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Original Article

Design of intelligent wearable equipment based on real-time dynamic ECG-monitoring system

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Abstract: Objectives: The coronavirus disease epidemic has largely restricted the traditional offline medical treatment model. With increasing requirements for virtual medical assistance, the design of smart medical apparel has received more attention. Methods: In this study, we designed electrocardiography (ECG)-monitoring smart clothing based on the Holter system after identifying and analyzing the needs of patients and doctors. This clothing is a wearable device that integrates monitoring and remote diagnosis, building a general network platform to support remote data transfer and sharing and online interactive auxiliary diagnosis. Creating wearable smart clothing includes multiple dimensions, such as ECG module design, clothing structural design, and a real-time monitoring app. This innovative technology is achieved by intelligently integrating limb lead wires, conductive fiber fabrics, lead interfaces, and electrode signal storage receivers, all based on the human body's sensing conduction principle. Wearable clothing that can monitor ECG in real time is designed and developed by intelligently integrating limb lead wires, conductive fiber fabrics, lead interfaces, and electrode signal storage receivers by using the human body-sensing conduction principle of real-time ECG monitoring. Results: Wearable real-time ECG-monitoring clothing can help patients achieve fast virtual medical care and auxiliary diagnosis and solve the design issues associated with electrode signal storage receivers. In addition, such clothing can be applied to automatically monitor groups at high risk of heart disease. Conclusions: Our design not only meets the accuracy requirements of traditional medical diagnosis but also combines traditional real-time ECG monitoring and smart clothing, providing new options for the daily needs of patients and doctors.

Keywords: Smart clothing, heart rate monitoring, health monitoring

Introduction

The continued development of smart devices has led to digital medical care that combines medical services and internet technology in modern medicine. Along with the rapid development of digital medical care, patient demand for real-time and reliable digital health monitoring is becoming more urgent. Wearable health monitoring equipment combined with digital technology has become a new direction for improving contemporary medical equipment [1]. Such devices negate the location limitations of traditional medical equipment, and patients can achieve self-control through telemedicine, which greatly saves time needed in medical treatment. However, it is crucial that these devices are reliable and easy for patients to use.

The World Health Organization's statistics show that approximately 17.9 million people worldwide died from cardiovascular disease in 2019, accounting for 32% of all global deaths [2]. The onset of cardiovascular disease is sudden, and the preceding symptoms are relatively subtle. Therefore, early detection and preventive treatment of cardiovascular disease are the main means to reduce its incidence [3]. Electrocardiography (ECG)-monitoring clothing can help people detect cardiovascular disease as early as possible [4].

Human research on remotely monitoring ECG can be traced back to the 20th century [5]. In 1903, Dutch professor Einthoven, "the father of electrocardiography", collected the world's first complete human electrocardiogram through a 1,500-meter cable, which is widely regarded as the prototype of remote ECG monitoring [5]. Since the 1960s, remote ECG monitoring technology based on telephone transmission has been gradually applied and popularized with good outcomes. With the continuous development of chip technology, real-time wireless remote transmission of ECG signals processed by a baseband processor chip has become more mature, and remote ECG monitoring is also rapidly developing in the direction of being portable, multi-functional, intelligent, and networked [6].

In the 21st century, mobile communication technology has been applied in the medical field on a large scale. In particular, the application of 3G/4G high-speed networks and the popularization of smartphones are making huge changes to the traditional medical model, creating extremely favorable conditions for developing a mobile medical model [7]. As an integrated product combining multi-disciplinary knowledge, smart clothing is currently studied in many fields, including the fields of biomedicine, situational awareness, and security protection. The main research direction of smart clothing is wearable textiles for real-time monitoring of physiological parameters and characteristics [8]. Among the smart clothing, fabric for monitoring physiological characteristics is an important research focus. Material technologies, such as conductive fiber textile fabrics and flexible sensors, have been used to monitor physiological characteristics [9]. These new sensor fiber fabrics are composed of flexible electronic components embedded into traditional fabrics and are used to make clothing with both the conductive properties of electronic components and the comfortable properties of traditional textiles, thus achieving the conductive function and comfortable and soft characteristics of smart wearable textiles. In addition, the clothing structure is designed according to the needs of physiological characteristics monitoring (dynamic electrocardiogram (ECG) and heart rate parameters). Different types of wearable monitoring textiles are designed with consideration for ergonomics, combining flexible intelligent electronic components and the human body structure to improve comfort, durability, and ease of cleaning the wearable textiles while ensuring the accuracy and safety of the monitoring module.

Based on the development of related monitoring technologies and sensing materials, the current primary function of health-monitoring smart clothing is to monitor physiological characteristics, such as heart rate and body temperature [10]. Health-monitoring clothing that can monitor ECG signals has also made progress in recent years. In 2011, Gilsoo Cho conducted analyses and experiments for the development of ECG electrodes based on textile technology using traditional textile techniques, copper sputtering, shielding over the electroless-plating, and embroidery with stainless steel thread [8]. This is an earlier study on textile ECG electrodes, and this paper piezoresistive experiments were conducted on different states of existing textile sensors to predict the future development of textile conductive fibers. In 2015, Cho and Lee conducted a study on the optimal placement of electrodes in an ECG-monitoring suit for men [11]. In 2018, Ming Yang designed health-monitoring smart clothing using conductive fibers, flexible sensors, and other physiological characteristic sensors to analyze different state data of users and send alerts about abnormal information to help guardians stay informed [5]. In 2019, Yu-Han Wang proposed smart clothing for older adults in home care; this smart clothing utilizes a three-lead electrocardiogram (ECG) designed with conductive fibers and four electrodes to capture physiological signals. The data is transmitted to a server through a gateway for ECG data analysis [1]. In 2018, Xiang An and George K Stylios designed a hybrid textile electrode for measuring electrocardiograms (ECG) and tracking motion, and identified two main factors that affect the skin-electrode impedance: textile material characteristics and electrode size [12].

Holter system-based real-time ambulatory ECG monitoring involves accurate monitoring of cardiac electrical activity over a continuous period of time. Due to the complexity of heart disease, dynamic and continuous 24-hour heart rate monitoring can help doctors identify potential factors of heart disease and sudden death in patients, which is of great significance in the prediction and analysis of the disease [13]. Wearable ECG monitoring clothing can support remote digital healthcare. In recent years, with the continuous development of computer, communication technology, and medical professional technology, remote digital medicine and AI-assisted diagnosis have rapidly developed [14, 15]. With increasing internet access, smart medical apparel can use telemedicine and AI-enabled devices to share sensed data with data platforms, providing an impetus for virtual treatment and more diverse forms of health-care for those at risk of or with Corona Virus Disease (COVID)-19. This shift is especially significant for those with limited access to face-to-face treatment in low-resource settings.

The current smart clothing for health monitoring focuses on monitoring human health and physiological characteristics, but there are still many shortcomings. For example, it is difficult for patients without a medical background to accurately position the electrode patch in practical clinical applications. Furthermore, patients find standard medical monitoring equipment uncomfortable to wear, and it is difficult to meet the needs of patients of various ages and sizes. In addition, as the aging population and the number of chronic disease patients continue to increase, patients in remote and island areas have difficulty accessing timely medical care. Furthermore, remote care can also improve the shortage of caregivers and save transportation time for patients in remote areas to hospitals. By combining remote digital medical assistance with improvements to the traditional offline medical model through the pairing of traditional medical equipment and internet technology, wearable ECG monitoring clothing can help patients receive remote digital medical assistance, generate and export reports to send to doctors, thereby supporting accurate and specific online medical diagnosis. Using these tools, high mortality diseases such as autonomic nervous system dysfunction, painless myocardial infarction, malignant arrhythmia, and sudden cardiac death can be diagnosed through real-time ECG detection. Traditional monitoring devices are difficult to use without assistance, so reliable and easy-to-use wearable monitoring devices are urgently needed for remote diagnosis and disease prevention.

Therefore, based on the study of real-time electrocardiogram (ECG) monitoring using the Holter system, this study mainly combines the currently used ECG real-time monitoring equipment in clinical practice with clothing. We collected existing clinical ECG real-time monitoring data, systematically sorted and summarized the analysis of ECG waveforms for different combinations, explored the key links of ECG real-time monitoring, and the possibility of combining them with clothing structural data. Combining the monitoring points with clothing design, wearing tests were conducted among users of different body types to compare the monitoring effect and determine the accuracy of clinical monitoring data.

Material and methods

The Holter monitor, also known as a Holter ECG, is a portable, dynamic ECG device for 24-hour heart monitoring (monitoring the electrical activity of the cardiovascular system) that has been clinically developed from single- and double-lead to 12-lead full recording. The detection of ECG signals is divided into single-lead, double-lead, and 12-lead recording, which means that ECG signals can be captured by placing 2-12 electrodes on the body surface. ECG signals can either be processed locally and used to detect anomalies with machine learning algorithms or sent wirelessly to the cloud for remote analysis [16].

When used to study the heart, much like a standard ECG, Holter monitors record electrical signals through a series of electrodes attached to the chest. The electrodes are placed on the bone to minimize artifacts caused by muscle activity. The number and locations of the electrodes vary by model. The electrodes are connected to a small piece of equipment attached to the patient's belt or hung around the neck, and they record the electrical activity of the heart throughout the desired recording period. The 12-lead Holter system is useful when precise ECG information is required to analyze the exact source of abnormal signals. The ECG signal is generated by the electrical potential difference in human heart cells, which reflects the physiological state of the heart to a large extent. ECG can record the changes in electrical activity produced by the heart in each cardiac cycle. As the most widely used cardiac examination technology in clinical practice, ECG can help doctors diagnose a patient's cardiac status.

Different from typical functional clothing, wearable real-time ECG-monitoring clothing needs

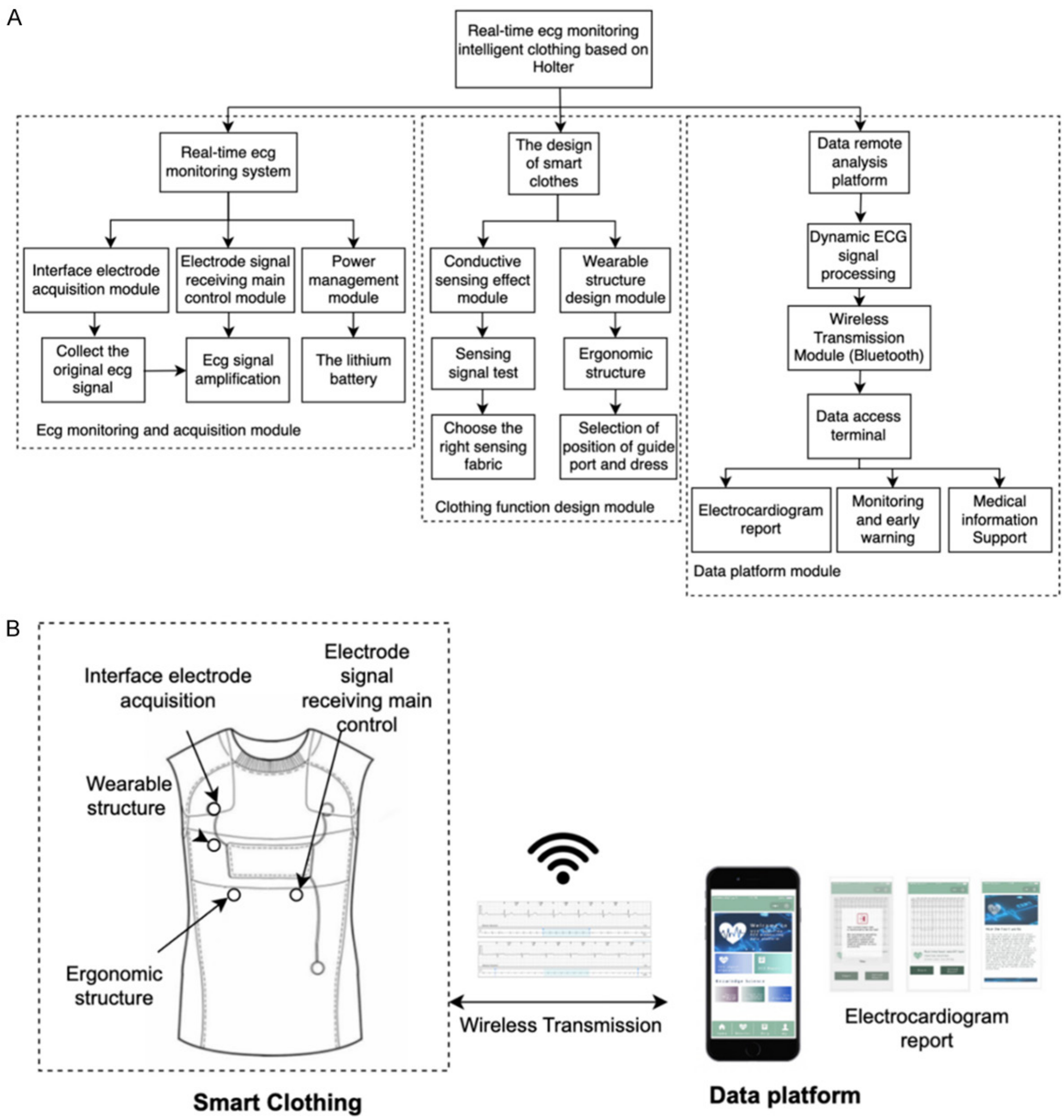

Figure 1. Overall design diagram of smart clothing for real-time electrocardiography (ECG) monitoring.

to consider the electrode patches and storage instruments used in monitoring. The design of clothing structure needs to conform to ergonomics and comfortable design, in order to adequately serve the patients. The design of the real-time ECG monitoring garment is divided into three modules: ECG monitoring and collection, clothing function design, and the data platform (**Figure 1**). Among them, the ECG monitoring module performs signal acquisition and data processing through an acquisition chip and a single-chip microcomputer. The clothing function module is designed with consideration of the conductivity and structure of the clothing fabrics. The data platform module presents data and analysis results to patients.

The ECG monitoring module includes electrode acquisition, signal reception, and power management. Electrode acquisition is divided into chest and limb electrodes. The chest electrode is covered with silver guide cloth that is placed directly on the clothing structure. The limb electrodes and chest electrodes are separately connected, which means that the position of the limb electrodes can be more accurately

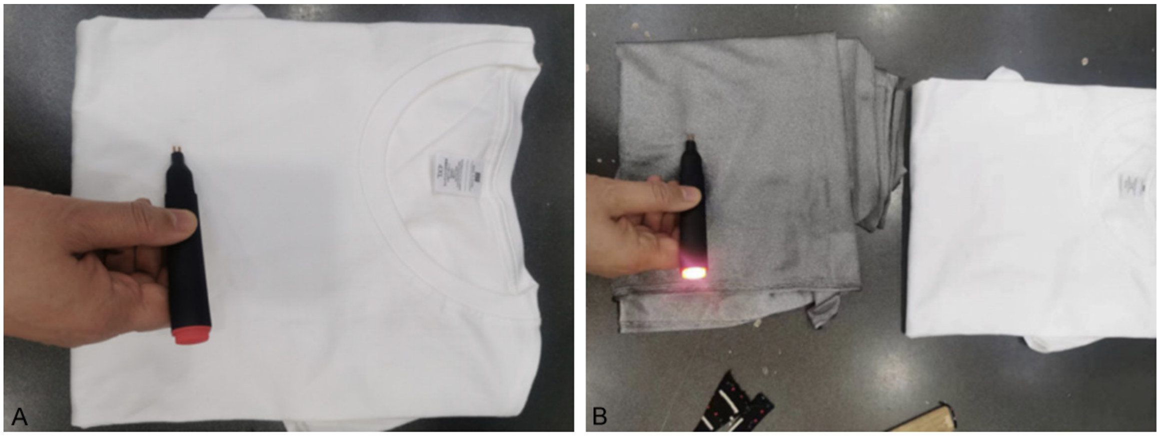

Figure 2. Electrical conductivity test of silver guide fabric and ordinary fiber fabric.

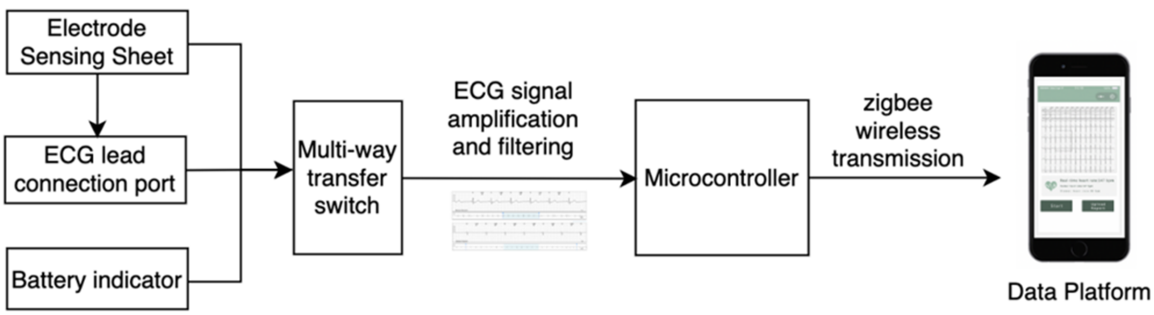

Figure 3. Real-time electrocardiography (ECG) monitoring hardware module.

adjusted based on the user's different body types. The clothing function module includes structural design and fabric selection. The goals of clothing structure design are to influence the conductive effect of various fabrics on the actual monitoring data based on a clinical 12-lead dynamic ECG (Mason-Likar lead system) experiment and to combine the structure with the electrode site under ergonomic principles. At the electrode sites of chest leads, the selection of silver-conductive fabric (100% silver-coated polyester fibers) is preferred due to its excellent conductivity. This fabric effectively mitigates the impact of factors such as sweat on electrocardiogram (ECG) signal acquisition, enabling real-time ECG monitoring (**Figure 2**). The utilization of this fabric ensures that the conductive material does not interfere with the monitoring of clinical ECG signals and physician diagnoses.

The data platform module is mainly designed for patient users who lack medical knowledge. Users can view real-time ECG data through the applet, which can automatically record real-time ECG data, issue early warnings to remind the user to seek medical attention when the data are abnormal and provide relevant medical knowledge support so that users without a medical background can operate the clothing on their own.

The whole design is based on the ECG monitoring system, combined with ergonomics, and assisted by the monitoring platform to provide a good experience for users who need real-time ECG monitoring and to meet the overlapping needs of patients and doctors.

ECG monitoring module design

The ECG monitoring module mainly includes electrode acquisition, signal reception, and power management (**Figure 3**). The ECG signal is a bioelectric signal that reflects the physical state of the heart by the potential difference generated by the cell membrane of human heart cells [17]. As this is a weak physiological

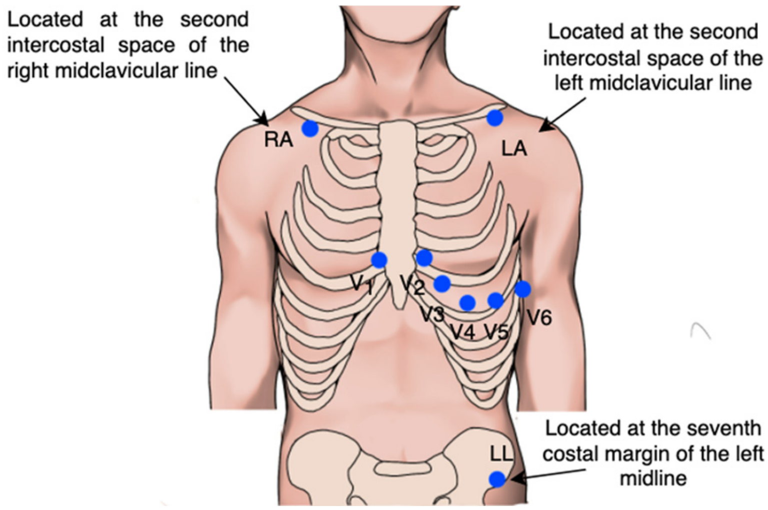

Figure 4. Installation diagram of the trunk electrodes of the Mason-Likar lead system.

signal with strong nonlinearity and randomness, it can be displayed as an ECG waveform after amplification and filtering to show the process of atrial and ventricular polarization and negative polarization. To collect the signal more accurately and analyze the status of the heart, the low-power ECG acquisition chip ADS1191 is used to send the ECG signal to the single-chip microcomputer for further analysis after processing. A SanDisk Ultra solid-state drive, featuring a built-in single-level-cell cache, serves as the storage chip, offering a storage capacity of 32-128 GB while optimizing performance, enhancing stability, and markedly improving read and write speeds. Power is managed using a DC power supply, which can support the stable use of the equipment and wireless transmission modules [18].

Clothing structure design

The real-time ECG monitoring module is based on a 12-lead Mason-Likar system, which is widely used in clinical practice and contains 10 electrodes (including chest and limb leads) in the human body. The structural design of the clothing is based on the points of the ECG monitoring system combined with the user's own needs and ergonomics. In addition, considering the different needs of users of different ages and body types for real-time ECG monitoring, we adjusted the fabric and structural design, hoping to meet both the physical and emotional needs of users. The actual human body-monitoring electrode locations in the 12-lead Mason-Likar system are shown in **Figure 4**. Currently, the conventional 12-lead dynamic ECG widely used in the clinical setting has 10 lead wires (RA, LA, LL, RL, and prethoracic leads V1-V6) [19, 20]. Overall observation and measurement of the P wave, QRS wave, T wave, U wave, R-R interval, Q-T interval, and ST segment channel data with the 12-lead synchronous Holter monitor can help diagnose myocardial ischemia and arrhythmia (**Table 1**).

We then combined these points with the clothing structure and chose easy-to-wear and comfortable styles according to the audience and functional characteristics of the clothing. The vest-type monitoring clothing that we designed is shown in **Figure 5**. The basic vest style has a Velcro closure and can readily adapt to the different body types of the wearers. The ECG monitoring positions deviate for people with different body types, but the positions of the chest leads are relatively fixed. Therefore, in order to achieve accurate and valid monitoring data, the limb electrode leads can move freely within a certain range according to the different body types of users. The garment is designed with a basic vest silhouette and features a Velcro closure at the shoulder, which conforms to the body structure for ease of wearing and removal. This shirt's signal storage device is located on the chest to reduce the impact on daily life as much as possible.

The fabric of real-time ECG-monitoring clothing can be divided into three parts: the main body, the chest lead electrodes, and the limb lead electrodes. The main fabric is used for the basic vest version, which is designed as a two-piece adhesive structure to facilitate wearing and taking it off, accounting for 90% of the overall clothing fabric. The chest and limb lead electrodes account for 7% and 3% of the overall fabric, respectively.

The electrodes of the chest leads are made of silver conductive fabric (100% polyester silver fiber), which has good electrical conductivity and can greatly reduce the influence of sweat

Table 1. ECG detection position

Lead	Electrode	Electrode position
Chest lead	V1	Fourth intercostal space at the right margin of the sternum
	V2	Fourth intercostal space at the left margin of the sternum
	V3	Middle position of the V2-V4 connection cable
	V4	Left midline of the clavicle intersected with the fifth costal
	V5	Left axillary front, at the same level as V4
	V6	Left midaxillary line, at the same level as V4 and V5
Limb lead	RA	Second intercostal space of the right midclavicular line
	LA	Second intercostal space of the left midclavicular line
	LL	Seventh costal margin of the left midline
	RL	Seventh costal margin of the right midline of the clavicle

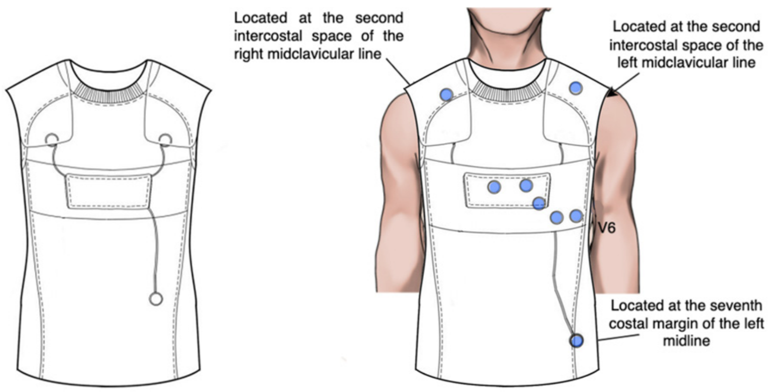

Figure 5. Design of the wearable equipment.

on ECG signal acquisition to avoid affecting the doctor's diagnosis [8]. As a layer of pure silver permanently bonded to the surface of the fiber, silver fiber not only maintains the original textile properties but also endows the garment with the electrical conductivity of silver, which is several times or even hundreds of times greater than that of general conductive metals [21]. Silver fibers are excellent materials for shielding electromagnetic radiation, and garments with these fibers can meet the conductive needs of real-time ECG monitoring systems. Silver fiber is made by tightly polymerizing silver and fiber, which provide stronger wear and water washing resistance, while being lightweight, comfortable, soft, and breathable. Compared to traditional textile fabrics, they have better comfort [21]. Textile electrodes have a huge advantage over gel-based electrodes because they avoid causing damage to sensitive skin. Textile electrodes are also malleable, lightweight, and washable [22]. During the fabrication process, silver-coated conductive yarns are attached to the fabric of the woven electrodes, and the impedance of the fabric electrodes is very high - ranging from 1 to 5 MΩ/cm^2 - compared with disposable Ag/AgCl electrodes.

The main fabric of the garment is made of soft, breathable, and quick-drying elastic fabric, making it comfortable for patients who wear it for a long time. Due to the need to adjust the placement and stickiness of the limb electrodes during use, the spunlace cloth of conventional physiotherapy electrode pads are used; this cloth has good adhesion and can be reused, and some of its adhesive properties can be restored after washing with water. In terms of clothing color, the overall fabric has gray and white tones.

Data monitoring platform

In order to assist users in receiving remote digital medical treatment, the smart clothing transmits data to the WeChat app through the wireless signal transmission module so users can see real-time ECG monitoring data through the app at any time, including data from RA, LA, LL, RL, and V1-V6 of the anterior lead.

As an emerging wireless network, Zigbee operates at short distances and high speeds with low power consumption, low complexity, and a geolocation function [18]. Zigbee has obvious advantages in its equipment consumption, system costs, anti-interference capabilities, and bit error rate. It can connect with the Web, existing public land mobile networks, and other communication networks to establish a medical monitoring network within a local area network, overcoming the limits of existing medical monitoring networks. The patient wears a low-cost ECG sensor node, and when the patient moves within the network coverage area, the sensor node collects the patient's ECG data and sends it to the Zigbee router node. Then, the router node connects to the internet or satellite through the Zigbee convergence node inside the network and transmits the ECG data to the hospital management center, where the doctor can view the ECG report and check the patient's status. This system is convenient and efficient, does not affect patients' daily lives, increases the interaction between patients and doctors, and ensures real-time monitoring.

The app provides a variety of interactive functions, including ECG signal collection (**Figure 6**) and report generation and export, as well as basic medical knowledge (mainly covering equipment wearing guidelines, first aid knowledge, and ECG knowledge). However, the method for judging symptoms via ECG is relatively complicated, and it is difficult for users without relevant medical knowledge to understand. At present, there is not enough patient data from the wearable ECG-monitoring clothing to construct a data set for machine diagnosis training. Only when the heart rate exceeds 100 beats per minute will the app issue an alarm to identify the tachycardia and remind the user to send the ECG report to the online doctor for further evaluation.

Results

Evaluation of clothing design

In order to evaluate the monitoring effect of smart clothing, 25 patients were recruited. The participants were 35±10 years old (15 males and 10 females), weighed 70±10 kg, had no heart-related diseases, and had not performed activities that would have affected the ECG data, such as vigorous running, before the experiment. They wore the traditional Holter dynamic ECG equipment and real-time ECG-monitoring smart clothing, and 24-hour real-time monitoring was conducted. Their RR band and heart rate were further analyzed (**Table 2**). The experimental procedures included short-term tests: all subjects wore the smart garment for sitting in place, in-place exercise (including multiple cycles of standing up and sitting down), walking (starting from the same place and walking for 30 seconds), and during resting activities. The long-term wear test consisted of all subjects wearing the smart garment for 24 hours; the subjects' ECG data were recorded and stored in an SD card, and all data were retrieved from the SD card for analysis at the end of the study (**Figure 7**).

Through a user experience survey of participants wearing intelligent electrocardiogram monitoring apparel, evaluations were made from three aspects: remote medical experience, appearance comfort experience (fabric, electrode, wire), and functional monitoring experience (**Table 3**). The remote medical experience was evaluated through interface simulation trials and explanatory interviews. A total of 15 valid questionnaires were collected, with 0 invalid ones, and an in-depth interview was conducted. The satisfaction level is directly proportional to the evaluation score, with values ranging from 1 to 10, representing worst to best, respectively.

Remote medical and visual design experience: According to the survey results, the intelligent apparel (9.14) showed a significant improvement in remote medical experience compared to traditional electrocardiograms (2.47) with an increase of +6.67. The visual design of the smart apparel also received positive feedback (+5.67). Most participants reported that pairing with an online platform provided a better remote experience, reducing the inconvenience of offline visits required by traditional cardiac equipment, saving medical resources and time. Furthermore, the real-time monitoring data provided by the remote medical smart apparel has better timeliness. Wireless transmission ensures the accuracy and speed of real-time data, offering patients a superior user experience and medical quality.

Comfort experience: The questionnaire results showed that, compared to traditional cardiac monitoring equipment, participants experienced a noticeable improvement in the overall comfort of the smart apparel (+4.80). Scores in fabric, electrodes, and wires all showed significant improvements. The fabric experienced the most noticeable improvement in comfort

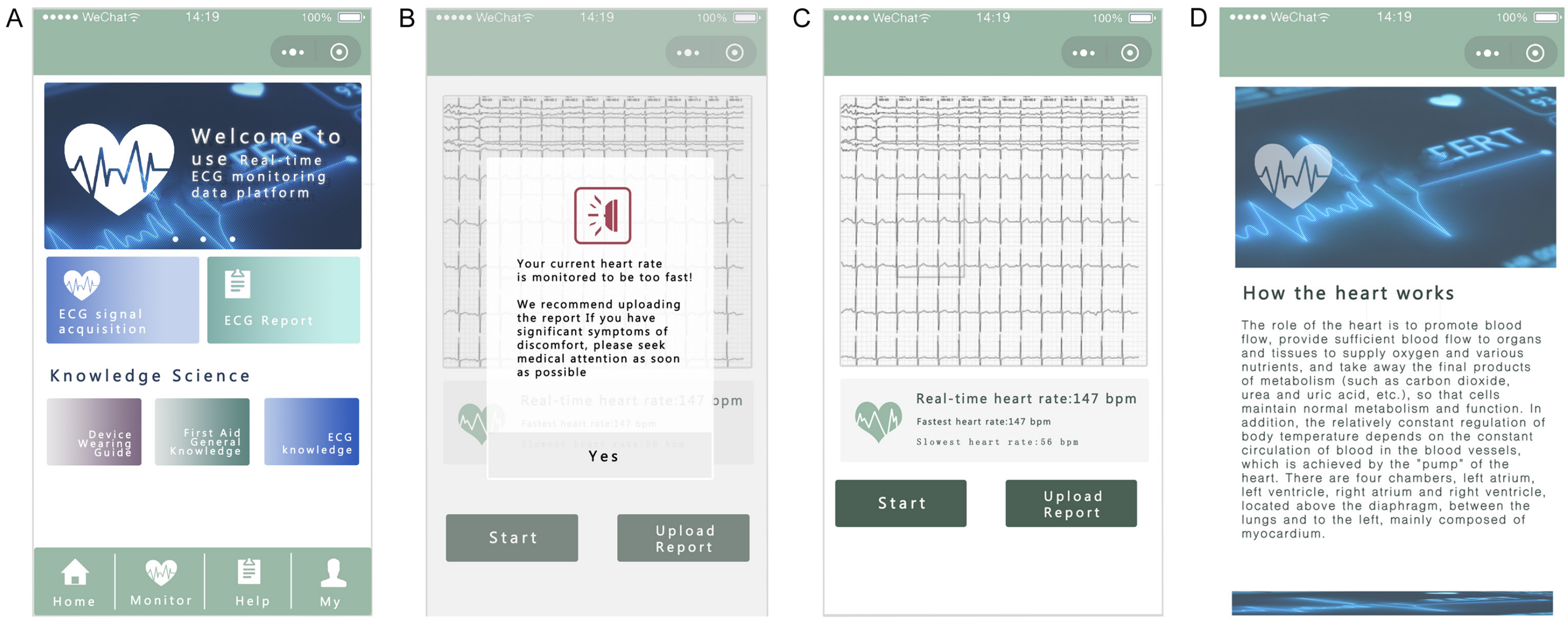

Figure 6. Online platform design.

Table 2. Comparison of hourly mean heart rate monitoring results (excerpts)

Subject Number	Average heart rate monitoring results (times/minute)		Maximum heart rate (BPM)/slowest heart rate (BPM)	
	Holter dynamic electrocardiogram	Intelligent monitoring clothing	Holter dynamic electrocardiogram	Intelligent monitoring clothing
1	89.12±3.62	90.03±4.41	141/61	145/60
2	94.01±2.47	95.47±3.61	150/56	152/51
3	74.00±5.35	75.67±5.87	137/51	138/51
4	85.17±6.42	87.01±6.98	161/53	163/55
5	65.10±4.87	65.34±4.88	145/58	149/62

BPM, beats per minute.

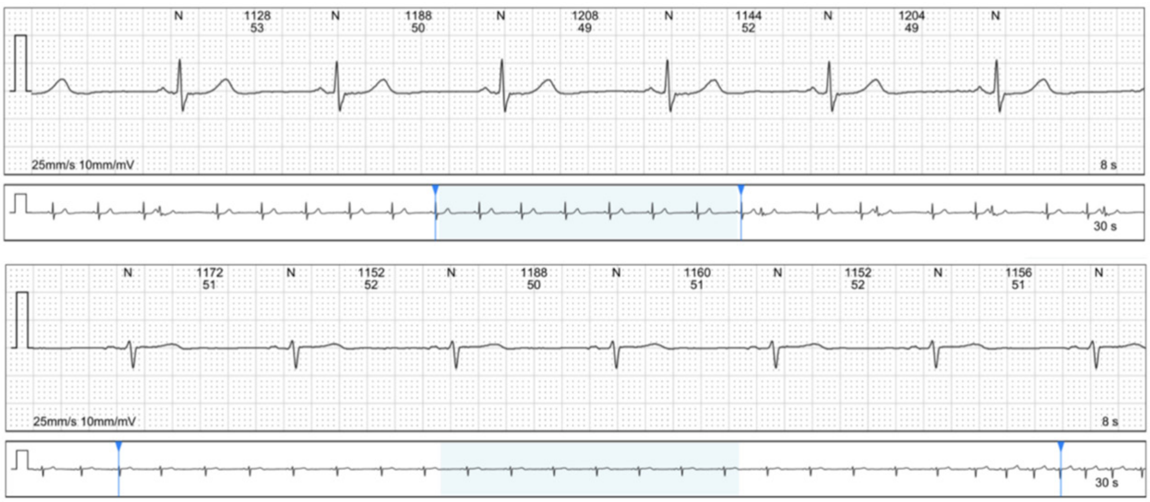

Figure 7. Mean heart rate (excerpt).

Table 3. Scoring sheet for wearing experience of Holter dynamic ECG and intelligent real-time ECG monitoring apparel

	Remote medical experience		Appearance comfort experience		Functional monitoring experience	
	Traditional	Smart	Traditional	Smart	Traditional	Smart
Fabric	-	-	3.25	8.89	-	-
Electrode	-	-	5.97	8.35	-	-
Wire	-	-	6.08	6.88	-	-
Comprehensive	3.78	7.53	5.10	8.04	6.16	5.94

(+5.54). The smart apparel, designed based on specific principles, showed significant improvement in comfort. The monitoring electrodes of the smart apparel, being hidden compared to traditional equipment, improved comfort feedback (+4.40). The design principles of the smart apparel received relatively satisfactory user ratings (7.49). The structure of the real-time cardiac monitoring smart apparel met the overall comfort improvement requirements, but there's room for further optimization in the touch experience of the electrode patches.

Operational convenience experience: Survey results indicated that, compared to traditional cardiac monitoring equipment, participants found the smart apparel significantly more convenient in real-time cardiac monitoring (+5.11). The smart apparel showed significant improvements in structure, electrodes, and wire operations. The apparel structure had the most noticeable improvement in operational convenience (+6.06). The design principle applied to the smart apparel structure greatly enhanced operational convenience. Additionally, the hidden monitoring electrodes in the smart apparel structure helped improve operational convenience (+4.47), and the optimized wire arrangement was also acknowledged by participants (7.27).

In cardiac monitoring, the design of the real-time cardiac monitoring apparel aids patients and doctors in self-repositioning and quick location, saving time and reducing potential monitoring errors. The smart apparel generally meets participants' wearing and visual experience. The current remote experience mainly focuses on real-time viewing of cardiac data, only monitoring parameters like heart rate. Real-time diagnosis based on electrocardiograms is still challenging. In future research, the smart apparel can further optimize preliminary online auxiliary diagnosis as an aid for doctors to achieve remote medical treatment. The apparel structure, designed based on a traditional vest pattern, meets the accuracy requirements of monitoring electrodes and addresses sudden situations like electrode dislocation and detachment that can occur in daily life. Future optimizations can focus on feedback regarding wire experience in the smart apparel structure. After actual testing and confirmation, the monitoring data of the smart garment does not affect the diagnosis results of doctors compared to traditional monitoring modules. The smart clothing in general meets the subjects' wearing and visual experience needs, but the current remote experience, which is mainly for the real-time view of ECG data, can only monitor for early warnings of users' heart rate and other parameters, and it is difficult to achieve specific, real-time diagnosis with ECG. Subsequent research should further optimize the smart clothing to support preliminary online auxiliary diagnosis by telemedicine physicians.

Discussion

Real-time ECG-monitoring clothing based on the Holter system uses an intelligent design with heart rate monitoring at its core. The system is based on three modules - ECG monitoring, clothing structure design, and a data platform - which can solve some of the drawbacks of traditional ECG monitoring equipment. In order to support digital medical treatment and provide wireless data transmission capabilities, the design can provide online diagnosis and real-time remote ECG monitoring support for digital medical treatment in the context of a global epidemic.

The design described here combines real-time ECG monitoring equipment with clothing structure and is applied to home or clinical medicine to realize real-time ECG monitoring in the form of digital medicine. First, in the intelligent Holter system, real-time ECG-detection clothing helps patients and doctors to self-reset and quickly locate electrodes, saving time and reducing possible ectopic monitoring errors. Second, COVID-19 has affected the traditional offline medical model, and remote digital medical assistance is constantly developing as an alternative to traditional medical care. The wearable device is combined with an online data module to transmit data remotely, facilitating the combination of digital medical assistance and offline diagnosis.

By comparing normal and abnormal values through ECG monitoring, a verification experiment was carried out to confirm the heart rate monitoring effect of the wearable device. The results show that the wearable ECG-monitoring smart clothing - designed by combining a monitoring module in the appropriate monitoring position with the clothing - can be synchronously monitored using the app in real time, record and save the patient's ECG information in real time, and detect dangerous abnormal ECG signals in a timely fashion, which allows doctors to diagnose patients using the generated reports. The combination of sensing textile materials and clothing structure design with silver fiber and elastic textile fabrics resulted in a satisfactory experience for wearers with different body types. However, the effect of real-time ECG-monitoring clothing proposed in this study should be verified for participants with greater differences in body size and age, with a view toward sustainable optimization, to meet the requirements of different wearers.

The wearable electrocardiogram monitoring garment designed in this study can meet the remote medical needs of patients and provide more medical options for them. However, there are still many problems in its practical clinical applications. In-depth development of auxiliary diagnosis should be carried out in the future. Specifically, future research should perform a more thorough analysis and visualization of the collected ECG data; develop automatic diagnostic techniques for the ECG data; perform cluster analyses of the collected real-time ECG monitoring data set using a neural network model; and enable self-diagnosis and early warnings of cardiac issues for patients.

Disclosure of conflict of interest

None.

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References

[1] Wang YH, Chung CG, Lin CC and Lin CM. The study of the electrocardiography monitoring for the elderly based on smart clothes. 2018 Eighth International Conference on Information Science and Technology (ICIST) 2018; 478-482.
[2] Tsao CW, Aday AW, Almarzooq ZI, Alonso Á, Beaton AZ, Bittencourt MS, Boehme AK, Buxton AE, Carson AP, Commodore-Mensah Y, Elkind MSV, Evenson KR, Eze-Nliam C, Ferguson JF, Generoso G, Ho JE, Kalani R, Khan SS, Kissela BM, Knutson KL, Levine DA, Lewis TT, Liu J, Loop MS, Ma J, Mussolino ME, Navaneethan SD, Perak AM, Poudel R, Rezk-Hanna M, Roth GA, Schroeder EB, Shah SH, Thacker EL, VanWagner LB, Virani SS, Voecks JH, Wang NY, Yaffe K and Martin SS. Heart disease and stroke statistics-2022 update: a report from the American Heart Association. Circulation 2022; 145: e153-e639.
[3] Xu P, Zhang H and Tao X. Textile-structured electrodes for electrocardiogram. Textile Progress 2008; 40: 183-213.
[4] McCann J, Hurford R and Martin A. A design process for the development of innovative smart clothing that addresses end-user needs from technical, functional, aesthetic and cultural view points. Ninth IEEE International Symposium on Wearable Computers (ISWC'05) 2005; 70-77.
[5] Yang MY and Cheng JH. Research and development of smart health monitoring clothing system. 2018 37th Chinese Control Conference (CCC) 2018; 8231-8234.
[6] Serhani MA, T El Kassabi H, Ismail H and Nujum Navaz A. ECG monitoring systems: review, architecture, processes, and key challenges. Sensors (Basel) 2020; 20: 1796.
[7] Lin WY, Ke HL, Chou WC, Chang PC, Tsai TH and Lee MY. Realization and technology acceptance test of a wearable cardiac health monitoring and early warning system with multichannel MCGs and ECG. Sensors (Basel) 2018; 18: 3538.
[8] Cho G, Jeong K, Paik M, Kwun Y and Sung M. Performance evaluation of textile-based electrodes and motion sensors for smart clothing. IEEE Sensors Journal 2011; 11: 3183-3193.
[9] Cai Z, Luo K, Liu C and Li J. Design of a smart ECG garment based on conductive textile electrode and flexible printed circuit board. Technol Health Care 2017; 25: 815-821.
[10] Chen M, Ma Y, Song J, Lai CF and Hu B. Smart clothing: connecting human with clouds and big data for sustainable health monitoring. Mobile Networks and Applications 2016; 21: 825-845.
[11] Cho H and Lee JH. A study on the optimal positions of ECG electrodes in a garment for the design of ECG-monitoring clothing for male. J Med Syst 2015; 39: 95.
[12] An X and Stylios GK. A hybrid textile electrode for electrocardiogram (ECG) measurement and motion tracking. Materials (Basel) 2018; 11: 1887.
[13] Muhlsteff J, Such O, Schmidt R, Perkuhn M, Reiter H, Lauter J, Thijs J, Musch G and Harris M. Wearable approach for continuous ECG--and activity patient-monitoring. Conf Proc IEEE Eng Med Biol Soc 2004; 2004: 2184-2187.
[14] Taylor SA and Sharif H. Wearable patient monitoring application (ECG) using wireless sensor networks. Conf Proc IEEE Eng Med Biol Soc 2006; 2006: 5977-5980.
[15] Raskovic D, Martin T and Jovanov E. Medical monitoring applications for wearable computing. Comput J 2004; 47: 495-504.
[16] Dimarco JP and Philbrick JT. Use of ambulatory electrocardiographic (Holter) monitoring. Ann Intern Med 1990; 113: 53-68.
[17] Denes P. The importance of derived 12-lead electrocardiography in the interpretation of arrhythmias detected by Holter recording. Am Heart J 1992; 124: 905-911.
[18] Rehman A, Haseeb K, Fati SM, Lloret J and Peñalver L. Reliable bidirectional data transfer approach for the internet of secured medical things using ZigBee wireless network. Applied Sciences 2021; 11: 9947.
[19] Vozda M and Cerný M. Methods for derivation of orthogonal leads from 12-lead electrocardiogram: a review. Biomed Signal Process Control 2015; 19: 23-34.
[20] Pérez-Riera AR, de Abreu LC, Barbosa-Barros R, Nikus KC and Baranchuk A. R-peak time: an electrocardiographic parameter with multiple clinical applications. Ann Noninvasive Electrocardiol 2016; 21: 10-9.
[21] Mestrovic MA, Helmer RJN, Kyratzis L and Kumar D. Preliminary study of dry knitted fabric electrodes for physiological monitoring. 2007 3rd International Conference on Intelligent Sensors, Sensor Networks and Information 2007; 601-606.
[22] Castano L and Flatau AB. Smart fabric sensors and e-textile technologies: a review. Smart Mater Struct 2014; 23: 053001-1-053001-27.