ECG Circuit: Analyzation and Application

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Keywords: Electrocardiogram (ECG) Circuit, ECG Monitoring, Wearable ECG Sensors, Heart Rate Variability, Wearable Devices.

Abstract: Cardiovascular disease has become the most common cause of death worldwide. According to the 2013 Global Burden of Disease Study, cardiovascular diseases are estimated to cause 17.3 million deaths worldwide. As the primary technique for monitoring the heart's activity, the ECG plays an irreplaceable role in the management of heart disease. Currently, there are two main types of devices used to measure ECGs. One is the larger devices used in hospitals, such as medical ECG machines, and the other is smaller devices for home use, mainly wearable devices such as the Samsung Galaxy Watch and Apple Watch. Compared to traditional devices used in hospitals, wearable devices offer the advantages of small size, low energy consumption and portability. In the future, lower noise, greater noise immunity, lower energy consumption and higher ECG accuracy are necessary for developing wearable devices in the field. However, there are still many difficulties at present. For example, as smart wearables need to minimize the device's size, the power supply circuitry is also somewhat limited, and the device's battery life becomes a major issue. This review introduces the application of ECG monitoring devices on wearable devices, introduces different wearable ECG devices, and analyzes the performance of wearable ECG devices, points out the gap between current wearable ECG and large medical ECG monitoring devices, analyses the causes of wearable ECG noise generation, and proposes to reduce wearable ECG from electrodes, circuitry and other aspects monitoring and improve the monitoring accuracy. Finally, the review summarizes the gap between wearable ECG and medical-grade ECG monitoring devices, predicts the future challenges of wearable ECG, and expresses an outlook on the future of wearable ECG devices.

1 INTRODUCTION

Cardiovascular diseases (CVD) have become the most common cause of death worldwide. According to the 2013 Global Burden of Disease study estimation, CVD caused 17.3 million deaths globally. CVD replaces 31.5% of all deaths and 45% of all non-communicable disease deaths, more than twice that caused by cancer, as well as more than all communicable, maternal, neonatal, and nutritional disorders combined (Townsend, Wilson, Bhatnagar, Wickramasinghe, Rayner and Nichols ,2016) Electrocardiogram (ECG), as the main technique for monitoring cardiac activity, plays an irreplaceable role in treating cardiac diseases. ECG diagnosis is one of the most reliable methods for treating arrhythmia, and it has great application value (R., B., and K. D. 2005). Currently, the devices that measure the ECG are divided into two main categories. The one is the large devices used in the hospital such as medical ECG monitor, and the another is the home devices that measure the ECG mainly with wearable devices such as Galaxy Watch and Apple Watch.

The devices that measure the ECG are constantly evolving with the development of technology. Compared with conventional devices applied in hospitals, the wearable takes advantage of small-size,

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Ge, W., Sui, J. and Wu, P.
ECG Circuit: Analyzation and Application.
DOI: 10.5220/0011367500003444
In *Proceedings of the 2nd Conference on Artificial Intelligence and Healthcare (CAIH 2021)*, pages 283-290
ISBN: 978-989-758-594-4

low energy consumption, portable, etc. In the future, Lower noise, stronger anti-noise ability, less energy consumption and higher accuracy of an electrocardiogram are necessary for wearable device development. However, there are still many difficulties remaining. For example, because smart wearable devices need to minimize the device's size and the power supply circuit is also limited to a certain extent, the device's battery life has also become an important issue.

This paper summarizes the circuit used in wearable devices which measure the ECG, including the comparison with the devices applied in hospital, as well as analysis of the typical ECG amplify circuit, describing different types of ECG electrode, listing some parameters about op-amp design, and the current application of wearable devices which can measure the ECG. Finally, the existing problems in ECG research are discussed, and the future development direction has prospected to bring some references for related research.

2 THE APPLICATION OF ECG CIRCUITS IN WEARABLE DEVICES

The traditional medical ECG monitoring equipment applied in hospitals (see Fig.1) usually uses the common technique of 12-leads ECG to perform heart analysis. It records heart electrical activity through electrodes on the body surface and represents it into a grid.

Figure 1: Medical ECG monitoring equipment and dry electrodes used in traditional ECG monitoring.

Indeed, this technique offers different views of heart electrical activity, allowing cardiologists to gain a full, complete view of the patient heart, so some anomalies of the ECG record symbolize pathologies, can be easily detected, and lots of deaths prevented. But this approach has two main drawbacks: one is that patients and physicians should be in the same place together with the electrocardiograph, which means it cannot be detected anytime and anywhere. As a result, this approach can't predict and escape some heart-related complications, such as cardiac arrest, irregular heartbeat, congestive heart failure, coronary artery disease, etc. Another is the traditional disposable dry electrode which is often used for ECG monitoring in hospitals at present (see Fig.1) (Beniczky, Conradsen, Henning 2005). The conductive glue and other substances contained in the dry electrode will penetrate the skin of patients, which will cause skin allergies and other adverse reactions in some patients. At the same time, using the dry electrode for a long time will cause the electrode strip to fall off and poor contact due to the drying of conductive adhesive, so the measured ECG signal will not be accurate (Zhang, Bai, Zhou 1997).

In the current year, wearable devices have suddenly appeared on people's horizons. Compared with large and heavy equipment in the hospital, wearable devices take advantage of low energy consumption, portability, and higher accuracy of electrocardiogram, so people start to pay attention to applying the wearable devices to monitor ECG. The ECG circuits are the key portions of wearable devices.

2.1 The Measurement Principle of ECG Circuits in Wearable Devices

The biological electric change of the heart itself passes the conductive organization and humoral fluid around the heart, reflecting on coming up to the body surface. It makes each part of the body also produce regular electric change activity in each cardiac cycle. ECG is a technology that uses an ECG circuit to record the heart's electrical activity produced by each cardiac cycle of the graph from the body surface.

2.2 The ECG Circuits in Wearable Devices

2.2.1 A Wearable ECG Acquisition System with Circuit Board-based Shirt

Fig.2 is a wearable ECG acquisition system based on a planar-fashionable circuit board (P-FCB)-based shirt. The system removes cumbersome wires from the traditional Holter monitor system for convenience. Dry electrode screen printing directly on the fabric allows long-term monitoring without skin irritation. The ECG monitor shirt uses a monitor chip with a set of electrodes around the body. Electrodes and interconnects are implemented using P-FCB to enhance wearability and reduce production costs (Yoo, Yan, and Lee 2009).

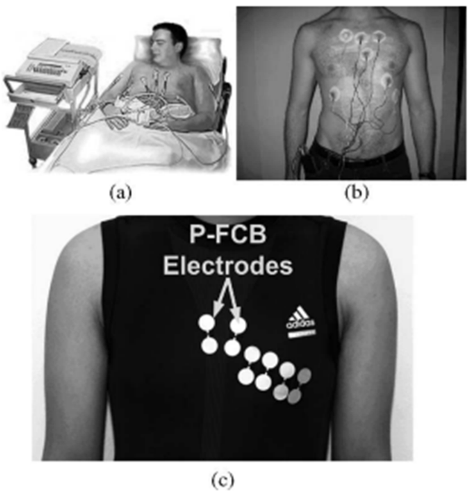

Figure 2: (a) Clinical ECG monitoring system. (b) Conventional Holter monitor system. (c) Proposed ECG monitoring shirt with P-FCB electrodes.

Fig.3 shows the structure of the ECG monitoring chip. It consists of an amplifier (1A) with a programmable gain amplifier, a 10 b SAR ADC, a compression accelerator, an AES-128 encryption accelerator, an internal memory, an MCU, I/O interface, and a pair of P-FCB electrodes. The electrode is data compressed using a secondary compression accelerator (Randazzo, Ferretti, and Pasero 2019). Then encrypted and stored in internal memory. To improve safety, the AES-128 accelerator is used (Kim and Yoo 2008). If the internal memory is full, external memory can be used through the external memory interface. Internal memory is accessed through the fast-mode I^2C interface.

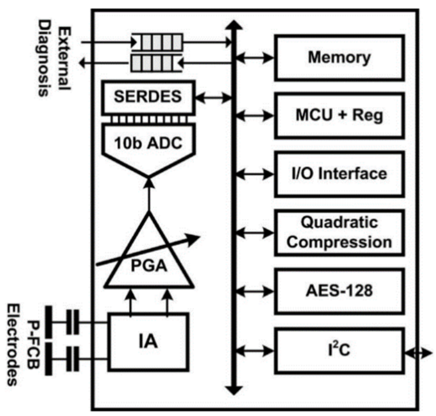

Figure 3: ECG monitoring chip architecture.

2.2.2 ECG WATCH

The ECG WATCH (Fig.4) is developed for standard techniques such as 12-lead electrocardiography (ECG) or dynamic electrocardiogram systems that are insufficient to fully resolve sporadic ECG abnormalities such as atrial fibrillation. It is an inexpensive, wearable, easy-to-use health device that can monitor the heart activity of patients with cardiovascular disease anytime and anywhere without the need to go to the hospital or cardiologists. The recording takes 10 seconds. It also embedded an algorithm to detect possible atrial fibrillation episodes.

Figure 4: The ECG WATCH.

Fig.5 shows the ECG WATCH PCB. A TI MSP430 series low-power microcontroller collects the ECG signal with a 10b 200kbps SAR ADC. ECG signals are collected at 1kbps, which are sufficient to obtain good temporal resolution. The external voltage reference provides an accurate DC reference voltage for the ADC. In order to identify the risk of atrial fibrillation, a 10-second ECG acquisition is sufficient for the implementation of the algorithm. On the other hand, the flash memory on the microcontroller has enough space to store a few seconds of collected data on the board at 1kbps, eliminating the need for external storage modules and thus reducing the size of the circuit (Kim, Kim, and Yoo 2008).

Figure 5: ECG WATCH PCB.

2.2.3 Wearable Mobile Ear-based ECG Monitoring Device

This work presents the design and evaluation of a wearable mobile ear-based ECG monitoring system based on a highly conductive material graphene electrode. Smartphones and headphones are becoming more common across generations. Here, a novel design aims to advance the development of an ear-based graphene sensor that, via a mobile connection, generates high-quality, long-term, real-time ECG measurements in a system more familiar to the end user.

A typical ECG monitoring system consists of electrodes and a front-end data acquisition circuit. A three-electrode system is used to collect ECG signals. In a three-electrode system, two active electrodes are used for differential input to the ECG amplifier. The third electrode is connected to eliminate common-mode interference and improve signal quality. In the proposed work, two electrodes are placed near the ear-the one is attached behind the ear, the other is placed on the neck, and a third electrode is connected to the arm on the ground to obtain ECG signals, as shown in Fig.6. a. The electrodes are tested in a developed wearable device (see Fig.6b) that sends the raw ECG signal from an ear-based electrode to a measurement circuit mounted on the arm. The ECG data is digitized, amplified, filtered in the measurement circuit, and then transmitted to the smartphone through Bluetooth for continuous monitoring (Celik, Balachandran, and Manivannan 2019).

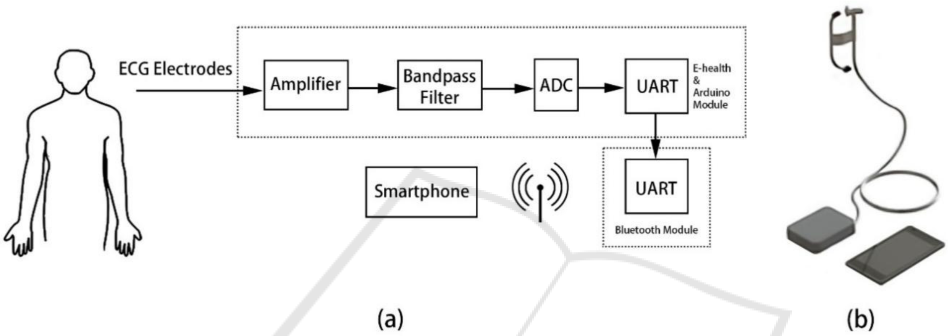

Figure 6: (a) Electrode placement and block diagram of the ECG monitoring system; (b) Prototype design of ear-based ECG monitoring system.

3 METHODS TO OPTIMIZE THE PERFORMANCE OF ECG SENSOR

In the ECG monitoring of wearable devices, the accuracy of ECG signal detection for the wearer has become an important index to measure the performance of wearable ECG monitoring devices, which is one of the main reasons why wearable ECG monitoring devices cannot replace medical-grade ECG monitoring devices at present. For well-known reasons, the interference of ECG signals collected by wearable devices is significantly greater than that of medical-grade ECG monitoring devices.

The basic structure of major wearable ECG designs is shown in Fig.7. To detect the ECG signal from the human body, the system needs a sensor that consists of 2 parts (electrode and amplifier). The sensor can get the ECG signal and convert it to an electronic signal that the signal processor can process.

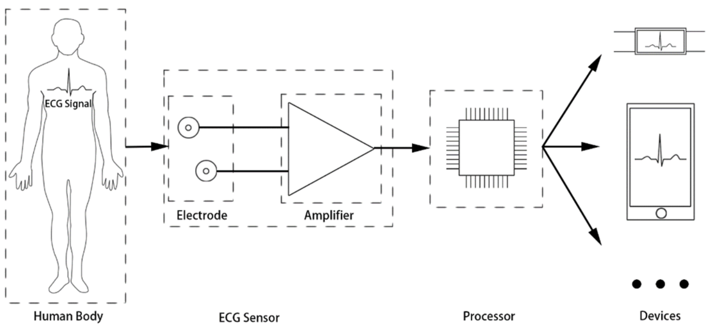

Figure 7: The basic structure of major wearable ECG designs.

Every step of these processes causes problems (consuming power, generating noise etc.), influencing the system's performance. Therefore, it is important to find the methods to optimize the performance of the ECG sensor.

3.1 Electrodes of Wearable ECG Equipment

Fig.8 shows various bio electrodes: wet electrode, dry electrode, non-contact electrode, which are widely used in ECG equipment.

Figure 8: Some ECG electrodes.

Wet electrodes are a kind of electrode of common ECG equipment used by hospitals because it uses gel to keep good contact of skin to make sure the signal is good. However, most wearable ECG sensors do not use this kind of electrode. The reason is simple: Wearable devices should be comfortable and portable. But the gel of wet electrodes is inconvenient. People feel bad when putting gel on them, and it is hard to replace gel after old gel becomes useless.

The dry electrode is a replacement for the wet electrode. They do not need gel to keep the connection between electrode and skin at the expense of the performance. Fig.9 shows the noise of a wet electrode and a dry electrode. We can find that dry electrodes generate more noise than wet electrodes, which means the result of dry electrodes is more imprecise.

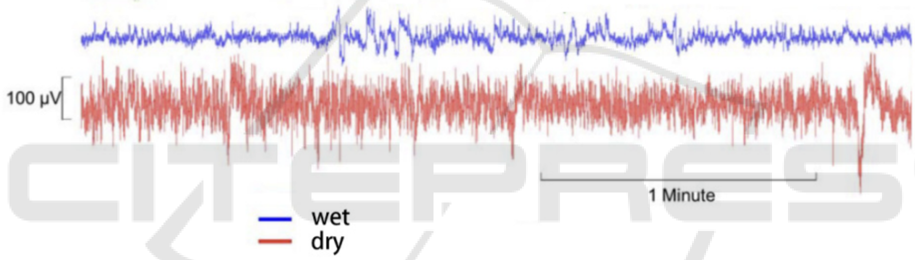

Figure 9: The noise of a wet electrode (blue) and a dry electrode (red).

Meanwhile, using dry electrodes is uncomfortable, too. People need pressure on the electrode and skin to keep the electrode on the skin, which causes a strong pressing feeling. Using a non-contact electrode can solve this problem. However, it brings some problems: Firstly, non-contact electrodes generate more noise than wet and dry electrodes, making a huge challenge in the amplifier design. Secondly, it is hard to keep the distance between electrodes and skin, especially using wearable devices like smartphones or T-short sensors. As a result, the distance of the electrode will change rapidly and causes more noise. Fig.10 shows the effect of sensor separation distance on input-referred noise of an ECG device. When the distance between the electrode and skin increases, the input-referred noise increases.

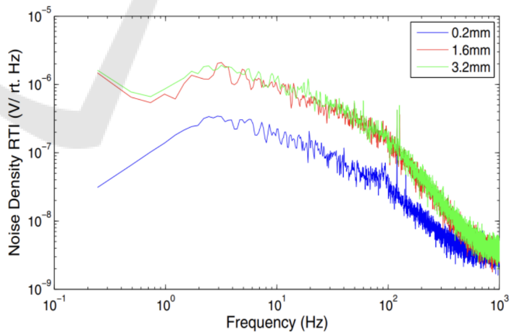

Figure 10: The effect of sensor separation distance on input-referred noise of an ECG device (Brain Support. 2020).

In conclusion, every electrode has some advantages and disadvantages. And a better user-friendliness electrode has lesser accuracy. So, it is important to select an appropriate electrode by considering all working situations of the design.

3.2 Typical ECG Amplify Circuit

Table 1 is the comparison of some parameters of the ECG signal. The voltage range of the ECG signal is 0.5-4 mV. It is too small to be processed. As a result, we need an amplifier, whose gain is recommended larger than 40 dB, to amplify the signal. And the signal frequency range is 0.01-250 Hz. So, a filter is recommended to decrease another useless signal.

Table 1: Some parameters of ECG signal.

Parameter or Measuring Technique	Principal Measurement Range of Parameter	Signal Frequency Range	Standard Sensor or Method
Electrocardiography (ECG)	0.5-4 mV	0.01-250 Hz	Skin electrodes

Wearable ECG sensors always use typical instrumentation amplifiers (INAs) and common-mode feedback circuits, which connect to the human body, to solve the biasing problem.

Fig.11 is a typical INA circuit for ECG devices. There are 3 parts to it: The First part is the full differential input buffer, which consists of A1 and A2. The second part is the common-mode feedback circuit. The voltage of the human body is unknown, so using it to set the biasing voltage to the body voltage. In the third part, a differential amplifier converts the differential input into a single end output.

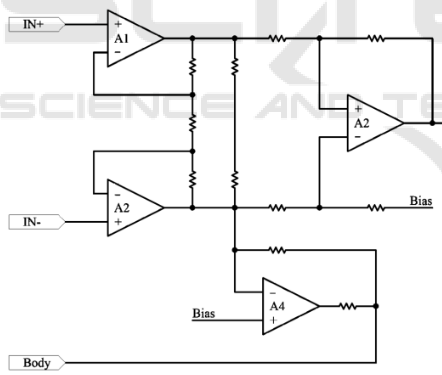

Figure 11: Typical INA circuit for ECG devices.

Instrumentation amplifiers amplify small input signals accurately. It is appropriate to build an ECG sensor. But, because of the small input signal, reducing noise is very important. However, building the noise model of the whole circuit is very complex. But using an integrated INA noise model is simpler. Fig.12 is the noise model of integrated INAs. In this figure, Eno is the noise of the output stage, and en is the RMS sum of the noise of the input and output stages. G is the gain of INA. in is the noise current.

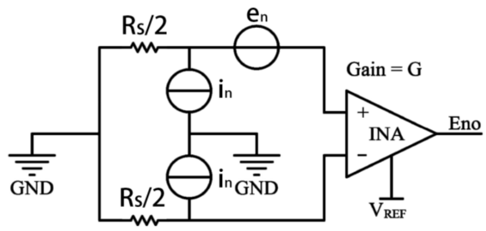

Figure 12: Integrated INA noise model.

Sometimes, manufacturers may give eni, which is the noise of the input stage. In this situation, we can use (1) to calculate en:

$$e_n=\sqrt{e_{ni}^2+(e_{no}/G)^2} \tag{1}$$

Then we can find the result of output noise of the circuit is Eno:

$$\text{Eno}=G\cdot\sqrt{NEB}\cdot\sqrt{e_{n(RTI)}^2+2i_n^2(R_S/2)^2} \tag{2}$$

In equation (2) (Sullivan, T. J., Deiss, S. R., Cauwenberghs 2008), NEB is the noise equivalent bandwidth. According to (2), we can reduce the signal bandwidth through filters or use lower resistor values to reduce noise. But it also brings some problems: It is impossible to reduce the bandwidth to a very small value. Because the frequency of the ECG signal is 0.01-250 Hz, we cannot make the bandwidth lower than 250 Hz. Secondly, using lower resistors cost higher power consumption. As a result, users should recharge their devices frequently. In conclusion, every method to reduce noise leads to other problems. So, selecting values according to the product requirements is the best choice.

3.3 Pretreatment of ECG Signal

In the preprocessing of ECG signal, the baseline drift caused by power line interference and interference of body breathing movement can be removed first.

The interference amplitude of the power line is usually with volt magnitude, which is far larger than that of the ECG signal with millivolt magnitude (Renesas 2020). Therefore, some methods, such as adaptive zero-phase shift notch filter based on least mean square (LMS) algorithm, are used to remove power line interference and avoid phase distortion of signals (Gu, Hu, Zhang, Ding, Yan 2020).

And the baseline drift caused by breathing and body movement is also an inevitable interference in ECG signal acquisition by wearable devices. To eliminate the baseline drift, we can estimate or extract the baseline component, remove the component caused by the drift by subtraction (Kuo, Morgan 1995), or use a high-pass filter (Blanco-Velasco, Weng, Barner 2008).

4 CONCLUSION

After years of development, the gap between wearable ECG devices and medical-grade ECGs is getting smaller and smaller. Today, wearable ECG devices can be found everywhere, such as mobile phones, smartwatches, and headphones, which can measure your heart rate, pressure, and blood oxygen saturation. We can use this wearable ECG data to analyze your physical health. to prevent disease. But it must be acknowledged that although wearable ECGs have developed rapidly over the years, they still cannot replace large medical ECG machines. In some cases, wearable ECG monitors are not as accurate as medical-grade devices. For example, noise and voltage. The increasingly miniaturized wearable ECG devices are also becoming more and more problematic in terms of battery life. Of course, we have a lot to look forward to in the future of wearable ECG devices.

In the future, wearable ECG devices will become even smaller and more accurate. It may also rely on the body's energy to provide a long-life span, with functionality not limited to ECG monitoring but even whole-body health monitoring. Although there is still a long way to go, we expect this day to come.

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