Development of an ECG system based on the ADS1194 integrated circuit

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Abstract

In this paper, the possibilities of using the integrated circuit ADS1194 for measurement of ECG signals were investigated. A group of integrated circuits ADS119x enable an extensive range of configurations of internal electronics for various low-noise biopotential measurements. An 8-bit ATmega328P microcontroller was used to configure the ADS1194 circuit and acquire data. It has been shown that it is possible to measure the ECG signal with three electrodes taped to the chest in different configurations. The results were compared with a standard analogue electrocardiogram measurement circuit.

Keywords: ECG system, ADS1194, biopotential measurements, Einthoven's triangle, mass casualty situations

1 Introduction

The human heart is a remarkable organ that plays a pivotal role in sustaining life. Its ceaseless beating ensures the delivery of vital oxygen and nutrients to every cell of the body while efficiently removing waste products. Throughout history, the heart has captivated the attention of scientists, philosophers, and artists alike, symbolizing not only the physical essence of life but also the seat of emotions and the core of human existence.

Understanding the heart's function and monitoring its health is of paramount importance in modern healthcare. Vital signs, including heart rate, serve as fundamental indicators of cardiovascular well-being and provide crucial information for diagnosing and managing various cardiac conditions. Continuous assessment of heart rate variations can help detect abnormalities, identify potential risks, and guide appropriate interventions, ultimately improving patient outcomes [1].

One of the most widely employed methods for assessing heart rate and cardiac electrical activity is the electrocardiogram (ECG). An electrocardiogram is a non-invasive diagnostic tool that records the electrical impulses generated by the heart, offering valuable insights into its rhythm, conduction, and overall performance. ECG systems have revolutionized cardiovascular medicine, providing clinicians with a reliable means to evaluate cardiac health and make informed decisions regarding patient care [2].

The measurement of the electrical activity of the heart through an ECG involves the placement of electrodes on the skin surface, which detect and transmit the electrical signals produced by the cardiac muscle. These signals, known as electrocardiographic waveforms, represent the depolarization and repolarization of different regions of the heart during the cardiac cycle. By analyzing these waveforms, healthcare professionals can assess the heart's rhythm, identify arrhythmias, and detect signs of ischemia or myocardial infarction [3].

ECG measurements are routinely performed in a variety of clinical settings, including hospitals, outpatient clinics, and ambulances. Advances in technology have led to the development of portable and wearable ECG devices with real-time Internet of things, enabling long-term monitoring of cardiac activity outside traditional healthcare environments [4, 5]. In future, ECG devices will offer many advantages, such as early detection of arrhythmias, remote patient monitoring, real-time data transmission to healthcare providers, and with the algorithm that evaluates the quality of signals measured in unsupervised environments [6]. Portable ECG devices empower individuals to actively participate in the management of their cardiovascular health, promoting early intervention and potentially preventing serious cardiac events.

The interpretation of ECG recordings requires specialized knowledge and expertise. Clinicians skilled in electrocardiography can discern subtle changes in waveforms, identify abnormalities, and make accurate diagnoses. However, the growing demand for ECG analysis and the need for prompt results have prompted the exploration of automated algorithms and artificial intelligence (AI) techniques to aid in ECG interpretation. These developments hold promise for increasing efficiency, reducing diagnostic errors, and expanding access to quality cardiac care [7].

The intended application is rapid mass casualty triage, where the simplified 3-lead ECG system can provide quick cardiac screening to prioritize the treatment of critically ill patients. In chaotic emergency scenarios, accelerated sorting of patients into categories is crucial, and the idea of our system is to enable fast vital sign evaluation to aid prompt triage decisions.

In this paper, we aim to delve into the intricacies of ECG measurement and explore the ADS1194 integrated circuit designed for low-noise biopotential measurements. We discuss the measurement with three electrodes, different lead configurations and show the results of ECG signals. We also compare the measurements with our ECG system to measurements with a standard analogue electrocardiogram measurement circuit.

2 ECG waveforms using three electrodes

Electrocardiogram waveforms hold crucial diagnostic value, as abnormalities or deviations from normal patterns can indicate various cardiac conditions. One of the most comprehensive methods for assessing cardiac electrical activity is the 12-lead electrocardiogram (ECG). Unlike single-lead ECGs, which provide a limited view of the heart's electrical activity, the 12-lead ECG simultaneously records electrical signals from 12 different perspectives. A set of 10 electrodes are placed on the patient's body to capture electrical signals from various angles, as shown in Figure 1. In table 1, names and body positions of all electrodes for 12-lead ECG are presented.

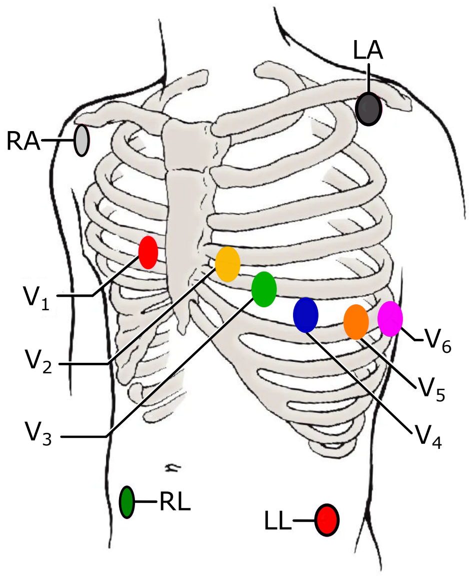

Fig. 1 12-lead electrocardiogram electrode placement.

Each lead represents a specific view of the heart's electrical activity, allowing clinicians to assess different regions and aspects of cardiac function. By examining the waveforms recorded in each lead, healthcare professionals can gather valuable information about the heart's rhythm, conduction, and potential ischemic changes.

In mass casualty situations, such as natural disasters or large-scale emergencies, the prompt and efficient assessment of vital signs, including heart rate, is of utmost importance. Traditional 12-lead ECG systems may not be practical in these scenarios due to limited resources, time constraints, and the need for rapid triage and intervention. In such cases, a simplified approach using only three electrodes can be employed for fast ECG measurement and vital sign monitoring.

Table 1 12-lead ECG electrodes position

Electrode	Placement
RA	right forearm or wrist
LA	left forearm or wrist
LL	left lower leg, proximal to ankle
RL	right lower leg, proximal to ankle
V1	4th intercostal space, right sternal edge
V2	4th intercostal space, left sternal edge
V3	midway between V2 and V4
V4	5th intercostal space, mid-clavicular line
V5	anterior axillary line in straight line with V4
V6	mid-axillary line in straight line with V4 and V5

In the field of electrocardiography, the Standard Limb Leads play a crucial role in assessing the electrical activity of the heart. These leads form a triangle on the body, commonly referred to as Einthoven's triangle, providing valuable information about the heart's rhythm, conduction, and overall cardiac health [8]. Additionally, in mass casualty situations where time is of the essence, a simplified ECG measurement using three electrodes can be employed for fast and efficient monitoring of vital signs.

The Standard Limb Leads consist of three electrodes placed on specific locations of the patient's body: the right arm (RA), the left arm (LA), and the left leg (LL), shown in the Figure 2.

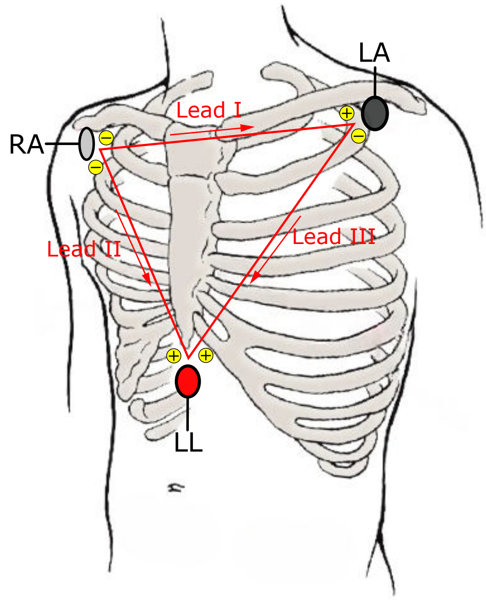

Fig. 2 Standard Limb Leads (Einthoven's triangle).

Table 2 Elements of Standard Limb Leads [9].

Lead	Positive Electrode	Negative Electrode	View of Heart
I	LA	RA	Lateral
II	LL	RA	Inferior
III	LL	LA	Inferior

The electrical potentials recorded from these leads provide a frontal plane view of the heart's electrical activity (Table 2), with Lead I measuring the potential difference between RA and LA, Lead II measuring the potential difference between RA and LL, and Lead III measuring the potential difference between LA and LL. Lead II is particularly valuable in assessing the heart's electrical activity. It is commonly called a monitoring lead, providing information on heart rate, regularity, conduction time, and ectopic beats [9].

Using a simplified three-electrode setup enables healthcare providers to rapidly attach ECG electrodes to the patient's body, facilitating immediate vital sign monitoring. The acquired Lead II ECG tracing can quickly provide information on heart rate, rhythm irregularities, and gross abnormalities. Although the simplified measurement does not offer the comprehensive assessment provided by a full 12-lead ECG, it serves as a valuable tool for initial screening and triage in mass casualty situations.

3 Materials and methods

For the measurement of ECG signals, we used the ADS1194 integrated circuit from Texas Instruments [10]. The ADS1194/6/8 are a family of multichannel, simultaneous sampling, 16-bit analogue-to-digital converters with a built-in programmable gain amplifier (PGA), internal reference, and an onboard oscillator. With their high levels of integration and exceptional performance, they enable the creation of scalable medical instrumentation systems at significantly reduced size, power, and overall cost. Their applications include patient monitoring, Holter, event, stress, and vital signs, including ECG, AED, and Telemedicine. Mikroelektronika produces the PCB board (ECG 2 click) with the ADS1194 and all peripheral components, and it can be connected with the microcontroller and ECG electrodes [11]. In Figure 3, an electrical schematic of the ECG system with ATMega328PU, ADS1194, and FTDI232 chip is presented.

An 8-bit ATmega328-PU microcontroller was used to configure, communicate, and acquire data from ADS1194 via Serial Peripheral Interface (SPI). Sending data to the computer from the microcontroller is achieved through serial communication using the FTDI232 chip. ECG 2 click board (ADS1194) have a 3.5 mm phone jack input for a 3-wire cable where adhesive electrode pads can be used to record electrocardiogram signals, in our case, RA, LA, and LL electrodes.

As already mentioned, three electrodes can be placed in Einthoven's triangle and measure ECG signals in three different configurations (Lead I, II, and III) using LA, RA, and LL electrodes. In each configuration, one electrode is the positive input, the second one is negative, and the third one is the common-mode (or the right leg drive signal). Using multiplexers in the ADS1194, it is possible to reroute the right leg

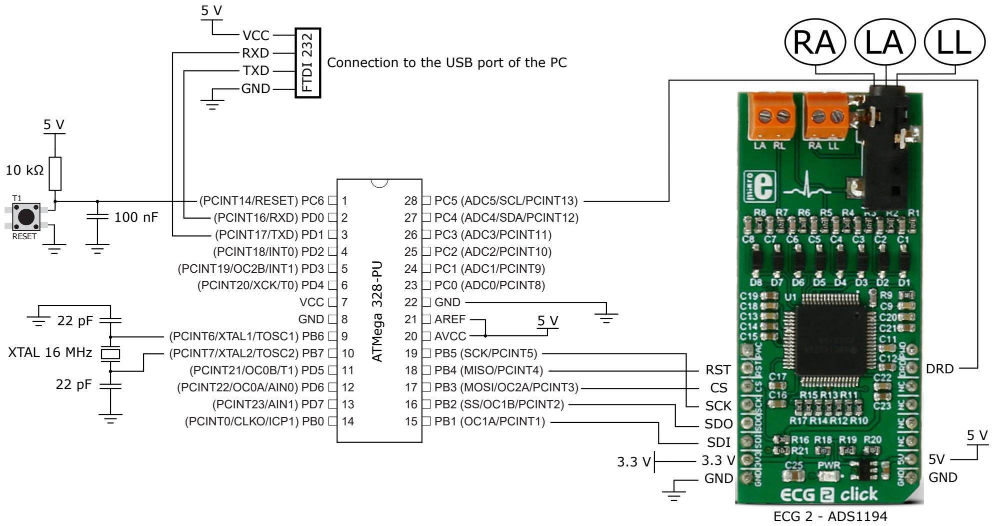

Fig. 3 Electrical schematic of the ECG system with ATMega328PU, ADS1194 and FTDI232 chip.

drive signal to enable measurements of all configurations of the Einthoven's triangle (Figure 4).

The right leg drive (RLD) signal is an important component in electrocardiography that helps the reduction of common-mode interference and improves the quality of ECG recordings. The RLD signal is derived from the electrical potential of the right leg, hence the name, but it actually refers to the reference point for the ECG measurement system, and depending on the measurement configuration, various electrode positions on the body can serve as a reference point, not necessarily the right leg. The primary purpose of the RLD signal is to minimize common-mode interference, which refers to unwanted electrical signals or noise that can affect ECG recording. Common sources of interference include power line noise, muscle artifacts, and electromagnetic interference. These interferences can distort the ECG waveform and make it challenging to accurately interpret and analyze the electrical activity of the heart. By incorporating the RLD signal, the ECG system can actively cancel out common-mode interference. The RLD electrode serves as a reference point that allows the ECG amplifier to measure the potential difference between the active leads (such as Lead I, Lead II, etc.) and the reference (RLD) lead.

The ADS1194 contains flexible input multiplexers that allow the RLD signal to be dynamically routed to any electrode input. This enables different ECG lead configurations to be measured by changing the reference point on the body. Specifically, the RLD signal is generated by averaging the signals from selected channels using resistors `RLD_SENSP` and `RLD_SENSN`. This averaged signal is buffered and appears at pin `RLDOUT`. An inverting amplifier can then be used externally to invert the phase and generate the actual RLD signal applied to the patient's body through an electrode. Critically, the `RLDIN` pin on the ADS1194 allows the RLD signal to be internally fed back and routed to any input channel's multiplexer. By setting the MUX bits in the

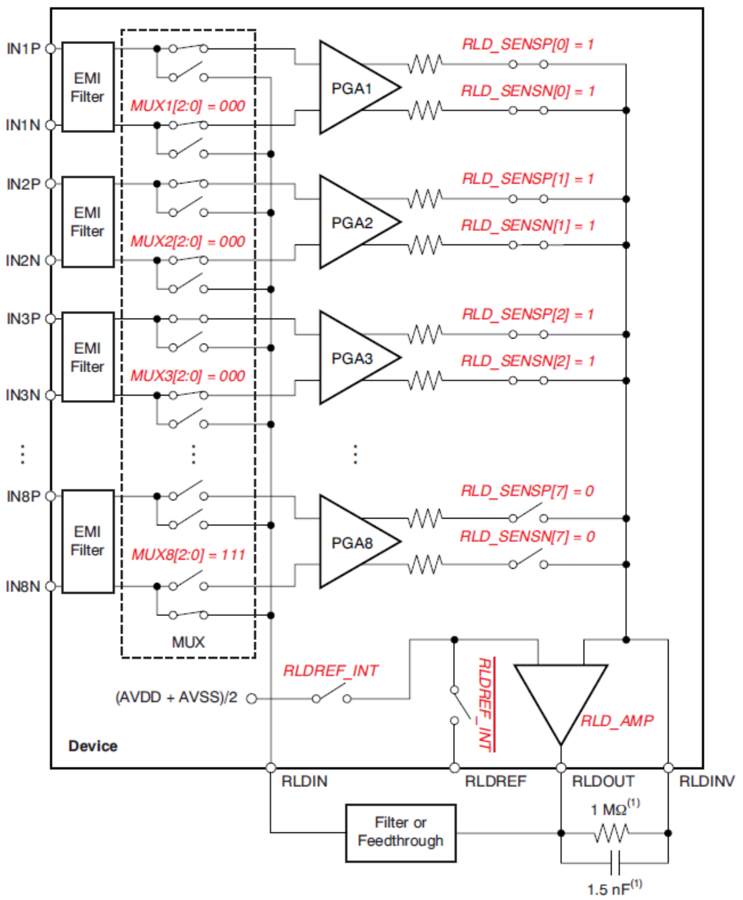

Fig. 4 Rerouting the RLD signal via multiplexer inside the ADS1194 integrated circuit [10].

channel set registers, `RLDIN` can be connected to either the positive or negative input of any channel. For example, Figure 4 in the datasheet shows `RLDIN` being routed to the negative input of channel 8. This enables channel 8 to use the RLD signal as its reference when measuring lead configurations I, II, or III. The RLD electrode is now effectively channel 8's negative input. This allows different ECG leads to be derived by rerouting the RLD signal without having to physically move electrodes on the patient. The key advantages of rerouting RLD internally are faster lead switching since electrodes remain in place and only multiplexer settings change, and continued noise reduction by maintaining a closed RLD feedback loop even as lead configurations change. Proper use of the ADS1194's RLD rerouting capability requires careful configuration of the `RLD_SENSP/N`, `CHnSET`, and `CONFIG3` registers per application needs. The flexibility adds complexity, but enables superior ECG systems.

While the ADS1194 integrated circuit provides an exceptional foundation for ECG systems, realizing a high-performance ECG still requires significant customization. The ADS1194 has myriad parameters and configurable blocks intended for diverse biopotential measurements. Out-of-the-box use will not necessarily yield optimal ECG results. Factors like electrode type and placement, filter settings, data rates, gain selection, pace detection, and lead-off detection require extensive experimentation to tune for ECG signals specifically. Additionally, creative use of features like right leg drive rerouting and Wilson center terminal generation is needed based on lead configurations. Thorough testing and optimization is crucial, backed by an in-depth understanding of ADS1194 capabilities as well as electrocardiography fundamentals. The information in the datasheet provides a starting point, but ultimately robust ECG performance stems from engineering ingenuity in applying the ADS1194 flexibly.

In order to validate the ECG measurements obtained using the ADS1194 integrated circuit, a reference measurement was performed using a standard analogue electrocardiogram circuit produced by Mikroelektronika [12]. This analogue circuit, implemented on a printed circuit board, consists of an instrumentation amplifier front-end for differential signal acquisition, followed by further amplification and filtering stages to condition the ECG signal.

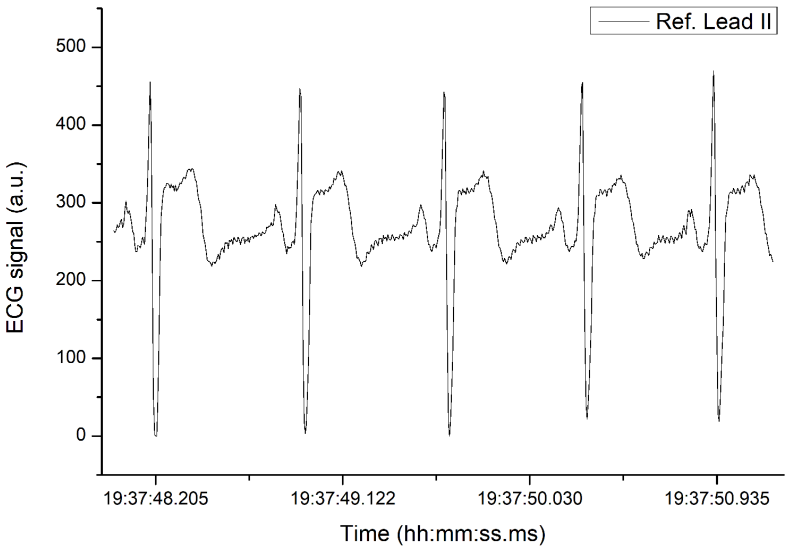

Fig. 5 Reference ECG signal of the Lead II measured with a standard analogue circuit.

The circuit is designed to acquire Lead II ECG measurements, providing a single-ended output that can be digitized by an analogue-to-digital converter (ADC) on a microcontroller. To enable a direct comparison using the same electrodes, the output of the reference ECG circuit was connected via a 3.5 mm jack to the testing system. This allowed the simultaneous acquisition of Lead II ECG signals from both the reference analogue circuit and the ADS1194 integrated circuit under identical conditions. The reference ECG waveform obtained is shown in Figure 5., providing a baseline for evaluating the signal quality achieved using the ADS1194.

4 Results

The results are compiled from ECG signals obtained from three electrodes in an Einthoven's triangle configuration, Lead I, II, and III, using the ADS1194 integrated circuit with internal rerouting of the RLD signal (Figures 6 to 8). It can be observed in all figures that the ECG signals are stable with low noise.

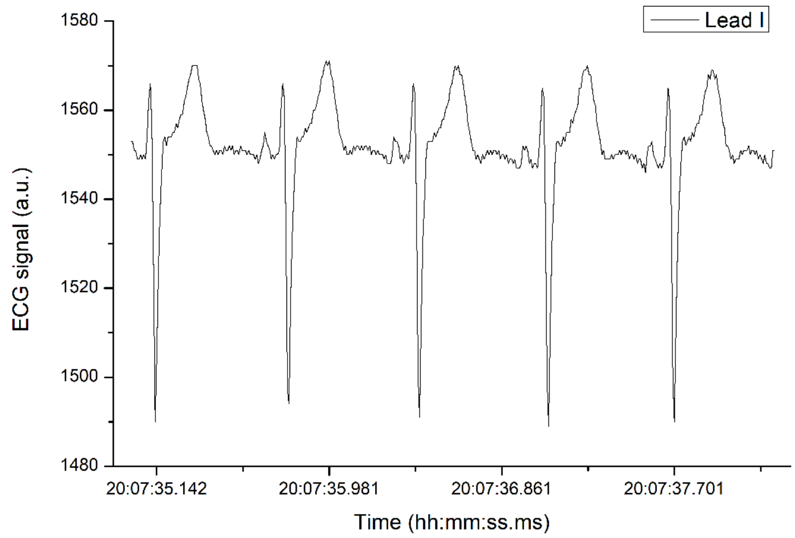

Fig. 6 ECG signal of the Lead I.

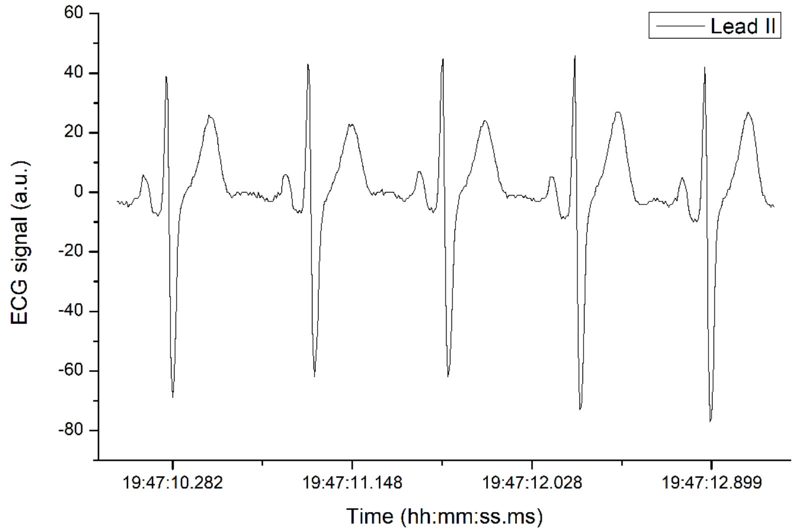

Fig. 7 ECG signal of the Lead II.

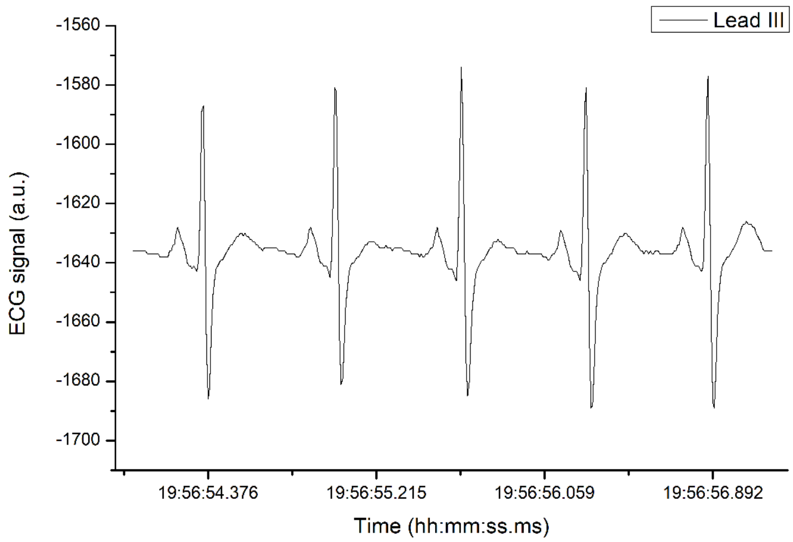

Fig. 8 ECG signal of the Lead III.

5 Discussion

The key findings of this study demonstrate the feasibility of using the ADS1194 integrated circuit for ECG measurement with just three electrodes. The ADS1194 successfully acquired ECG waveforms in all Lead I, II, and III configurations by rerouting the right leg drive (RLD) signal internally. This enabled each electrode to serve as the positive, negative, or reference input as needed to derive the different leads.

Comparing the signal quality obtained from the ADS1194 with that of a standard analogue circuit, it was observed that the ECG signals acquired with the ADS1194 exhibited stability and low noise. In contrast, the reference circuit displayed slightly higher noise, possibly due to network interference. Quantitatively, the noise voltage with the ADS1194 was approximately 20 microvolts lower compared to the standard circuit. Also, apparent high-frequency noise was observed while using the standard circuit, the noise not being present when using ADS1194. The origin of the noise may be AC mains interference at 50 Hz. Additionally, differences in the signal shape were observed, likely resulting from variations in the internal electronics between the ADS1194 integrated circuit and the standard analogue circuit.

Subtle variations in ECG waveform morphology were also observed between the two systems. The ADS1194 recordings exhibited a steeper RS transition compared to the reference circuit. This is likely due to differences in frequency response shaping between the ADS1194's configurable digital filters and the reference circuit's passive RC filtering. Overall, the programmable nature of the ADS1194's signal path affords greater flexibility in tuning performance for ECG applications.

Our findings align show that integrated biopotential acquisition systems like the ADS1194 enable miniaturized, lower-power, and cost-effective ECG monitoring. While further optimization is still necessary, this study demonstrates the ADS1194's potential for rapid triage ECG screening using simplified 3-lead measurements. Easy electrode placement facilitated by 3-lead systems could allow faster attachment in emergency situations to quickly evaluate heart rate and rhythm. The next step in investigation would be to reference our system against a clinically validated commercial ECG system as a gold standard comparison.

The findings of this study contribute to the growing body of research on advanced ECG measurement techniques and technologies. In summary, the configurable ADS1194 integrated circuit can reliably acquire multi-lead ECG measurements using just three electrodes. With further refinement, this technology could aid in prompt cardiac screening for mass casualty triage when rapid assessment is critical.

6 Conclusion

In conclusion, this study investigated the application of the ADS1194 integrated circuit for ECG signal measurement. The results demonstrated that the ADS1194, in conjunction with the ATmega328P microcontroller, enabled the successful acquisition of ECG signals using three electrodes in different Standard Limb Leads configurations. Further research and exploration of the ADS1194 integrated circuit, along with other emerging technologies, are warranted to fully unlock their potential in enhancing ECG monitoring, diagnosis, and patient care.

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