Wearable Medical Monitoring Systems Based on Wireless Networks: A Review

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***Abstract*— The last decade has witnessed a rapid increase of interest in new sensing and monitoring devices, including wireless wearable mobile devices and sensing networks for medical health applications. This paper reviews current wearable mobile medical monitoring systems (WMMMSs) with emphasis on devices based on textile and wireless sensing networks. These monitoring systems consist of various types of small physiological sensors, transmission modules, and processing capabilities. In addition, WMMMSs have a potential to change the health care model by providing inexpensive wearable unobtrusive solutions for continuous medical health monitoring. It is with the hope that the current survey is able to provide a direction for future research improvements and also serve as a reference for current achievements and their maturity level. In this review, a great number of system implementations are compared according to different classifications. Besides, these systems also act as an effective approach to identify the technological advantages and disadvantages of the current state-of-the-art in wearable devices solutions.**

***Index Terms*— Wearable sensor, wireless communication technology, health monitoring system.**

I. INTRODUCTION

WMMMS have attracted much more attention from the research community and the industry during recent years. This is shown by the numerous projects [1]–[5] in this field which have been carried out at an increasing speed as well as broad market requirements. With the development of mobile communication technology, mobile broadband networks and services are vigorously expanded in modern times. At the same time, higher quality of information services is provided through mobile terminals such as mobile phones or Personal Digital Assistants (PDAs).

It is known that various diseases are prevalent all over the world to threaten our health. Four non-communicable diseases combined—cardiovascular disease, chronic respiratory disease, cancer, and diabetes—will cost the global economy US $30 trillion from 2011 to 2030 [6]. Investigations have shown that the incidents of coronary heart disease are projected to increase by approximately 26% from 981,000 in 2010 to 1,234,000 in 2040, and prevalent coronary heart disease by 47%, from 11.7 million to 17.3 million. Coronary heart disease-related health care costs are projected to rise by 41% from US $126.2 billion in 2010 to US $177.5 billion in the year of 2040 in the United State [7].

Manuscript received February 19, 2016; revised July 7, 2016; accepted July 16, 2016. Date of publication August 2, 2016; date of current version November 4, 2016. The work of Y. J. Yuan was supported by the National Natural Science Foundation of China, General Program Funds under Grant 31170954 and Grant 30870664. The associate editor coordinating the review of this paper and approving it for publication was Prof. Jun Ohta. *(Corresponding author: Yong J. Yuan.)*

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Digital Object Identifier 10.1109/JSEN.2016.2597312

In recent years, the rapid development of wireless communication technologies, microelectronics and embedded system technologies enhances the progress of mobile medical health to such an extent that traditional hospital models also have entered into a substantive change. According to a China Electronics Supply Chain topical report from IHS Inc. [8], China's medical electronics market had reached a strong double-digit-rate expansion at the end of 2013. The expansion is set to increase in the next few years ahead, propelled by a demand for equipment in a country increasingly beset by First World-type ailments. Thus, it is estimated that by 2017, China's medical electronics markets will be worth around US $9.25 billion [8]. Meanwhile, medical electronic devices market hit US $67 billion in 2012, and it is predicted that it will grow to over US $82 billion in 2017 [9].

In fact, wearable mobile medical monitoring devices are practical for a patient to be able to monitor his own health status, wherever he is. As a consequence, it is anticipated that the quantity of wearable equipment health monitoring and chronic diseases will continue to grow especially in remote areas. Besides, the huge economic market makes sure the development space of these devices.

Certainly, there were various wearable devices which had been successfully utilized. For instance, Georgia Tech [1], which can be easily and comfortably worn by soldiers, is a typical application in the US military as a "wearable motherboard" to monitor a variety of vital parameters through a vest. A smart shirt [2] has six electrodes on the chest to measure a detailed electrocardiogram (ECG) obtained with unipolar precordial leads. Besides, they develop a conductive foam block that fills this gap between the smart shirt and the body. EU-funded projects such as BIOTEX [3], Proe-TEX [4] and AMON [5] use sensor-based and wrist-worn devices to measure various parameters such as sweat rate, respiratory activity, ECG and heart rate (HR). These projects are mainly to monitor the state of a patient and also those who are living in harsh environments. A research team of Development Division led by Haahr, has devoted themselves to a wireless long-term health monitoring system with lower power consumption. It is reported that they have fabricated reflectance pulse oximetry sensor embedded in ring-shaped photodiode [10] and electronic patch [11] to detect physiological parameters.

WMMMS are generally composed of three parts, as shown in Fig. 1 [12], [13]. The first part is made up of a great number of different types of miniature wearable or implantable sensors

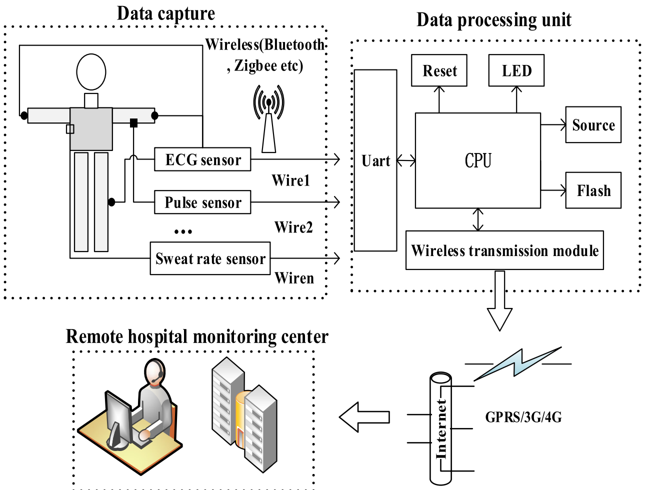

Fig. 1. The structure of wearable mobile medical monitoring system.

and transmission modules. For example, Bluetooth, which function is to acquire physiological signals such as HR, blood pressure (BP), respiration rate (RR), body temperature (BT), oxygen saturation (SpO2) and ECG, is designed to transmit physiological signals to a processing unit. The second component is a terminal which is made up of wireless communication module to receive or send effective data to a data processing unit. The last component is a remote monitoring center, which mainly is applied to provide medical services and rescue.

WMMMS have such a great deal of merits that are popular in the consumers' market. Merits are listed as follows:

- Real-time monitoring
- Flexibility of geographic
- Easy to detect
- Intelligent features
- Human characteristics
- Security and reliability
- Lower cost and power
- Context-awareness

In this review, the current state in research and development of wearable inexpensive unobtrusive systems was elaborated for monitoring applications in different situations. The most promising achievements of several worldwide projects and commercial products were also discussed and compared in the context. Several familiar short-range wireless communication standards for wearable mobile medical health monitoring systems based on collecting physiological signals were compared and discussed. The review provides an incisive outline into dynamic development in the area of wearable health monitoring system.

II. Fundamental Principles of Medical Sensor Technologies

This section mainly introduced five basic sensing technologies widely utilized in wearable monitoring systems. Medical sensors vary according to different working principles such as piezoelectric effect, photoelectric effect and Hall effect. Sensors in the systems that are used to obtain physiological parameters from patients are consisted of sensitive element and the conversion elements. In general, sensing element, transmission element, signal conditioning conversion circuit and auxiliary circuit are presented in a sensor device. Sensors can be divided into two types based on electrical signal parameter and non-electrical signal parameter [14]. Bioelectricity electrode is an electrical signal parameter sensor based on all kinds of bioelectricity that derives from body such as ECG, electroencephalogram, electromyogram, and neuronal discharge. On the other hand, physical sensors, chemical sensors and biosensors belong to the type of non-electrical signal parameter [15], [16].

Modern medical sensors compared with traditional medical sensors are more intelligent, miniaturized, low power, multi-parameter, and noninvasive. The review puts emphasis on the principle of several common and important medical sensors rather than the all basic principles of sensors and classifications. Five sensors used universally in wearable monitoring systems will be introduced in detail in the following subsections A, B, C, D and E.

A. Pulse Oximetry Sensor

Pulse oximetry is one of the most commonly employed monitoring modalities in the critical care. It takes full use of spectral analysis to measure the ratio of oxyhemoglobin (HbO_2) to reduced hemoglobin (Hb) in arterial blood and displays this value as oxyhemoglobin saturation (SpO_2). Two important values obtained from the pulse oximetry including the oxygen saturation of Hb in arterial blood and the pulse rate in beats per minute.

Pulse oximeters depend on spectrophotometry, the detection and quantification of compounds in solution by their unique light absorption characteristics [17]. The central theory of spectrophotometry is the Beer-Lambert law, which states that the amount of light emerging from a substance in solution is determined by the concentration of the absorbing material, the distance that the light must travel through the sample and the probability that a photon at that particular frequency will be absorbed by the material [18].

The value of oxygen saturation is decided by the relative concentrations of reduced Hb and oxyhemoglobin. Therefore, a wavelength of light must be used that each chromophore will preference absorb. Currently available oximeters use an electronic processor and two light-emitting diodes (LEDs) facing a photodiode through a translucent part of the patient's body, such as a fingertip or an earlobe. The two LEDs emit light at the 660nm (red) and the 940nm (infrared) wavelengths respectively, because HbO_2 and Hb have different absorption spectra at these particular wavelengths as shown in Fig. 2 [19].

According to Fig. 2, HbO_2 absorbs fewer red lights than infrared lights, thus, the tissue's cycling blood volume at high saturation has less influence on the detected red signal. On the contrary, Hb absorbs fewer infrared lights than red lights so that the tissue's cycling blood volume at low saturation has less influence on the detected red signal than on the infrared signal as Fig. 3.

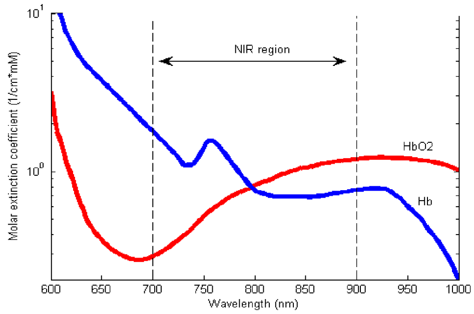

Fig. 2. Absorption spectra of normal and abnormal hemoglobins.

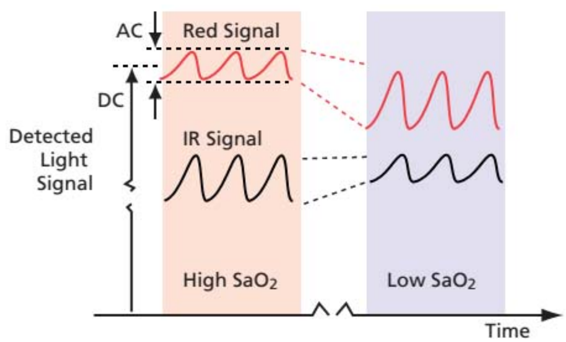

Fig. 3. Red and IR light signals at high and low arterial oxygen saturation.

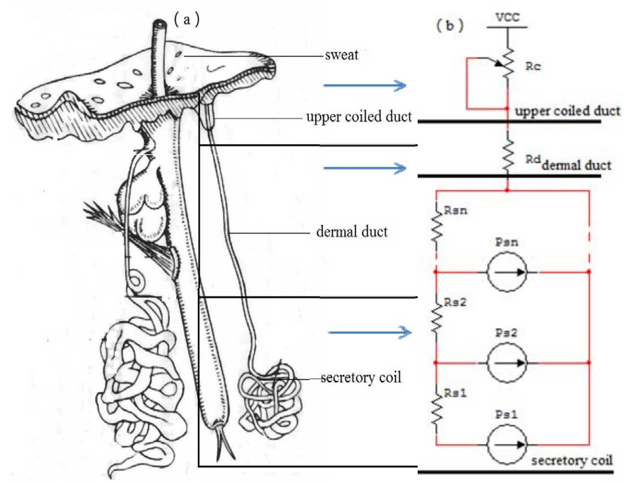

Fig. 4. Structure of the human sweat gland showing the (a) skin cross-section and (b) microfluidic equivalent.

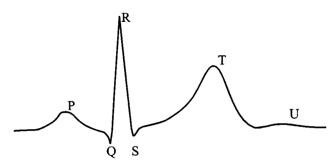

Fig. 5. Schematic diagram of ECG.

Currently, a large number of pulse oximetry used in wearable devices for monitoring patients have been accepted in daily life, which have a great impetus to current medicine [20], [21]. The Nellcor™ OxiMax pulse oximetry as a leader in this field is an outstanding instrument to monitor patients [22].

B. Sweat Rate Sensor

The idea of using wearable devices for monitoring sweat rate is a fairly novel concept, primarily proposed by De Rossi and his colleagues in the year of 2010 [23]. Their device was designed to measure sweat rate by integrating two humidity sensors on a textile substrate. The difference in two humidity sensors' responses is proportional to the vapor pressure gradient, which can be used to calculate diffusion flow according to Fick's first law. Besides, a conductivity sensor based on sweat sensing system packaged as a wrist watch was proposed [24]. This system collected sweat from the forearm, recognized the conductivity value and wirelessly transmitted data to a smartphone by Bluetooth. The idea was to have a small hole on a plastic piece where sweat is guided through a plastic tube.

In the absence of biomarker partitioning and microfluidic transport models for sweat will weaken discovery of new biomarker opportunities in sweat. Sonner et al. solved the issues [25], by microfluidic models for eccrine sweat generation and flow as well as reviewed several blood-to-sweat biomarker partition pathways. The research was on the basis of prior research in the dermatological and related bioscience fields.

Fig. 4 is an intuitionistic picture to state the structure of human sweat gland and the microfluidic equivalent circuit format [26]. The human eccrine sweat gland is made up of three geometrically distinct portions, including secretory coil, dermal duct and the upper coiled duct. Because each fluid has a different total solution volume, it tremendously influences concentration levels. In order to acquire sweat rate, some ions such as Na^+ and Cl^- should be measured by using ion-selective electrodes or electrical conductivity of the sweat [27].

The microfluidic models for eccrine sweat generation and flow was built upon a much more simplified pressure-driven model, which was previously proposed for an in-vitro skin and sweat mimic [28]. It is based on the theories in TABLE I, according to their research and previous achievements [29]–[31].

C. ECG Electrode

ECG [32] is one of the most important human physiological signals. It reflects the electrical activity of the heart excited process, which has a significant reference value for its cardiac basic function and pathology research. Various arrhythmias can be analyzed and identified through ECG, and it may also reflect the degree of myocardial damage and development process as well as the function structure situation of arterial and ventricular. ECG can roughly be divided into the phases of depolarization and repolarization of the muscle fibers making up the heart. The depolarization phases correspond to the P-wave (atrial depolarization) and QRS-wave (ventricles depolarization) while the repolarization phases correspond to the T-wave and U-wave (ventricular repolarization) as shown in Fig. 5.

Willem Einthoven has recorded the ECG of clear graphic and clinical application available using string type ECG

TABLE I
RELATED EQUATIONS

Symbol	Equations	Parameters
R	$R=\frac{128\mu L}{\pi d^4}$	R is the fluid resistance for a specific geometry μ is the viscosity L is the length of the region d is the diameter of the circular cross-section
P	$P=R\cdot Q$	P is the pressure differential in the interest region R is the fluid resistance for a specific geometry Q is the volumetric flow rate
P_L	$P_{L}=\frac{2\gamma\cos\theta}{a}$	P_L is the Laplace pressure γ is the surface tension of sweat θ is the contact angle of the sweat a is the radius of the base of the droplet
P	$P=\sigma RT\Delta C$	P is the change in pressure □ is the osmotic reflection coefficient R is the gas constant T is the temperature of the body ΔC is the difference in concentration between plasma and sweat
C(z)	$C(z)=C_s\cdot e^{\frac{2k\pi R}{Q}[z+L]}$	C(z) is the concentration of the solute L is the length of duct z=0 Cs is the concentration of the solute in the preliminary sweat k is the reabsorption permeability constant of the solute in the sweat duct R is the radius of the duct Q is the volumetric flow rate
v_{diff}	$\bar{v}_{diff}\big\vert_0^R=\frac{D}{R}\ln\left[\frac{\Delta C+C(0)}{C(0)}\right]$	$\bar{v}_{diff}$ is the average diffusional velocity from zero to R D is the diffusivity of the analyte R is the full radius of the sensor ΔC is the concentration difference from zero to R C(0) is the concentration at r =0
$\bar{v}_{flow}$	$\bar{v}_{flow}\big\vert_0^R=\frac{Q\cdot\rho\cdot R}{4g_{eff}}$	$\bar{v}_{flow}$ is the average flow velocity from zero to R Q is the sweat flow rate per gland ρ is the density of sweat glands underneath the sensor region R is the radius of the sensor g_{eff} is the effective gap height

machine since 1903. Nowadays, ECG electrodes are more likely to be flexible, biostable, biocompatible, effective and simple without having use to electrolyte gel or adhesive. Traditional or commercial electrodes for medical use such as Ag/AgCl electrodes require an electrolyte gel or adhesive between sensor and body tissue to establish a reliable skin-to-electrode connection. During the course of procedure, a drastic decrease of the signal may occur due to the drying up of the electrolyte gel [33], [34]. In recent years, wireless ECG is expanded in a monitoring system using non-contact sensors in an increasing number of research and industry. At the same time, many textile-electrodes have been developed and are also widely applied. The advantages of these ECG electrodes are that they are washable and can be used with a long time for accurate monitoring [35]. The basic signal processing framework is depicted in Fig. 6.

D. Glucose Sensor

The blood glucose level is an important indicator of the ability of human metabolism and diagnosis of diabetes. There are mainly three ways to test glucose concentration, including colorimetric and fluorescence methods, especially glucose biosensors with high selectivity and high sensitivity, and fast detection. Therefore, the study of glucose biosensors has been a hot research of chemical and biological sensors. This paper

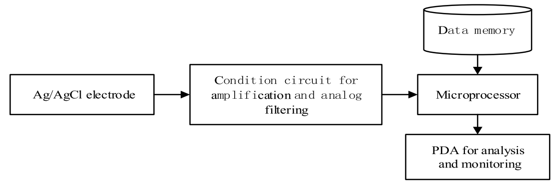

Fig. 6. The system framework of ECG.

focused on the principle of electrochemical glucose biosensors widely used in wearable monitoring systems. Electrochemical sensors are mainly subdivided into amperometric, potentiometric or conductometric types [36].

The history of glucose enzyme electrodes has been developed 54 years since 1962 [37]. The electrochemical glucose sensor is one of the earliest developed biosensors. The electrochemical glucose sensor is divided into enzyme-based electrochemical glucose sensors and non-enzymatic electrochemical glucose sensors. Electrochemical glucose sensors have experienced three generations' development [38]. The first glucose sensor was based on Clark and Lyons' theory. With the high pace development in science and technology, the principle of electrochemical glucose sensors was optimized and improved though it is also obey the original theory. The main reactions are as follows

Enzymatic glucose recognition

$$\text{D-Glucose} + O_2 \xrightarrow{\substack{\text{glucose}\\ \text{oxidase}}} \text{D-Gluconolactone} + H_2O_2 \tag{1}$$

$$\text{D-Gluconolactone} + H_2O \rightarrow \text{D-GluconicAcid} \tag{2}$$

Electrochemical oxidation of H_2O_2 for label-free sensing

$$H_2O_2 \rightarrow 2H^+ + O_2 + 2e^-. \tag{3}$$

E. Acceleration Sensor

An acceleration sensor is a kind of electronic device that can measure variable forces caused by falling, tilt, motion, position, vibration and shock. It includes angle accelerometer improved by gyro (angular velocity sensor) and the line of the accelerometer [39]. Generally, most of the acceleration sensor is based on the piezoelectric effect to work. Acceleration sensors are used in various fields such as intelligent products, position detection devices or terminals, Global Positioning System (GPS) navigation systems and blind angle compensation.

Nowadays, the triaxial accelerometer sensor is one of the common types of accelerometer sensors. They are applied in the position and walking exercise, a novel automatic method using 3D acceleration sensors to evaluate the intensity of walking exercise successfully. More attention is drawn to human motion for walking. However, in the near future, estimation formula will be applied in other motions to improve and increase its functions. With the cooperation of the Engineering School at Chang Gung University and Taiwan Textile Research Institute, a new textile based intelligent wearable vest for real-time multi-posture monitoring [40] and warning of emergency

TABLE II
SHORT-DISTANCE WIRELESS COMMUNICATION TECHNOLOGY

Wireless communication technology	Protocol standard	Working frequency	Communication distance	Communication rate	Typical * modulation mode	Power consumption	Merit and demerit
Bluetooth	IEEE802.15.1	2.4GHz	10m	<1Mbps	FHSS	1-100mW	Communication is fast Good mobility High consumption
ZigBee	IEEE802.15.4	868MHz 915 MHz 2.4GHz	10-75m	20Kbps 40Kbps 250Kbps	DSSS	very low	Low power, Low cost, Large network Safe and reliable
NFC	ISO/IEC 18092	13.56 MHz	20cm	106/212/ 424Kbps	ASK	very low	Short network setup time Short transmission Distance security
UWB	IEEE802.15.3	3.1-10.6 GHz	30m >100m	100-1024Mbps	OFDM	<=1mW	Extremely wide bandwidths Good confidentiality Low transmission power
Wi-Fi	IEEE802.11a/b/g	2.4GHz	<100m	11Mbps	OFDM DSSS	60-70 mW	Fast communication speed Good mobility High consumption

* FHSS = Frequency Hopping Spread Spectrum, DSSS = Direct Sequence Spread Spectrum, ASK = Amplitude Shift Keying, OFDM = Orthogonal Frequency Division Multiplexing

condition [39] was developed. Modern accelerometers are often small micro electro-mechanical systems (MEMS) and indeed the simplest MEMS devices possible.

III. SHORT-RANGE WIRELESS COMMUNICATION STANDARDS

Short-distance wireless communication technology usually refers to wireless communication within a hundred meters. There is a series of technical standards and specifications such as Bluetooth, wireless High Security (Wi-Fi), Radio Frequency Identification (RFID), Near Field Communication (NFC), Ultra-wideband (UWB) and ZigBee. They respectively have their own characteristics as shown in TABLE II. From the viewpoint of transportation rate, it can be concluded that the performance can be ranked as follow: UWB > Wi-Fi > Bluetooth > RFID/NFC > ZigBee. However, conclusion also can be drawn from standpoint of the transportation distance. The performance can be ranked as: Wi-Fi > ZigBee > UWB > Bluetooth > NFC. From the power consumption point of view, UWB gives better performance than Bluetooth and ZigBee. UWB provides a highly integrated low-cost solution in current short-range high data rate communication according to a report from Texas Instrument [42]. Fig. 7 provides a distinct impression on several wireless technologies based on their power consumption and transmission distance as an excellent comparison.

Short-range wireless communication technology is one of the important components in WMMMS. It is responsible for transmitting data from sensors collecting physiological parameters to sensor nodes or data processing platforms such as smart phones, PDAs, and PC. Bluetooth, ZigBee and Wi-Fi will be introduced in the following sub-sections and a comparison will be made according to their communication protocol standards, communication rate, modulation mode advantages and disadvantages.

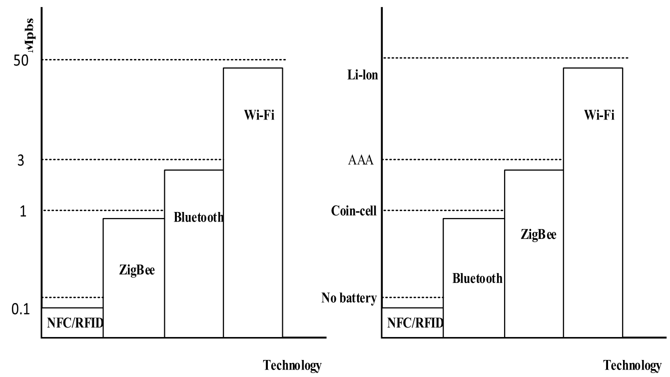

Fig. 7. Comparisons of wireless communication technology.

A. Bluetooth

Bluetooth technology [43] is one of the global wireless standards. It is an essential element for bringing everyday objects into the connected world and creates seamless contact around everyone. Bluetooth is intended to replace the cables connecting portable and/or fixed devices while maintaining high levels of security, low power and low cost. A fundamental strength of Bluetooth is its ability to simultaneously handle data and voice transmissions. It is a radio communication technology supporting device which allows communication in a short-range of 10 meters. Importantly, it is a proposed publicly available specification for RF specification. Information can be exchanged through Bluetooth technology using wireless among mobile phones, PDAs, headsets, laptops, and other related peripherals.

The use of Bluetooth technology can effectively simplify communication between the mobile communication terminal devices. It is also possible to simplify the communication successfully between the terminal device and the Internet. The most common Bluetooth include Bluetooth BR/EDR (basic rate/enhanced data rate) and Bluetooth Low Energy, two different versions of core specification.

TABLE III
APPLICATIONS OF NFC

Related literature	Application area	Platforms
Communication Protocol for Enabling Continuous Monitoring of Elderly People through NFC(2013)[56]	Health monitoring ECG,SpO_2 and other bio-signals	Smart phones
An mHealth system for toxicity monitoring of paediatric oncological patients using Near Field Communication technology (2015)[57]	BP, HR, temperature, body weight, C-reactive protein, etc.	Smartphone-based patient terminal
Using NFC Technology for Monitoring Patients and Identification Health Services(2015)[58]	Identification and monitoring of patients in health centers	Server, identification tag and the reader device
Innovative telemonitoring system for cardiology: from science to routine Operation (2010)[59]	Telemonitoring of chronic disease	Mobile phone
A Generic NFC-enabled Measurement System for Remote Monitoring and Control of Client-side Equipment (2011)[60]	Remote monitoring and control of client-side equipment	NFC-enabled mobile phone
Design and Evaluation of a Telemonitoring Concept Based on NFC-Enabled Mobile Phones and Sensor Devices (2012)[61]	Remote monitoring chronic disease	Mobile phone
Body Sensor Networks in Fetal Monitoring with NFC Enabled Android Devices (2012)[62]	Fetal health monitoring	Android devices
A 38 μA Wearable Biosignal Monitoring System with Near FieldCommunication (2013)[63]	Heart rate monitoring	Smart phone

Bluetooth technology uses frequency-hopping spread-spectrum (FHSS) communication in the 2.4-GHz industrial, scientific, and medical (ISM) band, where unlicensed devices are limited to communicate in most countries [44]. The Bluetooth system supports both point-to-point connection and point-to-multipoint connections. Its data rate is 1Mbps, using time division duplex transmission scheme to achieve full-duplex transmission. When a pair of Bluetooth devices communicates with each other, Bluetooth technology requires that one device must be a main role and the other subordinates from the main role so that the two devices can communicate.

Besides its applications in a number of gadgets such as mobile phones and PC which had been mentioned earlier, Bluetooth has recently become one of the most popular short-range wireless technologies as a solution of WMMMS. Bluetooth is widely applied in WMMMS for patients to transmit important signals such as ECG, BP and SpO2 to healthcare providers [45].

B. ZigBee

ZigBee [46] is a low power wireless specification based on IEEE standard 802.15.4. It has merits of short range, low-complexity, self-organizing, low power (battery life multi-month to years), high data rate (Data rates of 250 kbps (@2.4 GHz), 40 kbps (@ 915 MHz), and 20 kbps (@868 MHz). Consequently, ZigBee is mainly suitable for the field of automatic control and remote control and can be embedded in a variety of devices.

ZigBee is a standard-based technology for remote monitoring, control and sensor network applications [47]. The ZigBee standard was designed to emphasize the need for a low cost. Its application areas include home and building networks, such as temperature control of air conditioning systems, the automatic control of curtains, remote control of appliances [48]; industrial control, environment monitoring [49]; and medical monitoring used for the elderly and those with reduced mobility [48]. In short, ZigBee is gaining more and more attention and widespread applications [50], [51]. It is anticipated that ZigBee will play an active part in WMMMS to transmit physical parameters between patients and health carers.

C. NFC

NFC [52] is a short-range high frequency wireless communication technology, allowing non-contact point-to-point data transmission between the electronic devices at the range of 3.9 inches. This technology stems from RFID researched and developed by Philips, Nokia and Sony, based on RFID and interconnection technologies. NFC works at the 13.56 MHz frequency band and its transmission at the speed of 106 Kbit/s, 212 Kbit/s or 424 Kbit/s.

NFC-enabled devices to exchange data in active or passive mode are similar to RFID [53]. In passive mode, NFC initiating device also known as the master device provides RF fields in the whole communication process. It can choose one of the transmission rates to transmit data to other device. The other equipment called NFC target device does not generate the

TABLE IV
APPLICATIONS OF UWB

Related literature	Application area	Advantages
Design, realization, and test of a UWB radar sensor for breath activity monitoring (2014)[69]	Breath activity monitoring	Low cost High accuracy
IR-UWB radar demonstrator for ultra-fine movement detection and vital-sign monitoring(2013)[70]	Movement detection and vital-sign monitoring such as breathing	High movement precision Lower power
Accurate heartbeat monitoring using ultra-wideband radar (2015)[71]	Monitoring personal heartbeat	Low cost High accuracy
SoC CMOS UWB Pulse Radar Sensor for Contactless Respiratory Rate Monitoring (2011)[72]	Respiratory rate monitoring	Low power Low cost High miniaturized
End to End Vital Sign Monitoring System with FM-UWB Technology (2011) [73]	Monitoring of heart beat variability	Low power Low error Low SNR value
Stepped-FM UWB Sensor System for Health-care Support(2013)[74]	Monitoring vital signs for elderly person (breathing rate)	Accuracy monitor movement of multiple person in a room
System-on-a-Chip UWB Radar Sensor For Contactless Respiratory Monitoring: Technology and Applications(2014)[75]	Respiratory rate monitoring	Low power Low cost

RF field, using load modulation technology, which can transmit data in the same speed to return to the initiating device.

Recently, NFC technology is widely popular among mobile phone vendors and related fields, because NFC is compatible with already existing popular technologies such as RFID, smart cards and contactless cards. With merits of security and simplification, a number of trials and research projects have been conducted focusing on the usage of NFC in ticketing and payment applications as well as social networking and location-based services [54], [55]. Recently, more attention has been payed to applications of NFC on telemedicine monitoring [56]. It is anticipated that in the near future the development of information technology will inevitably affect the healthcare system. Its applications are as shown in TABLE III [57]–[64].

D. UWB

The Federal Communications Commission has allocated 7, 500 MHz of spectrum for unlicensed use of UWB in the 3.1 to 10.6 GHz frequency band [65]. UWB allows a very low energy level for short-range, high-bandwidth communications by using a large portion of the radio spectrum. UWB is one of the latest wireless communication technology [66] based on the use of narrow pulses of extremely short duration (a few nanoseconds) instead of continuous RF waves.

UWB technology has attracted widespread attention all over the world because of its potential applications in high-rate short-range communications. Like Bluetooth, UWB is expected to be extensively used in portable devices. However, UWB appeared to be more effective than Bluetooth as with UWB large-size multimedia or data can be exchanged in a few seconds, which makes UWB more attractive. UWB has numerous advantages such as high precision ranging, security and scalability [67]. Additionally, UWB supports very high data transmission rates of up to hundreds of Mbps and to a few meters far short-ranges [68]. Therefore, UWB radio is foreseen as one of the most promising technologies for ubiquitous communications in short-range wireless applications [69]. In recent decades, UWB technology is widely applied for portable devices or wearable monitoring system for patients. The applications are shown in TABLE IV [70]–[76].

E. Wi-Fi

Wi-Fi [77] includes IEEE 802.11a/b/g standards for wireless local area networks. It allows users to surf the Internet at broadband speeds when connected to an access point (AP) or in ad hoc mode. Wi-Fi also provides a high connecting speed of Ethernet without wire and the connectivity for different products from different companies. Due to the high data transport capacity of Wi-Fi, integrated Wi-Fi network has a bright future. Furthermore, Wi-Fi technology is one of the most popular techniques used in notebook computers and Internet access devices such as routers and cable modems [78].

A person can connect to the Internet with a Wi-Fi enabled device such as computers, smart phones or PDAs when in proximity of an AP [79]. Wi-Fi applications cover every area of life in many places such as restaurants, cafes, fitness areas

TABLE V
PROJECTS AND IMPORTANT RESEARCH

Literature	Physiological parameters *	Integrated sensors	Communication modules	Hardware description	Application	Advantages
BIOTEX(EU-funded project) (2010)[3]	Sweat rate ECG ,R ,SpO2	pH sensor, Solid sensor, ECG electrode	Bluetooth	Multi-parametric Patch, band vest	Personal health real-time monitoring	Low power, huge applications
Proe-tex(EU-funded project) (2010)[4]	HR, BP, BT,SpO2 dehydration	Piezoelectric sensors, textile electrodes	ZigBee Wi-Fi	Micro-controller, flexible band	real-time monitoring in harsh environment	Intelligent, low power, light
Magic system (2010)[82]	ECG, SpO2 R, Posture	ECG electrode, 3D-acceleration	Bluetooth	PDA, vest with textile sensor	Real-time monitoring in altitude mount	Lower weight, easy to carry
Glucose monitoring (2013)[83]	Blood sugar	Glucose sensor	RF	A loop antenna, wireless sensor interface chip, and glucose sensor on a polymer substrate.	Wireless contact-lens tear glucose monitoring	Low-power low-current-noise accurate detection
AMON(EU-funded project) (2004)[5]	ECG, SpO2, HR, BP, Pulse	ECG sensors\, two-axis acceleration	GSM-Link Bluetooth	Wrist-worn device	Remote monitoring and emergency	Multi-parameters, light, low power
Healthwear (2012)[84]	Pulse, HR, SpO2, activity	Optical biomedical sensor, fabric electrode	3G	Portable patient unit in a wearable garment	Continuous wireless monitoring of bio-signals	Lower weigh, power consumption high-quality
Smart phone healthcare(2014) [85]	SpO2, HR	ECG electrode, BT sensor	USB	Smart phone	Continuous monitoring	Low power, easy to use
Smart shirt (2015)[2]	ECG	ECG electrode,	Wires	Smart shirt micro-controller	The Holter monitor in ECG	High stability washing durability comfortable
Life shirt (2003)[86]	R, ECG, BT	Blood sensor, ECG sensor	Wires& Bluetooth	Sensor embedded In vest, PDA	All day monitoring	Low power, lower weight, comfortable
Posture monitoring vest (2014) [39]	Multi-posture	Accelerometer	Bluetooth	Micro-controller, vest	Long time monitoring and emergency	Low power low cost accuracy
Wearable sensing device (TTRI) (2014)[87]	Movements	Textile strain sensor	Conductive yarns &wires	Wearable gesture sensing device	Flexion angle monitor	Convenient to use precision
Sweat monitoring(2015) [88]	Sweat	Camera	Wires	Smart phone Micro-controller	Monitoring sweat rates via image analysis	Low power
Smart closes (2013)[89]	ECG, EMG, R BP	Wearable sensor	Wires& Bluetooth	Smart phone, Smart closes	Long time monitoring and emergency	Friendly user interface ,energy efficient

and railway stations. With the growing frequency in the use of Wi-Fi, it helps to extend the technology beyond the PC and into consumer electronics applications such as Internet telephone, music streaming, gaming, photo viewing, home video and medical information transmission. Nowadays, Wi-Fi has played an extremely important role in current society for its special characteristics such as long transmission distance, fast transmission speed, compatibility with other services and convenient to form the network and security.

Wi-Fi has begun to be involved in the medical field, especially in terms of wearable telemedicine devices. Many of physiological data from patients such as ECG, HR and BP can be transferred very quickly and safely to a doctor to ensure better therapeutic and diagnostic treatment. This helps to improve the efficiency of a doctor as well as improve patients' medical environments. This in turn makes a significant contribution to social harmony and development [80], [81]. However, there are not many projects or research involved in Wi-Fi technology in the field of telemedicine at the present time. With the increasing combination in Wi-Fi technology and mobile phones or PDAs, it is expected that more and more applications of medical devices will involve Wi-Fi technology resulting in rapid development in telemedicine applications [82].

IV. Current Research and Development

In order to have a better understanding of the development trend in this field for readers, this section introduced some outstanding programs in wearable medical devices. The wearable medical devices on current markets include smart glasses, smart watches, smart wristbands, smart shoes, smart rings, intelligent armbands, smart belts, intelligent helmets and smart buttons just to name a few. These WMMMS are specially chosen for reviewing due to the following reasons:

- Able to measure multiple parameters
- The frequency of their citation by other projects
- Security and high technologies
- Advanced representatives providing excellent examples

The wearable systems that have been chosen to introduce are listed in TABLE V [83]–[91], along with a depiction of their hardware and communication modules, the physiological parameters, integrated sensors, their stated application field and their advantages. This review focused on wrist-worn devices, wearable devices based on textile vests, shirts and other common wearable devices such as patches and rings.

A. Wrist-Worn Devices and Smart Watch

A great number of wearable medical monitoring systems have been developed in the world. Nonetheless, wrist-worn devices designed for monitoring the state of patients and applied in sports to monitor some parameters are extremely common in daily life [92].

A wrist-worn wearable medical monitoring and alert system (AMON) was designed for high-risk cardiac/respiratory patients 12 years ago. The wrist worn integrated health monitoring instrument with a tele-reporting device have been reported, and it was designed for emergency telemedicine and home telecare for the elderly [5]. The AMON project has been funded in Europe by the EUISTFP5 program, which is a prototype of the wrist-worn device. The system includes continuous collection and evaluation of multiple vital signs, intelligent multi-parameter medical emergency detection, and a cellular connection to a medical center. Continuous long-term monitoring can be performed without interfering with the patients everyday activities and without restricting their mobility. This is due to the fact that the whole system is integrated in an unobtrusive, wrist-worn enclosure device with applying aggressive low-power design techniques. Very importantly, this project makes a deep impression on the other research in this area of wearable devices and leads to new design ideas. Wander et al. developed a wrist-worn device for continuous radial pulse wave capture and pulse wave velocity measurement. The platform realizes continuous non-invasive hemodynamic monitoring and makes a creative progress [93]. Nowadays, a wrist-worn device for long time HR monitoring and fall detection is also presented. The device is useful to detect heartbeat problems in long-term vital sign monitoring such as combat medics and mountain climbers [94].

Smart watches belong to a branch of wrist-worn devices. A smart watch [95] embedded sensors to recognize objects has three outstanding functions. They are namely the recognition of tagged objects by means of RFID technology, the recognition of gestures of the forearm using inertial sensors and the recognition of fingers gestures, hand gestures and grasps by sensing the force exerted by tendons in the wrist. The wrist watch is the force exerted by tendons in the wrist. The wrist watch is very interesting because it allows detection of gestures that could not be recognized by inertial sensors. Related sensors including 3-axis accelerometer, force sensor and 3-axis gyroscope are integrated in the belt of the watch. Moreover, their research result shows that force sensors on the wrist are capable of retrieving vital information about hand and finger movement. Besides, the watch may be able to allow ordinary people to interact in their common life with real objects and customizable gestures in an intuitive and comfortable way.

Wrist-worn devices or smart watches are regarded as a personal wearable and notification control device, usually used to monitor health state. Recently, a large number of similar devices are presented for monitoring bio-signals. It is easy to see wrist-worn devices or smart watches worn on people's body for monitoring ECG, BP and HR. Besides, they serve as intelligent devices to surf the Internet or smart phone to make phone calls. All of the introduced devices are partial representatives in this filed, but they set a good example for these wearable devices. In the near future, wrist-worn devices will take up a more huge markets share and make an obvious influence on our daily life.

B. Textile-Based Wearable Systems

Textile-based wearable systems are widely studied in various projects, research institutions and colleges such as the outstanding and important BIOTEX [3], ProeTEX [4], Magic system [83] and Health Wear projects [85]. All of the textile-based wearable systems are mainly vests, shirts and small garments.

The BIOTEX [3] is an EU-funded project that aims to develop textile sensors to measure physiological parameters and the chemical composition of body fluids, with a particular interest in sweat. The BIOTEX system involves a network of textile sensors that can be easily integrated into clothing and provide real-time physiological feedback.

The ProeTEX project [4] specifically is designed for fire fighters. The device integrated several sensors for physiological activity and environmental variable monitoring is used in harsh environments to detect physiological parameters. This program aims at making a real-time monitoring of rescuers system in emergency contexts.

The magic system [83] is mainly developed to monitor ECG, respiration, SpO_2 and posture for climbers during sleep. Correlated data were collected by the textile-based MagIC system, thus, researchers can investigate performances and know about the health state of climbers at very-high altitude.

The Health Wear project [85] is based on the Wealthy prototype system. It pays attention to the technical solutions that enables the monitoring of health conditions by means of ECG, HR, SpO_2, impedance pneumography and activity patterns. This new approach may contribute to the implementation of innovative models for the delivery of care.

At present, there are an increasing number of papers including wearable smart vests and shirts, which are capable of detecting physiological signals such ECG, EMG, BP, HR, BT, respiration, posture and activity to improve the accuracy of the patient diagnosis. These vests and shirts are more likely to be non-invasive, comfortable, and convenient to wear.

The Smart shirt [2] designed to measure ECG has six electrodes on the chest; ECG signal is obtained with unipolar precordial leads. The electrodes and wires of the shirt are made of conductive ink that is flexible and stretchable. But there is a gap between the smart shirt and the bodies, so they take advantages of the characteristics of the conductive foam block to solve the problem. Another example is the Smart Vest [96], which is a washable shirt and the monitored physiological signals are ECG, photoplethysmogram (PPG), BT, BP, galvanic skin response and HR. This vest is constructed by integration of sensors into the fabric. When acquiring and transmitting the physiological data, wearable monitoring system that is made up of micro-controller and wireless communication modules and GPS modules is utilized. The Smart Vest prototypes have varying degrees of success in achieving medical accuracy on all measurement combinations, contributing to wearable physiological monitoring systems.

In the USA, Rai et al. have given a significant solution for health care to the requirements of individuals across a wide range of ages [97]. Their printable lower-cost sensor systems can be used to monitor young or elderly recuperating convalescent patients either in hospital or at home. Additionally, they also can be used by young athletes to monitor important physiological parameters to better design their training or fitness program. Besides, a planar screen printable sensor based on conductive inks can be utilized to monitor abdominal respiration effort, BP, PR and BT. Nowadays, an advanced smart shirt [98] is designed to monitor continuous cardiac status on a smart phone. Data are wirelessly transmitted to a small receiver dongle, using only off-the-shelf ICs that interfaces with a laptop or smart phone via USB for display/processing. The most obvious advantage is that the system is extremely low-cost.

C. Other Common Wearable Medical Devices

Wearable medical devices consist of different forms and emerge from the markets in various objects such as a patch, a ring-shape photodiode and a pair of glasses.

An Electronic Patch [12] is a new health monitoring system incorporating biomedical sensors, microelectronics for RF communication. Besides, there is a battery embedded in a 3D hydrocolloid polymer to measure pulse and SpO_2. It is anticipated that this type of health monitoring by small non-invasive devices will become a new paradigm in health monitoring.

A Ring-Shaped Photodiode [11] is designed for a reflectance pulse oximetry sensor in autonomous and low-power homecare monitoring system. It gives optimal gathering of light and thereby enables very low light-emitting diode (LED) driving currents for the pulse oximeter. The novelty of the reflectance pulse oximeter is a large ring shaped backside silicon pn photodiode.

Cyber Glasses [99] as a novel type of low-cost computational glasses has three contributions: an integration of low-cost commercial off-the-shelf components, an adaptive data collection mechanism to optimize the system and a suit of energy efficient algorithms to reduce sensor data size and to extract meaningful human vision information to high level applications. This type of glasses is a long-term large-scale human visual health monitoring device attracting more and more attention.

Currently, wearable health monitoring systems are more likely to be based on smart textiles, wireless sensor networks and some daily items such as watches, glasses and rings. In general, there are different kinds of wearable devices on the markets, but the demand is increasing with the high quality of life. Thus, wearable medical devices will have a bright future in the world.

V. Commercialization Opportunities

The purpose of this review is to discuss opportunities and challenges of current WMMMS in order to make an outline for readers to learn more about the advantages and disadvantages of these approaches to improve and promote the current systems rapidly.

Because various medical diagnostic technologies lack mobility and telemetric protocol for patients, non-obstructive, high accuracy and comfortable health monitoring systems are urgently needed. The upcoming systems are expected to provide proactive personal health management and better treatment of various medical conditions. WMMMS are able to provide numerous excellent functions. These include remote access provision to medical facilities and specialists that supports mobility and continuity in medical monitoring and treatment. This will result in improving patient satisfaction through on-line viewing and self-management of the healthcare process. Additionally, it will also improve the quality of patient care by reducing medical errors through automated order entry and alerting systems. As a consequent, WMMMS will play an extremely important role in medical systems for their novel and obvious merits.

Today, the emergence of wearable devices happened in such a great speed is beyond our imagination, especially clothing based on textile material have a relatively high quality, high wearability and comfortableness to users. This can achieve a high degree of reliability due to guaranteeing good contact between the skin and the biosensors even when the subjects are in motion. Because of this large area of clothing, a variety of sensors can be implanted to monitor more physiological signals. Moreover, smart textiles bring more innovation and functionality than traditional ordinary textile, and they also have the potential to make people's daily life more comfortable and safety.

WMMMS have an increasing requirement of WSN that allow the data of a patient's vital body signals and movements to be collected by small wearable or implantable sensors. Communication is achieved by using short-range wireless communication techniques such as Bluetooth or low-power Bluetooth, Bluetooth combined with NFC, UWB and ZigBee for transferring the health status information from sensor nodes to processing platforms. WSN have presented a great potential trend in improving healthcare quality, ranging from ubiquitous health monitoring and computer assisted rehabilitation to emergency medical response systems. Furthermore, the security and privacy of patient-related data can be ensured through WSN. Now, wearable devices combined with mobile phone APPs are so popular in the markets. APPs are responsible for displaying measured values from distant wearable devices by WSN. Additionally, with the improvement in studies of pattern recognition and intelligent systems, WMMMS can take advantages of this technology to provide patients a better monitoring and more accurate data analysis. In short, a conspicuous trend that wearable devices using in medical health monitoring or sports, even in entertainment will also increase rapidly with the development of science and technology in communication systems.

However, there have been some issues that should be taken into consideration. A set of challenges will be required to be emphasized by further researchers in order to improve efficiency, interoperability, reliability, comfort and security. These challenges include technological barriers such as the limitation of currently available battery technologies and energy scavenging, security of private information transportation, further improvements in sensor miniaturization and efficiency. Additionally, these challenges also include cultural barriers such as standardization and cooperation at all levels and clinical validation. Importantly, some WMMMS are not as perfect as expected. For instance, the price is relatively so high that common families could not be able to afford it, and the precision of some devices cannot satisfy our needs leading to misdiagnoses. Although facing so many challenges, we also consider that WMMMS will be improved and their functions will be extended with more effort and resources are put into practical projects and research.

VI. Conclusion and Future Work

This review not only presents the state-of-the-art in research and development of WMMMS for health monitoring, but also emphasizes the wireless communication technology applications in textile and fabric clothing, such as smart vest and smart garments. Additionally, wearable wrist-worn devices such as smart watch and other type of devices are also introduced. Wireless communication technologies play an extremely vital role in WMMMS. Therefore, several short-range communication technologies are discussed and their applications are presented. Besides, the rapid growth of wireless technologies has extended worldwide into consumers' markets, resulting in a veritable explosion of lightweight, lower-cost and lower consumption portable devices such as PDAs, tablets, notebook and PCs. As a consequence, WMMMS have an access to make full use of the technology and opportunities to strengthen the products.

According to the research and projects that had been discussed, WMMMS have the potential to revolutionize healthcare by providing low-cost solutions for ubiquitous, real-time, unobtrusive mobile health monitoring. Importantly, they have a bright and promising trend to enable early detection and diagnosis in elderly patients with chronic diseases. An early detection will allow treatments to be rendered and this will help to save more lives. However, the current status of developing integrated, reliable, cost-effective and user-friendly wearable medical systems is far from the goal of "affordable, real-time, anywhere, high security and accuracy", and only a minority of the projects can achieve this goal. Clinical validation is also a significant component to realize the worth of these systems, but in fact, not all of them are used or applied to the public.

Sensors, battery and on-body hardware size tend to miniaturize as well as low power requirement serve as a powerful impetus to medical devices to be used widely. Textile integration modules is an efficient alternative approach, which has been adopted worldwide for promoting the high pace development in this field, and makes a huge contribution to most of the patients. Not only the textile and fabric items but also the WSN will make contributions to current wearable medical devices. Since 2004, the IEEE Engineering in Medicine and Biology Society (EMBS) has established a technical committee on wearable biomedical sensors and systems (WBSS) to raise awareness, which promotes excellence and encourages collaboration to progress R&D. In 2013, wearable markets equipment and design trend seminar was held in Shenzhen province, China [100]. The theme of this seminar was on wearable health and medical market development trend, the key components and system design strategy. We have already conducted the research on electrocardiography monitoring system based on wireless communication [101]. Therefore, IEEE Sensors Council should play a significant role in wearable medical monitoring systems based on wireless networks in the future.

Developed countries currently have a superior performance on wearable intelligent devices. But with the development of science and technology, developing countries may catch up and develop wearable medical monitoring devices that will contribute to improving the health care of the world population, particularly for vulnerable patients such as the very young and elderly. Besides, with the advent of the era of mobile Internet, cloud storage technology and Big data, smart terminal devices tend to mature. The use of algorithms to ensure that data can be used to accurately reflect the patient's physiological parameters will be a focus in the related area. Therefore, the research of algorithms on wearable medical devices will be a primary technology in the next step.

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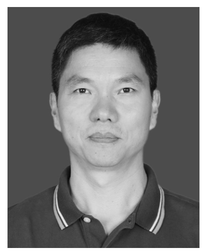

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