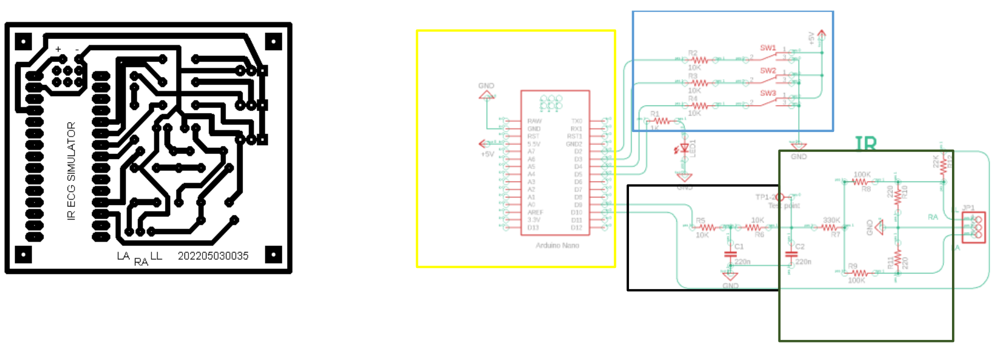
Various studies have attempted to design ECG simulators with diverse approaches and platforms. Andrianto and Sakinah (2017) created an ECG simulator based on Proteus software with analog circuits; however, the design was less practical and the resulting signal still contained noise [5]. Cahyo and Kholis (2019) utilized FPGA and Python for 12-lead real-time simulation, which is suitable for long arrhythmia scenarios—despite having an average error of around 6% [6]. Meanwhile, Whinangun et al. (2019) developed a 12-lead ECG simulator using an Atmega2560 microcontroller and an MCP4921 DAC with very low sensitivity (<1.2%), an integrated battery, and low production costs [7]. On the other hand, Firmansyah and Wijaya (2023) presented a wearable wireless ECG monitoring system based on the ATMega328 capable of displaying PQRST and R-R intervals, with a usage duration of more than 14 hours and a transmission range of >20 m [8].

Although various previous studies have produced ECG simulators using diverse approaches, most existing devices still exhibit technical and practical limitations that reduce their suitability for real-world clinical implementation. Analog-based simulators, such as the design by Andrianto and Sakinah [5], continue to suffer from relatively high noise levels that degrade PQRST waveform clarity, while other studies rely on high-cost and high-complexity platforms such as FPGA systems, which require advanced programming skills and specialized hardware that are rarely available in primary healthcare settings [6]. Even microcontroller-based systems utilizing high-capacity units like the Atmega2560 [7] can generate precise signals but remain less feasible due to their higher production costs compared to simpler and more accessible alternatives. These challenges highlight the need for an ECG simulator that is not only accurate and stable but also affordable, compact, and easily replicated—particularly for resource-limited healthcare environments where access to commercial calibration tools is restricted. The use of an Arduino Nano in this study addresses these gaps by offering a low-cost, low-power, and flexible platform capable of PWM-based signal generation with sufficient stability for producing clinically appropriate bipolar waveforms. This approach enables the development of an accessible ECG simulator that meets medical device calibration accuracy standards while supporting broader adoption in underserved clinical settings. Furthermore, the simulator provides four clinically relevant modes covering both normal and pathological rhythms and has been validated against the ECRI 410-20010301 standard, strengthening its potential use as a reliable calibration and training tool.

2. Methods

This research was conducted by designing an ECG simulator with standard bipolar (Einthoven) leads using an Arduino Nano microcontroller. The study followed an experimental approach involving structured observation trials using both a patient monitor and a clinical ECG device to validate the generated signals. The research process began with a two-month preparation stage, which included literature review, identification of signal parameters, and component selection. This was followed by a three-month development phase consisting of program sketch creation, schematic design, PCB fabrication, and device assembly. The final one-month testing phase involved collecting data from the simulator by running each operating mode ten times for Lead I, Lead II, and Lead III. The output signals displayed on the ECG and patient monitor were recorded and compared by examining BPM values and PQRST waveform morphology. Accuracy was calculated by comparing the readings from both devices with the predefined programmed values, enabling a systematic assessment of measurement deviation and device performance.

This research uses tools and materials, namely Arduino Nano, 5V 2A USB charger adapter, 9V battery, PCB board, 3-lead ECG cable, 3-pin header terminal, SPDT switch, green LED light, capacitor and resistor. The design of this research considers the aspects of cost and practical form. Meanwhile, the PCB board circuit design was created using Autodesk Eagle software and printed using a laser printer then transferred to a fiber-type PCB board so that the results are obtained as in **Figure 1.**



(a) (b)

Figure 1. (a) Schematic Design (b) Circuit Design

Figure 1. is a schematic design used to facilitate research in designing a tool. The design is divided into several blocks, namely the blue block as a mode switch circuit to select the desired mode combination, the yellow block as a microcontroller as a command for all circuits, the black block is a second-order low pass filter circuit, while the green block is a circuit before the output as a voltage divider. Furthermore, the design of the casing box plan on the tool as the placement of all tool components that will be made using 2 mm white acrylic material is made as minimal as possible so that the tool looks more practical using the Autodesk thinkercad application [6].

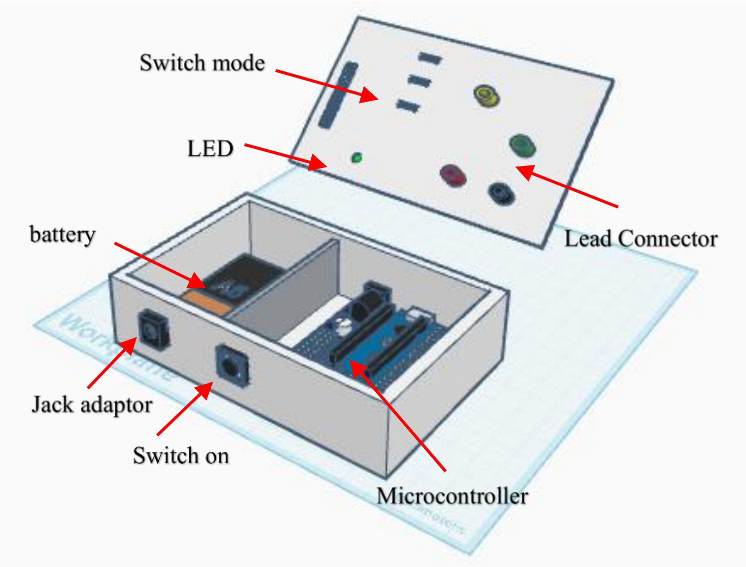


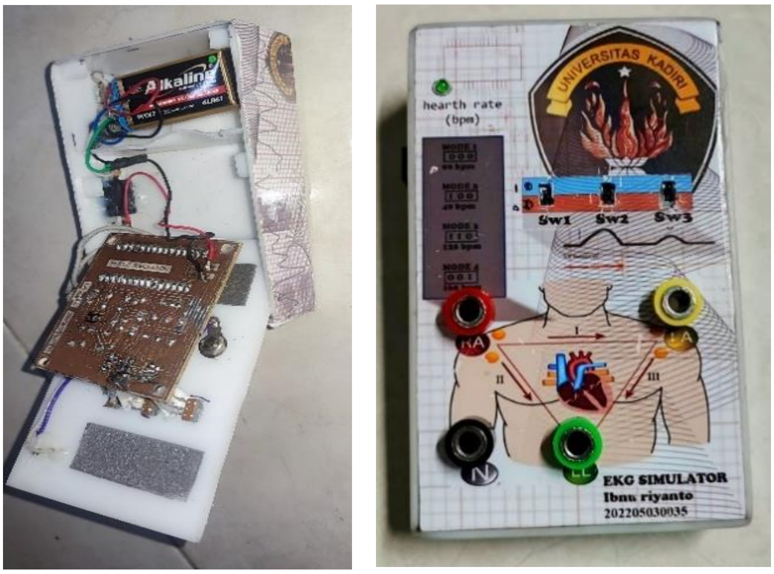
Figure 2. Box Case Design

The box case design shown in Figure 2. serves not only as a structural enclosure for organizing the electronic components of the ECG simulator but also as an important feature that enhances durability and ease of use in clinical settings. The enclosure consists of two main sections—a top lid and a bottom compartment—where the lower section is divided into dedicated spaces for the microcontroller, battery, adapter jack, and power switch, ensuring a neat and stable internal layout. To support practical clinical operation, the box case is constructed using lightweight yet mechanically robust acrylic material, providing resistance against pressure, vibration, and minor impacts that commonly occur during calibration activities or device transport. Its smooth, easy-to-clean surface also facilitates the maintenance of hygiene standards required in healthcare environments. Meanwhile, the upper interface panel integrates essential user-accessible features such as the mode switch, LED indicators, and bipolar lead connectors, all of which are positioned for quick, intuitive access to streamline calibration procedures. By combining structural protection, modular internal organization, and user-friendly interaction points, the box case design not only safeguards the electronic system but also improves the reliability, practicality, and suitability of the simulator for routine clinical use.

3.Results and Discussion

3.1 Assembly of a Microcontroller-Based ECG Simulator Circuit

At the assembly stage of this simulator circuit, all components are installed on the PCB board that has been made, then the assembled circuit is installed in the box case according to the design of the tool. The next stage is the process of uploading the program to the microcontroller and continued with the testing stage of the research tool circuit which is carried out to find out whether the design can function properly or not. After testing the ignition and the function of the buttons on the research circuit and the tool are in accordance with the initial design, the next stage is the final assembly, namely closing the case and installing the sticker design using Corel Draw software [7]. Then the sticker is printed on glossy color sticker paper with an ink jet printer. The results of the tool design after the assembly and program upload stages can be seen in **Figure 3**.



(a) (b)

Figure 3. Results of the tool design (a) Internal view (b) External view

The ECG simulator assembly demonstrates the efficient integration of the analog module, microcontroller, and user interface in a compact and functional design. In **Figure 3a**, the signal amplifier circuit is neatly mounted on a circuit board connected to the Arduino Nano microcontroller module, which was programmed using the Arduino IDE through a USB serial interface. The upload process follows standard microcontroller programming procedures commonly applied in Arduino-based ECG development studies [3], [7], ensuring that the programmed waveform modes correspond accurately to the signals generated by the simulator. In **Figure 3b**, the user interface system is supported by a mode switch and indicator LEDs that provide visual feedback on operation, as well as colored lead connectors for easy identification of bipolar polarity. All these components are arranged in a structured enclosure that has dedicated space for the microcontroller board, battery, on/off switch, and output leads, creating a practical, modular, and ready-to-test ECG simulator.

During the assembly process, the main challenge was related to the varying quality of electronic components available in the market. Some passive components and signal amplifier modules had large tolerance values that affected the stability and clarity of the generated signal, a situation also reported in previous studies of analog-based ECG simulators [5]. Furthermore, some components did not fully meet the low-frequency stability requirements required for ECG signal generation, as confirmed by studies on the importance of signal source precision in cardiac monitoring systems [4]. Nevertheless, repeated component sorting and testing allowed achieving stable performance and provided practical guidance for the development of low-cost ECG simulators with varying component quality available in the market.

3.2 Microcontroller-Based ECG Simulator Circuit Test Results

Test data for the device design was collected using the ECG and patient monitor parameter values measured in four parameter modes. The test results are shown in **Tabel 1**. below.

Tabel 1. ECG Simulator Test Results

Mode	Heart Rate (bpm)		Accuracy (%)	Heart Rate (bpm)		Accuracy (%)
	Reference	Measurable		Reference	Measurable	
I	80	79	98,75	80	80	100
II	40	39	97,5	40	40	100
III	120	119	99,17	120	120	100
IV	160	159	99,38	160	160	100

The ECG simulator was evaluated with 10 repeated measurements per mode using both an ECG recorder and a patient monitor, resulting in mean accuracies of 98.70% for the ECG and 99.37% for the monitor, along with deviations of 1.30% (ECG) and 0.63% (monitor). These accuracy and deviation metrics fall within the ±5%, based on the ECRI standard 410-20010301, acceptance window commonly applied for vital-sign calibrators, which is consistent with established calibration practices for electrocardiogram devices [9], [10]. Given the simulator's ability to generate representative bipolar ECG morphology and the recognized importance of bipolar-lead fidelity for calibration, the data support that the simulator is effective for calibrating patient monitors with bipolar leads [11], [12].

The observed deviations (1.3% for the ECG recorder and 0.63% for the patient monitor) lie well within the ±5% acceptance window customarily applied in vital-sign calibrator evaluation, consistent with published simulator and calibration practice guidance [9], [10]. Deviations of this magnitude are unlikely to meaningfully alter heart-rate measurement or PQRST morphology interpretation. Studies have reported that small systematic differences below typical clinical tolerance do not change diagnostic performance in rhythm/arrhythmia detection [13]. Moreover, analyses emphasize that larger biases and limits of agreement—not sub-percent perturbations—drive ischemia-detection discordance [14]. Clinical interpretive variability remains a significant factor in diagnostic accuracy, further reducing the clinical impact of such small simulator offsets [15]. Together with prior simulator design and validation work that demonstrates realistic bipolar ECG generation for calibration, these data support the simulator's clinical adequacy for calibrating bipolar-lead patient monitors [9], [10], [11].

Previous studies have emphasized that calibration deviations exceeding 5% may lead to misinterpretation of cardiac rhythms or false detection of abnormalities, which could compromise diagnostic accuracy and patient outcomes [4]. In contrast, deviations below this threshold, such as those produced by the simulator in this study, maintain sufficient fidelity for safe internal calibration of bedside monitors and ECG units. This aligns with findings from Whinangun et al. [7], who likewise demonstrated that microcontroller-based ECG simulators with sub-5% deviations can reliably support routine testing without introducing clinically harmful discrepancies. Therefore, the minimal deviations observed here reinforce the suitability of the proposed simulator for use in healthcare facilities, including those with limited technical resources, without posing risk to patient safety.

4. Conclusion

This study successfully developed a low-cost Arduino Nano–based ECG simulator with bipolar leads that meets the ECRI 410-20010301 accuracy standard. Testing conducted across ten trials for each mode yielded high accuracy (98.70% on the ECG and 99.37% on the patient monitor) with deviations well within the ±5% tolerance, confirming the device's reliability for internal calibration of patient monitors. The results demonstrate that this simulator offers a practical and accessible alternative to commercial systems, particularly for resource-limited healthcare settings. Future enhancements may include support for additional lead configurations, integrated displays, wireless communication, and data logging to broaden its clinical and educational utility.

Authors' Declaration

Authors' contributions and responsibilities - The authors made substantial contributions to the conception and design of the study. The authors took responsibility for data analysis, interpretation, and discussion of results. The authors read and approved the final manuscript.

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Availability of data and materials - All data is available from the authors.

Competing interests - The authors declare no competing interest.

Additional information - No additional information from the authors.

References

[1] L. F. Tampubolon, A. Ginting, and F. E. Saragi Turnip, "Gambaran Faktor yang Mempengaruhi Kejadian Penyakit Jantung Koroner (PJK) di Pusat Jantung Terpadu (PJT)," J. Ilm. Permas J. Ilm. STIKES Kendal, vol. 13, no. 3, pp. 1043–1052, 2023, doi: 10.32583/pskm.v13i3.1077.

[2] Harskamp RE. Electrocardiographic screening in primary care for cardiovascular disease risk and atrial fibrillation. Prim Health Care Res Dev. 2019 Jun 25;20:e101. doi: 10.1017/S1463423619000355. PMID: 32800007; PMCID: PMC8060828.

[3] Guna Tyas Istiqomah , Welina Ratnayanti K , Franky Candra SA ," "Pengembangan Elektrokardiografi (EKG) Portable Sebagai Wujud Teknologi Tepat Guna "Program Studi Teknobiomedik Departemen Fisika Fakultas Sains dan Teknologi Universitas Airlangga

[4] A. Hapiddin, A. M. B. A.M. Boynawan, R. Ratnaningsih, Y. I. Pawestri, and B. Githanadi, "Peningkatan Kemampuan Ukur Kalibrasi Sumber Frekuensi Di Bawah 10 Hz Dan Simulasi Diseminasinya Dalam Heart Rate Electrocardiogram (Ecg)," Instrumentasi, vol. 46, no. 1, p. 35, 2022, doi: 10.31153/instrumentasi.v46i1.264.

[5] Suroso Andrianto and Laela Sakinah, "Perancangan Simulator Ekg (Elektronik Kardiogra) ," J. Ilm. KOMPUTASI, vol. 16, no. September, pp. 133–137, 2017.

[6] N. Kholis, "Rancang Bangun Simulator Elektrokardiogrammenggunakan Fpga yang Terintegrasi dengan Software Python," pp. 619–625, 2020.

[7] I. D. G. B. Whinangun, A. Pudji, M. R. Makruf, B. Utomo, dan S. Luthfiyah, "Electrocardiograph Simulator Berbasis Mikrokontroler," Jurnal Teknokes, vol. 12, no. 1, hlm. 5–13, Sep. 2019.

[8] M. A. Firmansyah dan F. Wijaya, Rancang Bangun Sistem Monitoring Nirkabel Elektrokardiogram (EKG) Berbasis Mikrokontroler ATMega328, Skripsi, Fisika Teknik, Universitas Gadjah Mada, Yogyakarta, 2023.

[9] C. Suharinto, A. Budianto, & N. Sanyoto, "Design of electrocardiograph signal simulator", Indonesian Journal of Electronics Electromedical Engineering and Medical Informatics, vol. 2, no. 1, p. 43-47, 2020.

https://doi.org/10.35882/ijeeemi.v2i1.9
[10] C. Melinda, I. Wisana, A. Pudji, & T. Triwiyanto, "Ecg and nibp simulators in one device display on tft nextion", Indonesian Journal of Electronics Electromedical Engineering and Medical Informatics, vol. 5, no. 3, p. 151-157, 2023. https://doi.org/10.35882/ijeeemi.v5i3.293
[11] M. Quiroz-Juárez, J. Rosales-Juárez, O. Jiménez-Ramírez, R. Vázquez-Medina, & J. Aragón, "Ecg patient simulator based on mathematical models", Sensors, vol. 22, no. 15, p. 5714, 2022. https://doi.org/10.3390/s22155714
[12] D. Ogiermann, L. Perotti, & D. Balzani, "Towards a physiologically accurate ecg from numerical simulations: comparative analyses in a simplified tissue model", Pamm, vol. 20, no. 1, 2021. https://doi.org/10.1002/pamm.202000136
[13] W. Choi, S. Kim, W. Lee, S. Kang, C. Yoon, T. Younet al., "Comparison of continuous ecg monitoring by wearable patch device and conventional telemonitoring device", Journal of Korean Medical Science, vol. 35, no. 44, 2020. https://doi.org/10.3346/jkms.2020.35.e363
[14] L. Ekenberg, D. Høfsten, S. Rasmussen, J. Mølgaard, P. Hasbak, H. Sørensenet al., "Wireless single-lead versus standard 12-lead ecg, for st-segment deviation during adenosine cardiac stress scintigraphy", Sensors, vol. 23, no. 6, p. 2962, 2023. https://doi.org/10.3390/s23062962
[15] L. Bilello, C. Pascheles, K. Gurley, D. Rappaport, D. Chiu, S. Grossmanet al., "Getting to the heart of the issue: senior emergency resident electrocardiogram interpretation and its impact on quality assurance events", Clinical and Experimental Emergency Medicine, vol. 7, no. 3, p. 220-224, 2020. https://doi.org/10.15441/ceem.19.070