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A Review on Material Comparisons and Signal Acquisition of Wearable Electrocardiogram Monitoring Flexible Electrodes

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Abstract:

The development of wearable medical devices has placed greater demands on the selection and performance optimization of electrode materials. Traditional gel electrodes have low impedance and good conductivity, but they tend to cause skin irritation, dryness, and unstable signals during long-term monitoring. In contrast, flexible electrodes based on polymers and textile materials have advantages in biocompatibility, and are gradually emerging as potential alternatives for long-term electrocardiography(ECG) monitoring. This review summarizes common quantitative indicators used to evaluate the quality of ECG signals, including signal-to-noise ratio (SNR), kurtosis, and skewness. These indicators can reflect the stability and usability of the signals from different perspectives, providing a systematic reference for comparing electrode performance. This study did not offer specific experimental values but instead organised and summarised the evaluation methods based on existing literature to provide a theoretical basis for the subsequent structural design, material optimisation, and application expansion of flexible electrodes in wearable medical monitoring.

Keywords: Flexible electrodes, ECG, SNR, Kurtosis, Skewness.

1. Introduction

With the rapid development of wearable medical devices, the selection and performance optimization of electrodes have become crucial factors for ensuring signal quality and wearing comfort. Traditional gel electrodes have low impedance and excellent conductivity in short-term monitoring. However, they often cause skin irritation and signal drift during long-term use, therefore limiting their application in continuous monitoring. In contrast, flexible electrodes based on polymers and textile materials, due to their excellent biocompatibility, breathability, and mechanical flexibility, have gradually become ideal alternatives for long-term monitoring of ECG.

To evaluate the usability of ECG signals, researchers have proposed various indicators of signal quality [1]. SNR can directly reflect the contrast between the signal and noise. Kurtosis can reflect the sharpness of the signal waveform and is often used to identify artifacts. Skewness reveals the asymmetry of the waveform. These parameters not only help to quantitatively compare the signal quality collected by different electrode materials but also provide essential information for future wearable electrodes in material design, structural optimisation, and improvement of signal processing algorithms.

2. Flexible Electrode Materials For ECG Monitoring

The textile-based electrodes can possess excellent skin compatibility, breathability and degradability, making them highly suitable for long-term ECG monitoring. These electrodes can be fabricated by coating, screen printing or fabric embedding methods, which can significantly reduce the electrode-skin impedance, improve the SNR, and reduce motion artefacts during long-term monitoring. For instance, the PEDOT: PSS textile electrode doped with aloe extract not only enhances the skin adhesion but is also regarded as a natural adhesive [2]. Hence, ensuring stability during long-term use.

The functional layer material is mainly derived from Intrinsically Conductive Polymers (ICPs), which are organic polymers that can conduct electricity. Typical representatives include PEDOT: PSS, PSS-doped polyaniline (PANI) and polypyrrole (PPy) [3]. This type of material possesses the flexibility of polymers and adjustable electrical cconductivity. Moreover, its conductivity can be significantly enhanced through chemical doping or solvent treatment [3].

Table 1. Comparison of flexible wearable ECG electrode materials

Materials	Key properties	Advantages	Limitations	Applications
Metals: Gold(Au), Silver(Ag/AgCl)	High conductivity, Chemical stability	High signal quality, Flexibility	High cost Ag/AgCl prone to skin irritation	Au serpentine electrode, Traditional Ag electrode
Conductive polymers: PEDOT: PSS, Composites	Transparent, Printable	High flexibility, Relatively low cost	Pure PEDOT: PSS has poor mechanical stability	Self-adhesive electrode tattoo, PEDOT: PSS electrode
Carbon nanomaterials: Graphene Carbon nanotubes (CNT)	Lightweight Made into conductive fibers	Integrate into textiles, Low impedance	Complex fabrication	Graphene textile electrode
Biocompatible Material-Derived: Hydrogels Silk fibroin (SF)	High Stretchability, Strong adhesion	Comfortable for long-term wearing Stable signals	Low mechanical strength	Self-healing hydrogel electrode

Flexible electrode materials have been widely studied in wearable ECG monitoring. See Table 1. Different types of materials have their own advantages and limitations. From the perspective of metals, gold (Au) and silver (Ag/AgCl) electrodes, due to their excellent conductivity and stability, can ensure high-quality signal output. However, metal electrodes are generally expensive and have insufficient flexibility for large metal pieces. The Ag/AgCl electrode also has problems with easy drying and skin irritation. Hence, its application is limited to long-term wearing scenarios.

In contrast, conductive polymer types (such as PEDOT: PSS and its composites) are printable, transparent, and flexible. They have relatively lower costs and can improve their mechanical properties and adhesion by adding additives and even achieve self-healing functions. These materials excel in comfort and processability, but the stability of a single polymer still needs to be improved.

Carbon-based nanomaterials such as graphene and carbon nanotubes have both high conductivity and lightweight advantages and can be combined with fabrics to form fibre or textile electrodes, suitable for dynamic monitoring during physical activities. However, their preparation process is relatively complex, and long-term stability remains a challenge.

Biocompatible material-derived, such as hydrogels and SF, have significant advantages in adhesion and comfort. Their self-healing and high adhesion properties are

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conducive to long-term monitoring, but their mechanical strength and environmental stability are still insufficient.

Overall, the comparison shows that if the focus is on the comfort and signal stability during long-term wearing, conductive polymer and hydrogel electrodes have greater application potential. If a high signal-to-noise ratio and accuracy are pursued, precious metal electrodes are still a more ideal choice. In future development, combining the composite structure of conductive polymers and nanomaterials may be the best solution to achieve the balance of flexible electrode performance and comfort. Based on current research and application needs, it is advisable to choose PEDOT: PSS composite electrodes as the key material, as they achieve a relatively balanced cost, flexibility, and signal quality. To be more specific, compared with traditional metal electrodes, PEDOT: PSS can flexibly conform to the minute deformations of the skin surface and will not cause significant displacement or detachment due to body movement, thereby reducing motion artefacts and signal loss. Secondly, it has high conductivity, which can significantly reduce the contact impedance between the electrode and the skin, thereby improving the signal-to-noise ratio. Its softness and good adhesion make it more comfortable during long-term wear, making it suitable for wearable medical devices. At the same time, PEDOT: PSS has good biocompatibility, reducing the risk of skin irritation and allergic reactions. Moreover, this material is easily processed by spin coating, spraying, or printing, with a low cost and is suitable for large-scale production.

3. Overview Design For ECG Acquisition

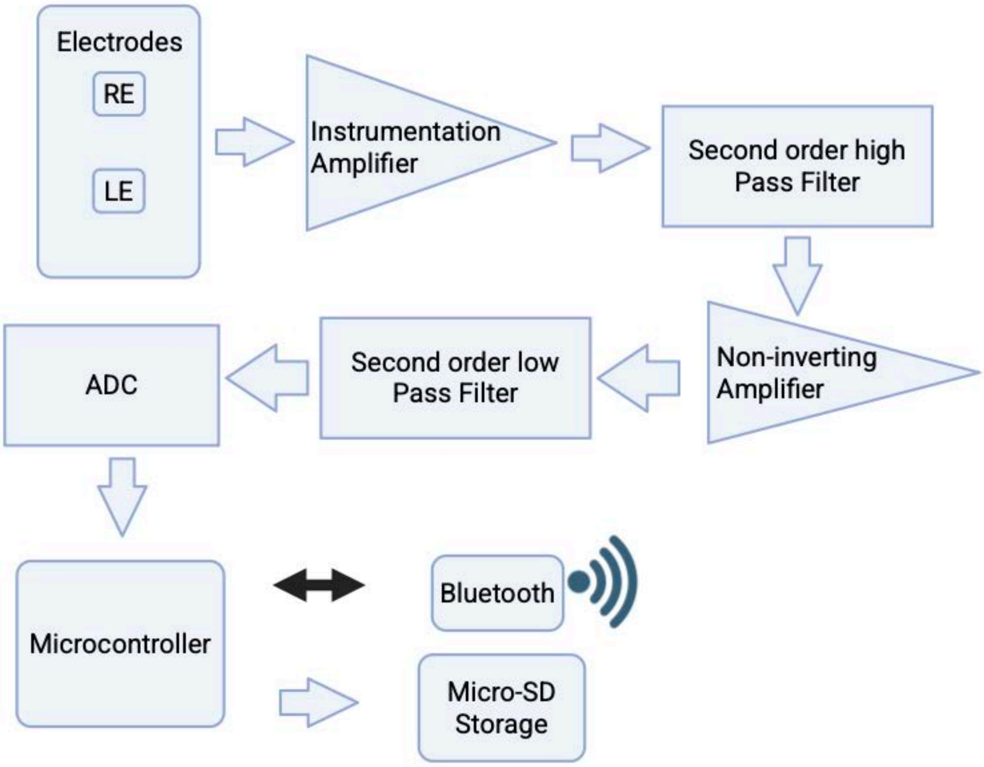

Fig 1. Block diagram of a typical ECG acquisition system

Figure 1 illustrates the block diagram of a typical ECG acquisition system. ECG monitoring requires the measurement of potential differences. The right electrodes (RE) and left electrodes (LE) detect the electrical potential differences generated by the heart. These signals are usually measured in millivolts. The original ECG signal ranges roughly from 0.5 mV to 5 mV, but the reference voltage for the analogue digital converter is usually 3.3V or 5V. Therefore, an instrumentation amplifier is needed to amplify and prevent common-mode interference.

The amplified signal is passed through a second-order high-pass filter. The reason for choosing a second-order filter is that it can better suppress out-of-band noise and eliminate low-frequency interferences such as baseline drift and motion artefacts compared to the first order. Then, the signal amplitude is further enhanced through a non-inverting amplifier to reach the range required for conversion. Then, the signal passes through a second-order low-pass filter to remove high-frequency noise. The combination of high pass and low pass here can be regarded as a band pass filter. After amplification and filtering, the analogue signal will be converted by the ADC. Finally, after Arduino reads the data from the ADC, the ECG data can be transmitted via Bluetooth to an external device or onto an SD card. This enables monitoring to be carried out, and the data can be preserved.

Furthermore, the design of the entire electrocardiogram requires not only the acquisition of signals. Other aspects also need to be taken into consideration. For instance, in practical applications, electrocardiogram monitoring often requires long-term or continuous recording. Therefore, the system's low power consumption and data storage methods become particularly important. Through Bluetooth transmission, the patient's electrocardiogram data can be transmitted in real-time to a mobile phone or computer, facilitating remote monitoring by doctors and enabling timely intervention. The Micro-SD storage module provides a local saving option, ensuring data integrity even in cases of unstable or interrupted wireless connections. This dual guarantee mechanism enables the system to strike a balance between real-time performance and security. Suppose more leads are needed in the future to obtain comprehensive electrocardiogram information. In that case, only the electrode and front-end parts need to be adapted, while the back-end filtering, ADC, and microcontroller structure can remain unchanged, thereby saving development costs.

4. Assessment Standard In ECG Signals

4.1 Signal-to-noise Ratio (SNR)

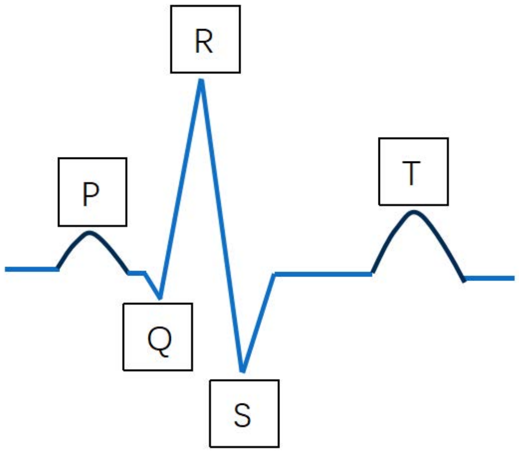

Fig 2. Typical ECG waveform

After the ECG data has been collected, as shown in Figure 2, with the P wave, QRS complex, and T wave, it is necessary to conduct an assessment to verify whether the signal conditioning and acquisition process were effective. Different waveforms correspond to different stages of the electrical activity of the heart. Specifically, the P wave represents atrial depolarization, so it is often used to determine whether the heart rhythm originates from the sinoatrial node and can help identify atrial conduction abnormalities. The Q wave is the initial manifestation of ventricular depolarisation, and is usually small under normal circumstances. However, if a pathological Q wave with significant deepening or widening appears, it often indicates a previous myocardial infarction. The R wave is the central waveform of ventricular depolarisation, and its amplitude and progression can reflect severe heart disease. In contrast, the S wave represents the end of ventricular depolarisation. When combined with the R wave to form the QRS complex, it is used to analyse the ventricular conduction status. For instance, when bundle branch block occurs, the QRS complex becomes significantly widened. Finally, the T wave corresponds to ventricular repolarization, and its morphological changes are of great significance for judging myocardial ischemia.

First, there is the SNR. SNR reflects the relative intensity between the effective electrocardiogram waveform and the background noise. SNR can determine whether the system can accurately capture the ECG waveform features in a noisy environment. For example, in the signal image of the standard ECG, whether the P wave, QRS wave complexes and T wave are clearly observed.

The SNR could be calculated in the formula below, where P_s represents the power of the signal and P_n stands for the power of the noise.

$$SNR(dB) = 10log\left(\frac{P_s}{P_n}\right) \quad (1)$$

For ECG signals, especially in the automatic QRS wave detection process, when the SNR is high or equal to -6 dB, the standard QRS detection algorithms can still maintain good performance. However, when the SNR is lower than -6 dB, the detection performance will significantly decline [4], particularly in the presence of low-frequency noise band width interference.

4.2 Improvement Of SNR

The improvement of SNR usually involves two aspects: an increase P_s or a decrease P_n. Firstly, the research demonstrated that when the recommended input impedance (10 MΩ) was used, significant waveform distortion would occur in the ECG [5]. The simulation results suggested that the input impedance should be higher than 3

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GΩ to meet the performance standards and prevent signal distortion. Therefore, the input impedance of the amplifier can be increased.

4.3 The Kurtosis And Skewness

Kurtosis and skewness characteristics are also parameters used to evaluate the characteristics of a signal. They are typically employed to measure the asymmetry and sharpness of the peak distribution in an electrocardiogram signal [6].

Specifically, kurtosis is an indicator that measures the degree to which data are concentrated around the mean. It describes the characteristics of the signal waveform, whether it is sharp or flat [7]. Usually, when the noise increases, the signal becomes flatter and the kurtosis decreases. Furthermore, Kurtosis performs particularly well in evaluating the relationship between ECG signals and noise levels, and has a very high correlation with SNR (r ≈ 0.95) [8].

Kurtosis can be defined as follows:

$$\text{Kurtosis} = \frac{1}{n}\sum_{i}^{N}\left(\frac{\sum_{i=1}^{n}\left(x_i - x^{-}\right)^4}{s^4}\right) \tag{2}$$

Here, x bar represents the mean of the sample, s is the sample size, and n is the sample capacity. A statistical approach was employed to measure the steepness of the data distribution. The primary definition is derived from the four central moments.

Skewness is a measure of whether the distribution of data is symmetrical. For instance, in the image of a standard ECG, the P wave and the T wave exhibit a highly asymmetrical nature. Hence, the skewness can indicate whether the waveform is typical.

Skewness can be defined as follows:

$$\text{Skewness} = \frac{\sqrt{n(n-1)}}{n-2}\left(\frac{\sum_{i=1}^{n}\left(x_i - x^{-}\right)/n}{s^3}\right) \tag{3}$$

Here, x bar represents the mean of the sample, s is the sample size, and n is the sample capacity. If the skewness is close to 0, it indicates that the distribution is approximately symmetrical. Positive skewness means that the right tail of the distribution is longer, indicating that the data are concentrated on the smaller side. While negative skewness means that the left tail of the distribution is longer, indicating that the data are focusing on the larger side. An ideal ECG signal should show a relatively regular waveform structure within a cycle, and the skewness value is usually close to 0. If electrode contact is poor, motion artefacts or noise interference cause waveform deviation, and the skewness value will significantly deviate from zero. Therefore, skewness can be used as an auxiliary indicator to reveal signal abnormalities and compare the stability of signals collected by different electrodes.

To enhance the functionality, durability and sustainability of the flexible electrodes [9]. The dip-coating technique holds promise for its future applications. Firstly, it is low-cost. Then, the thickness and uniformity of its coating highly depend on process parameters such as immersion speed and pulling speed. If these conditions are adequately controlled, a continuous and uniform conductive layer can be obtained, thereby ensuring the flexibility and comfort of the fabric while significantly improving the overall conductivity and skin adhesion, and thus obtaining more accurate data. However, the conductive layer remains prone to performance degradation due to factors such as water washing, friction, and sweat during prolonged use. Therefore, researchers propose introducing multifunctional transparent protective layers, such as PVA and PU, on the surface of the conductive layer. The dip-coating technology not only provides stable electrical properties to the textile electrodes but also meets the requirements of wearable devices for long-term use and comfort.

During the process of optimising the quality of ECG signals, the electrical conductivity of the material and the stability of the interface play an essential role. Conductive polymers, such as PEDOT: PSS, have relatively low initial conductivity. It can also significantly improve their performance through secondary doping. Studies have shown that adding DMSO or ethylene glycol to PEDOT: PSS significantly increases conductivity [10]. This order-of-magnitude improvement means that the impedance at the electrode-skin interface is reduced substantially, allowing the signal energy to be concentratedly conducted. For ECG signals, the main components, such as the R wave, are more prominent, which could be directly reflected by an increase in kurtosis.

5. Limitations And Outlook

Studies have shown that simply reducing the impedance at the skin-electrode interface does not necessarily lead to an improvement in the performance of ECG signals. For instance, although the dry textile electrode coated with PEDOT: PSS can significantly reduce the interface impedance, its SNR has not been enhanced considerably [11]. This indicates that although impedance is essential, it is not the sole factor determining the quality of the signal. Meanwhile, the flexible electrode is still prone to contact instability caused by mechanical deformation under movement conditions, thereby introducing motion artefacts. This is particularly evident when the electrode is used for an extended period or during high-intensity activities.

In the future, the research on flexible elastic electrodes in the field of ECG monitoring will not only involve exploring new conductive fabrics and nanocomposites with low resistance, high conductivity, durability and mechanical compatibility with the skin, but also reduce motion artefacts in the structural design. At the same time, active, flexible electrodes need to be combined with wireless transmission modules, which are expected to further improve SNR and signal stability in dynamic scenarios. At the hardware level, further optimization can also be carried out. For instance, the filtering and amplification circuits can be integrated with algorithms to achieve automatic adjustment for different environmental noises and individual differences, thereby obtaining higher signal-to-noise ratio electrocardiogram signals. In terms of data processing, artificial intelligence algorithms can be integrated into microcontrollers or edge computing units in the future to identify abnormal heart rhythms in real-time and issue warnings. This is particularly crucial for the early detection of arrhythmias and sudden cardiac events. Furthermore, more efforts should be made to improve the security of patients' privacy or medical data. This is also related to some ethical issues.

6. Conclusion

Overall, flexible electrodes, due to their excellent biocompatibility and mechanical properties, provide a new solution for long-term physiological signal monitoring. Through a comprehensive analysis of parameters such as SNR, kurtosis, and skewness, it can not only effectively evaluate the quality of the signals but also provide a basis for the optimization of future electrode design. With the continuous progress in material technology and data processing methods, the application prospects of flexible electrodes in wearable medical devices will be even broader, and they are of great significance for personalized health management. Meanwhile, the development of flexible electrodes also needs to address the issues of stability and durability further. For instance, during prolonged use, the electrodes may lose their performance due to sweat, friction, or environmental factors. Therefore, future research should continuously optimize in terms of material modification and structural design to ensure the consistency and reliability of signal acquisition. Additionally, integrating artificial intelligence algorithms with the data collected by flexible electrodes is expected to enable intelligent analysis and early warning of physiological signals such as electrocardiograms, thereby expanding their clinical and home application value.

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