Analog Front-End Pre-Amplifiers for Portable Capacitive ECG Monitoring Applications Analysis

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Abstract. In today's field of medical technology, the development of Electrocardiogram (ECG) monitoring systems is increasingly receiving attention. ECG, as a crucial tool for assessing cardiac function and heart health, plays an irreplaceable role in clinical diagnosis, health monitoring, and disease prevention. However, ECG signals are inherently low in amplitude and susceptible to interference, making the advancement of ECG electrode technology and Analog Front End (AFE) technology essential for achieving accurate and reliable monitoring. This research underscores the pivotal role of ECG electrode technology and the significance of the Analog Front End (AFE) in enabling efficient wireless ECG monitoring systems. With ECG signals being inherently low amplitude and prone to interference, the technology and choice of electrodes are crucial. This study dives deep into the evolution of ECG electrode technology, reviewing the pros and cons of wet, dry, and capacitive electrodes. The primary focus of the paper revolves around the IA-based pre-amplifier design, detailing its challenges and offering innovative solutions. Novel architectures utilizing capacitors, MOSCAPs, and CMRR improvement techniques are presented. The paper concludes by emphasizing the importance of accurate gain configuration, noise reduction, layout efficiency, and adherence to relevant standards.

Keywords: ECG, Analog Front End (AFE), IA-based pre-amplifier, capacitive electrodes, CMRR improvement.

1. Introduction

In recent years, the progress of artificial intelligence has sparked an increase in the utilization of integrated circuits for various biomedical applications. A prominent area of focus is the measurement of the electrocardiogram (ECG), which provides crucial insights into heart activity, including rate, rhythm, and strength. The demand for continuous ECG monitoring in the public domain has grown significantly. However, traditional ECG measurement setups are time-consuming and can make patients feel uneasy due to their complexity. To address these challenges and ensure seamless human mobility, there is a pressing need for low-power, affordable, and compact technologies. As a solution, wireless ECG wearable monitoring systems have emerged, enabling the capture and wireless transmission of data to devices such as smartphones and hospital information systems. In this context, the Analog Front End (AFE) plays a pivotal role in enabling efficient wireless ECG monitoring systems.

ECG signals are characterized by their low amplitudes and susceptibility to noise and interference. This paper delves into the evolution of ECG electrode technology, exploring the advantages and limitations of wet and dry electrodes. A groundbreaking approach involving capacitive electrodes is introduced, offering non-contact operation and improved user comfort. The accurate placement of ECG sensors and vector analysis techniques for precise imaging are discussed. The AFE system for ECG signal processing is detailed, with a focus on the traditional IA-based pre-amplifier. The limitations of this design lead to the exploration of innovative amplifier architectures using capacitors and MOSCAPs to enhance CMRR and signal fidelity. The paper also examines commercially available bioamplifier integrated circuits, showcasing a high-performance amplifier architecture. Key considerations for IA-based pre-amplifier design are highlighted, emphasizing accurate gain configuration, noise reduction, layout efficiency, CMRR improvement, and adherence to standards.

2. ECG and its Process

2.1. Electrocardiograph (ECG)

ECG monitoring is crucial for assessing the heart's normal function and diagnosing cardiac disorders. Electrocardiographs find extensive use in various medical settings, including catheterization labs and cardiology diagnostic applications.

ECG signals are weak due to their low amplitudes, ranging from 100 μV to 5 mV [1]. Normal ECG signal operation covers a bandwidth from 0.1 to 150 Hz [1]. The skin-electrode interface introduces a dc half-cell voltage of up to ±300 mV. In order to provide a bandwidth that falls within the 0.1 to 150 Hz range, it is imperative that the highest input-referred noise voltage does not surpass 30 μV. Moreover, ECG readings are susceptible to interference originating from the 50/60-Hz mains power, leading to the presence of common-mode signals that are connected to the human body and can reach about 1 mV in normal scenarios when the patient is electrically insulated from the earth ground [2]. Illustrated in Fig. 1 are sample ECG signals corresponding to a typical cardiac cycle [3].

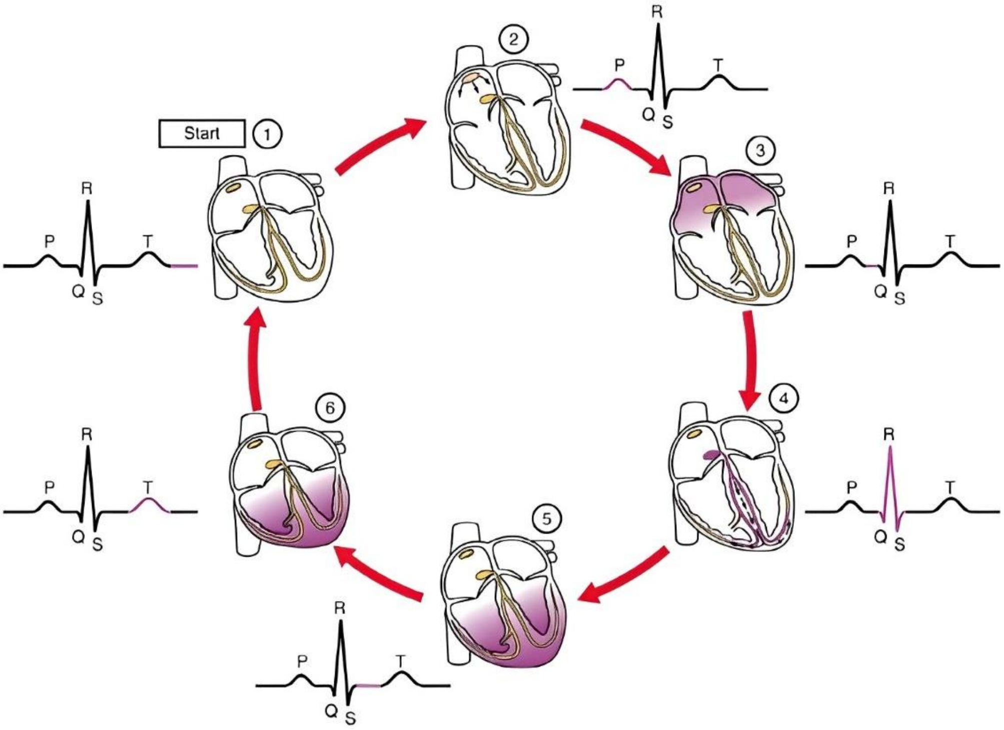


Figure 1. An illustration depicting a typical cardiac cycle alongside the corresponding ECG signal waves [3]

2.2. ECG Electrode Selection

In the realm of biomedical monitoring, electrode technology plays a pivotal role in ensuring accurate and comfortable data acquisition. Among the electrode options, wet electrodes utilizing low-impedance ionic gels, such as Ag/AgCl, offer a significant advantage in establishing optimal contact between the monitoring device's input and the skin. However, these gels present certain limitations, including susceptibility to electrical instability over time due to environmental factors like humidity, sweat, drying, and skin contact issues [4]. Furthermore, the use of gels and adhesives can sometimes lead to skin irritation and disruptions in daily activities, and in some cases, users might even experience allergic reactions to the gel [5].

In pursuit of enhanced user comfort and flexibility, dry electrodes have emerged as an appealing alternative. Notably, two variations – Spike Arrays and Soft Materials – exhibit commendable merits [6, 7]. Dry electrodes, as a category, offer improved mobility and comfort compared to their wet counterparts. However, it's worth noting that even dry electrodes necessitate direct contact with an electrically conductive substance on the skin, posing inconveniences and raising safety concerns.

A groundbreaking approach to electrode technology is evident in capacitive electrodes. These electrodes transcend the mobility and comfort benefits of gels and dry electrodes. Notably, capacitive electrodes operate without direct skin contact, a characteristic that stems from the electrode plate's integration with a dielectric material. This arrangement results in the formation of a capacitor when combined with the skin, as visually depicted in Fig. 2 [8].

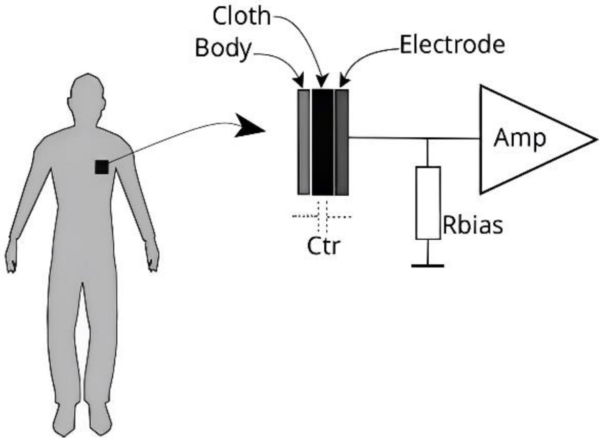


Figure 2. Capacitive electrode between human body and the AFE

The design enables the conveyance of the body's electrical potential to the input amplifier through capacitive coupling, facilitated by the transitive capacitance Ctr. An appealing attribute of capacitive electrodes is their non-irritating nature, making them a desirable option for wearable applications [8]. However, it's important to acknowledge that challenges exist in securing multiple electrode nodes and mitigating motion artifacts, a task that demands careful consideration.

In summary, electrode technology is evolving to provide optimal solutions for biomedical monitoring. While wet electrodes excel in establishing contact but face practical limitations, dry electrodes enhance comfort while introducing their own set of requirements. Capacitive electrodes offer a groundbreaking approach with non-contact operation and skin-friendly attributes, albeit with the challenge of electrode placement and motion-related concerns. As advancements continue, the choice of electrode type will depend on the specific monitoring needs and the balance between comfort, accuracy, and practical considerations.

2.3. ECG Sensor Placement

Fig. 3 illustrates the conventional arrangement of bipolar electrocardiogram (ECG) sensors and the associated waveforms [4].

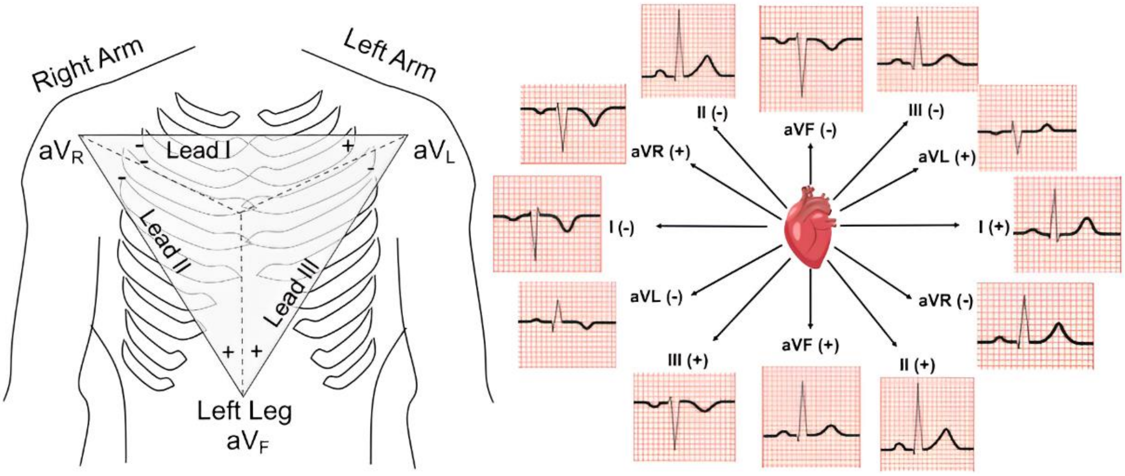


Figure 3. ECG sensor placement [4]

In Lead I, the anode extends from the right arm to the left arm. In contrast, Lead II encompasses a negative electrode that spans from the right arm to the left leg. Finally, Lead III is characterized by a negative electrode that extends from the left upper limb to the left lower limb. In order to improve the precision of cardiac imaging and ECG analysis, a measuring approach that incorporates vector analysis is proposed. This technique generates a reference point by calculating the average of two limb electrodes [9]. These supplementary leads are widely recognized in the medical field as Goldberger's leads. The term "aVL", "aVR", and "aVF" refer to augmented voltage left, augmented voltage right and augmented voltage foot, respectively.

The information gathered between aVR, aVL, and aVF forms "bipolar" leads, establishing Einthoven's triangle and separating the chest into three areas. Each area exhibits a distinct polarity in the QRS complex. In order to attain optimal monitoring, a body location that exhibits minimum mobility and is situated away from the center chest region is selected. The rib cage situated below the Lead III region is more favorable as it exhibits higher amplitudes of positive QRS peaks and a decreased likelihood of current injection danger [4].

2.4. System Overview

The Analog Front End (AFE) for an ECG comprises the following sub-circuits, as shown in the Fig. 4 [10]. The objective is to obtain a digital representation of the analog ECG signal at the output.

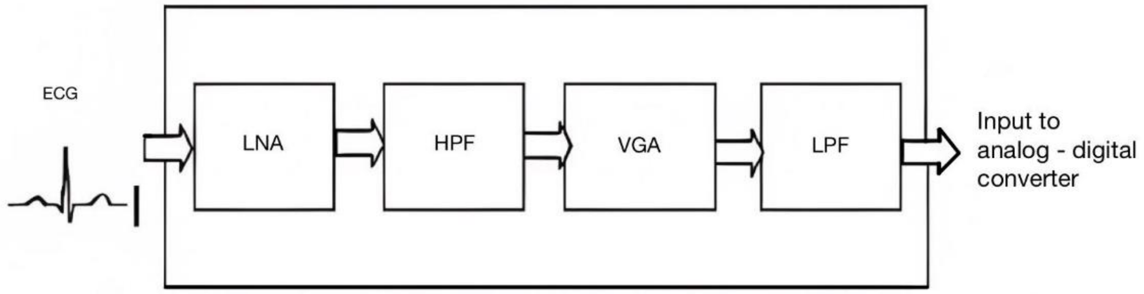


Figure 4. Block diagram for the AFE

First, the IA-based pre-amplifier circuit is designed to handle ECG voltages originating from electrodes, where all the properties of ECG should be considered as mentioned in the previous part. Second, low-pass filters, or low-pass and high-pass filters are employed to define the ECG signal's bandwidth. Third, a programmable-gain amplifier (PGA) is utilized to apply different levels of amplification based on the amplitude of the ECG signal. Finally, the Analog to Digital Converter (ADC) receives the output from the Analog Front End as its input.

3. Traditional IA-Based Pre-Amplifier

The primary function of the Low-Noise Amplifier (LNA) is to increase the low amplitude of the electrocardiogram (ECG) signal to an appropriate voltage level. The amplification technique is included into the design of a bandpass filter. This study will primarily concentrate on the design of the IA-based pre-amplifier, which is commonly employed as a LNA, among the several sub-circuits discussed before. Figure 5 depicts a dc-coupled classical three-op-amp instrumentation amplifier (IA), which is extensively employed in various commercial applications. The arrangement under consideration comprises of two-stage amplifiers that utilize resistive feedback. The initial phase of the process offers a well-balanced and high input impedance, characterized by a differential gain of (1+2R1/RG) and a common-mode gain of unity. Conversely, the second-stage amplifier functions as a converter from differential to single-ended configuration, exhibiting a differential gain of (R3/R2). It is worth mentioning that the common-mode gain is subject to the influence of resistor mismatch, which therefore impacts the common-mode rejection ratio (CMRR). As a result, the precise matching between R2 and R3 has critical importance. Enhancing the gain of the initial stage not only enhances CMRR, but also diminishes the overall circuit noise. This is due to the fact that the noise of the second stage is proportionally reduced by the gain of the first stage when it is referenced to the input. Nevertheless, the task of increasing the gain of the first stage is arduous as a result of the substantial direct current offset voltage present in the direct current-coupled input. The traditional 3-op-amp IA is shown in Fig. 5.

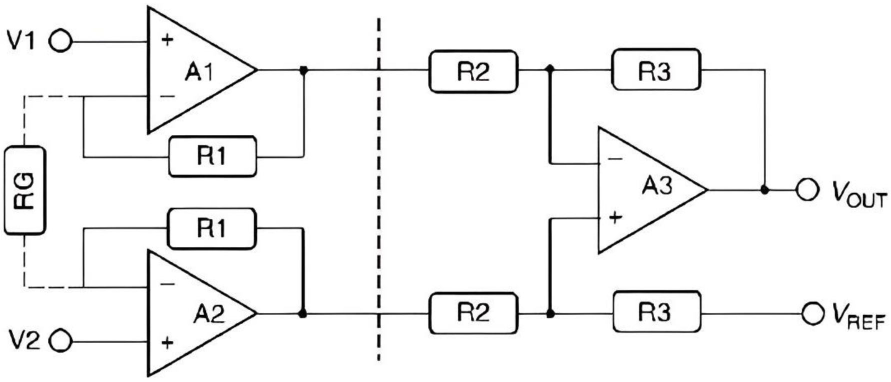


Figure 5. Traditional 3-op-amp IA

4. Review and Discussion

The conventional instrumentation amplifier relies on resistor ratios for accurate gain configuration. Nonetheless, resistors exhibit suboptimal matching properties, introduce noise, and necessitate considerable current, unless they're sizable, which leads to area-related costs. To address this, a new architecture developed by L. Fay, V. Misra and R. Sarpeshkar proposes capacitors are utilized for gain adjustment [11]. Even moderately-sized poly-poly capacitors within our fabrication process can be precisely matched within a 1% range through meticulous unit-cell layout [12]. It's noteworthy that capacitors do not contribute to noise. The circuit diagram of the proposed instrumentation amplifier is shown in Fig. 6.

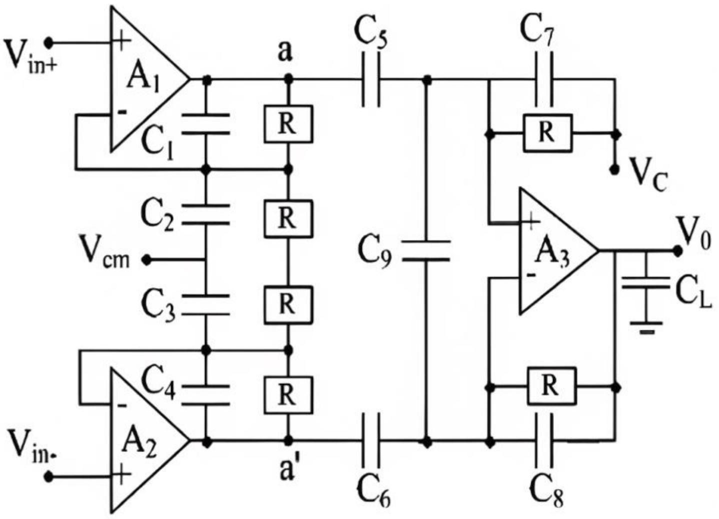
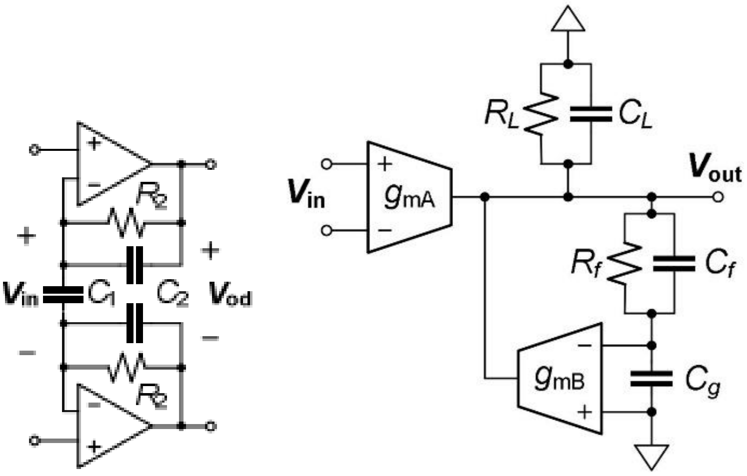


Figure 6. The circuit diagram of the proposed instrumentation amplifier [11]

The drawback associated with capacitors is the considerable space they occupy within the complete amplifier layout. One approach proposed by M. Ghamati and M. Maymandi-Nejad to address this issue involves employing MOSCAPs as a solution, given that MOSCAPs occupy only one-fourth of the area compared to MIM capacitors in the context of 0.18µm CMOS technology [13].

The initial phase of the conventional three-op-amp instrumentation amplifier lacks common-mode and dc rejection capabilities. Consequently, the task of attaining a substantial voltage gain becomes arduous in order to mitigate the adverse effects of electrode offset-induced saturation. P. Pantuprecharat, S. Masaree, P. Pawarangkoon and C. Sawigun replaced the first stage by Fig. 7(a) to achieve a high ac gain by the ratio of the capacitor [14]. Simultaneously, it is possible to maintain a dc gain of 0dB.



(a) (b)

Figure 7. (a) IA with only ac amplification and (b) proposed amplifier [14]

A slight modification enables CMRR enhancement independently of the differential voltage gain, allowing for the elimination of the second stage in the IA structure. Fig. 7(b) displays the proposed IA topology by P. Pantuprecharat, S. Masaree, P. Pawarangkoon and C. Sawigun, using current-feedback and a feedback setup similar to Fig. 5 [14]. CMRR is now managed by the utilization of an input transconductor, denoted as g_{mA}. This transconductor may be enhanced by employing a fundamental technique that incorporates a tail current source with a high-output impedance, as well as a differential pair transconductor. The primary focus of this amplifier is to achieve a large ac gain ranging from 50 to 200 times, rather than emphasizing dc suppression. This approach is considered more advantageous compared to dc-coupled designs that rely on a dc servo loop, as the latter often result in dc gain exceeding 0 dB without the aid of digital assistance [15].

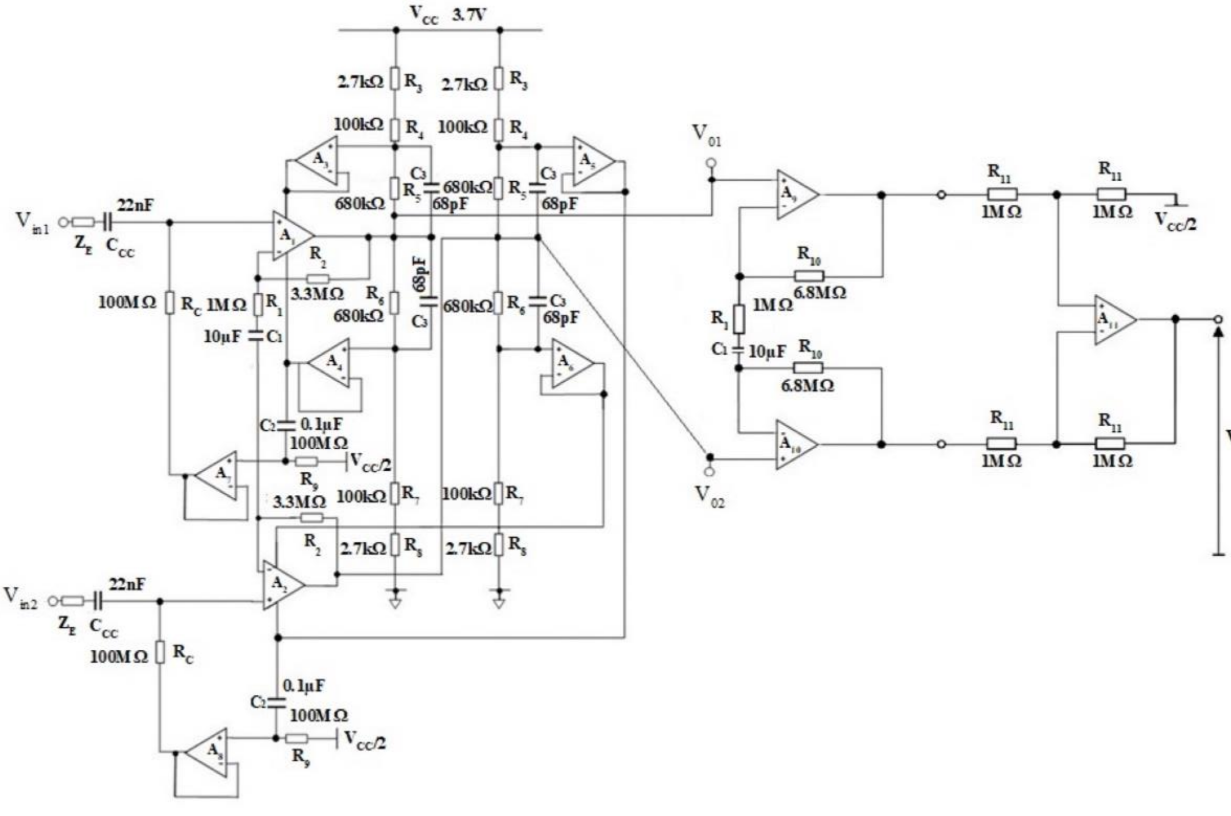


Figure 8. The complete three stage amplifier [16]

Commercially available bioamplifier integrated circuits often exhibit high power consumption, bias current, input capacitance, and, in some instances, lower amplifier input impedance [16]. In the architecture proposed by S. Maji and M. J. Burke, the author introduced a novel LNA, based on the classical 3-op-amp instrumentation amplifier, using dc coupled input impedance boosting, capacitance reduction by power supply bootstrapping, differential power supply bootstrapping, boosting CMRR strategy and reduction of amplifier initialization time, respectively, as shown in Fig. 8 [16].

The preamplifier stage successfully provides a 3-dB bandwidth spanning from 0.05 Hz to 450 Hz, hence satisfying the specified frequency response criteria. The system achieves a minimum input impedance of 10 $G\Omega$ across the frequency range of 0.1 Hz to 150 Hz. The bench tests have shown that CMRR exceeds 80 dB at a frequency of 50 Hz for challenging electrode models, in accordance with the specifications outlined in the IEC60601 standards.

In conclusion, there are some key considerations when designing IA-based pre-amplifier, based on the improvements of the classical three-op-amp instrumentation amplifier, proposed by the papers mentioned above. It's crucial to prioritize accurate gain configuration while minimizing noise and optimizing layout efficiency. Utilizing capacitors for gain adjustment can enhance precision, but their space requirements should be managed. Achieving high CMRR is vital, and techniques like input transconductor boosting and MOSCAP integration can help. Careful consideration of frequency response, power consumption, input impedance, CMOS technology compatibility, and reliable biasing is essential. Rigorous testing and validation, along with efficient integration and packaging strategies, are key to developing a successful amplifier that meets performance criteria and adheres to relevant standards.

5. Conclusion

The continuous advancement of ECG electrode technology plays a pivotal role in improving signal quality and patient comfort. While wet electrodes excel in establishing contact, dry electrodes and capacitive electrodes offer promising alternatives with enhanced mobility and non-contact operation. The IA-based pre-amplifier, a critical component of the ECG signal chain, has evolved to address its limitations, with novel architectures utilizing capacitors and MOSCAPs for gain adjustment and noise reduction. These innovations contribute to improved CMRR and signal fidelity. Commercially available bioamplifier integrated circuits further exemplify the progress in ECG signal processing. Designing IA-based pre-amplifiers requires careful consideration of various factors, including frequency response, power consumption, input impedance, CMOS technology compatibility, biasing, testing, validation, and adherence to standards. As technology continues to evolve, the choice of electrode technology and amplifier design will depend on the specific monitoring needs, balancing comfort, accuracy, and practical considerations for enhanced cardiac health assessment and diagnosis.

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