Health Technol.
DOI 10.1007/s12553-016-0171-1

REVIEW PAPER

A survey of remote patient monitoring systems for the measurement of multiple physiological parameters

K. Sruthi[1] · **E. V. Kripesh**[1] · **K. A. Unnikrishna Menon**[1]

Received: 5 May 2016 / Accepted: 12 December 2016

Abstract In rural areas, people die at their early ages because of lack of proper facilities and infrastructure for monitoring patient's health at the right time. Therefore, the design and development of a Remote Patient Monitoring System (RPMS) has a lot of significance in the scientific community and industry for the last few years. Nowadays, researchers give importance to wearable low cost RPMS which measure the body parameters in real time by using non invasive methods. This paper attempts to comprehensively review the current status of research and development of RPMS which measures physiological parameters continuously and sends the data to the healthcare professionals wirelessly in real time. The aim of this survey is to provide a reference for researchers and developers in this area to give direction for future research improvements.

Keywords Non invasive · Patient monitoring · Wearable system · Wireless

1 Introduction

Nowadays, progress in science and technology gives importance to the development of high performance monitoring systems with low cost, smaller size, high efficiency, high accuracy, etc. Many researches are focused on the design and development of RPMS to improve quality of human life, especially in rural areas. RPMS not only measures the physiological parameters, but also transmits the data in real time to healthcare professionals wirelessly [1]. This system is extremely useful for getting accurate and reliable information about body parameters and providing rapid access to health information. The general architecture of RPMS can be represented as shown in Fig. 1. Wearable RPMS consists of many wearable sensors which measure the physiological parameters namely Blood Pressure, Blood Glucose, Blood Oxygen level (SpO2), Pulse rate, Body Temperatures continuously. All the physiological data are processed using microcontroller and sent to a doctor's smartphone wirelessly for better health monitoring and analysis [2]. In order to avoid difficulties associated with monitoring parameters using conventional methods, non invasive methods are taken into account. There are many technologies available to measure vital parameters [3]. PhotoPlethysmoGraphy (PPG) based technology is one among these methods which is based on optical techniques. Blood volume changes in the arteries produce a proportional change in the light intensity transmitted or reflected through the very sensitive area of the body, such as finger tip, tongue, ear lobe etc. [4]. A PPG signal is obtained by passing an LED light through the body tissue [4].

Current research is going on the multi parameter monitoring system using Light Emitting Diode (LED) sensors such as Red, Infra Red (IR) Green, etc. and photo diodes. Sensors are fundamental elements of the RPMS which are designed to measure the body parameters accurately and reliably over a long duration. To achieve the benefit of wearable and continuous monitoring, the sensors should be small in size, low weight, low cost and transmission of data through wireless technologies. The battery life of the sensors should be long and low power technologies are preferred for long duration. Many attempts have been made with the development of small, wearable sensors over recent years [2, 3]. All the body parameters can be monitored using these wearable sensors [3].

✉ K. Sruthi
sruthik@am.amrita.edu

[1] Amrita Centre for Wireless Networks And Applications, Amrita School of Engineering, Amritapuri Campus, Amrita Vishwa Vidyapeetham University, Kollam, Kerala, India

Published online: 27 December 2016

Fig. 1 A block diagram representation of a RPMS

These sensors mainly help the healthcare professionals to monitor the vital signs of rural people who live in extremely remote areas. These RPMS helps to redefine the doctor patient relationships and reduce the healthcare costs. The PPG sensors are used to measure various parameters such as body temperature, blood pressure, blood glucose, blood oxygen levels, respiratory rate, and heart rate. Recent advances in optical technology have stepped up the use of high intensity green LED's for PPG sensors which makes the endorsement of non invasive measurement techniques [5]. Green light sources in PPG sensors reduce the motion artifacts compared to IR and red light sources [5]. The blood absorbs green lights better than red, IR light sources and it penetrates deeply into tissues. An example of PPG waveform is shown in [5].

The effective area on the body should be selected to get, the more accurate PPG signal. The finger tip, tongue, ear lobe, and nasal septum are common areas selected to get the PPG. Wrist type PPG sensors are also commonly used [4]. If the wearers do intense physical activities, motion artifacts will be added to the PPG signals. Many signal processing methods are introduced to remove these artifacts. Independent Component Analysis, Adaptive Noise Cancellation etc. are some of these methods [4]. Smart watches and smart wrist bands are the current emerging areas in heart rate monitoring using PPG sensors. Wrist based PPG signals are mostly affected by motion artifacts because of its large flexibility. A method based on singular spectrum analysis was proposed in [6] to remove these motion artifacts. The method presented in [7] has many advantages over [6]. The method in [7] develops the spectrum estimation of PPG and accelerometer signal into a Joint Sparse Signal Recovery Model.

PPG sensors can be used in two modes: transmission and reception. In transmission modes, LED and photo detector are placed on two sides of the body parts like finger tip, earlobe, etc. The transmitted light from LED is absorbed by the photo detector and the measured intensity will give the vital signs. Lower accuracy is expected from the use of non-invasive methods [8]. Researchers are looking into the development of sensors with high accuracy for non invasive methods [3, 9–11].

2 Wearable sensors in Rpms

Research in RPMS is emerging in response to the increased healthcare needs of an aging population, new wireless technologies, and better monitoring technologies, thereby decreasing healthcare resources, and reducing healthcare costs. It is specified in [12] that multi parameter monitoring is the second largest shareholder in the global market. According to Kalorama report, hospitals, home health care facilities and nursing homes will hold remote and wireless patient monitoring devices, to transmit patient data between different locations using wireless networks [13]. Advanced RPMSs are focused on utilizing the recently introduced technologies MEMS, flexible electronics, etc. in the development of wearable sensors. Current research in RPMS looks forward to minimizing the size of the system.

The development of the MEMS sensor technology has considerably reduced the size of RPMS. Furthermore, it has contributed towards the development of miniaturized, portable, disposable and wearable sensors that have the advantages of low power consumption and long duration [14–16]. MEMS system is used to design and make integrated mechanical systems by using micro fabrication techniques [16]. The development of MEMS has created a strong relationship between biology and electronics. In depth analysis of the applications of MEMS technology has been given in [14].In biomedical application, this technology is mainly used for the fabrication of sensors. Piezo electric, capacitive, electromagnetic, and piezo resistive principles are adopted as the techniques for the sensor fabrications [17]. Recently, many MEMS based sensors are available for healthcare applications. A Bio MEMS sensor for the detection of C-Reactive Protein (CRP) in the human blood is given in [17, 18]. [18] proposed a system which helps to measure the CRP level in the blood. CRP gets increased due to infection in the body which leads to cardiovascular diseases and heart attacks. A Fluorescence based bio-sensing technique is used to sense the CRP. A micro cantilever is fabricated using micromachining technology in order to detect the diseases related to CRP. Gold and chromium layers are deposited on the cantilever. Self

assembled molecules are injected to the sensor. Finally, the application of anti CRP adheres the sensor to the cantilever. The deflection of the cantilever due to the interaction of CRP and anti CRP measured optically. Detection of glucose using MEMS sensor is also reported [17]. A membrane based MEMS sensor that can reject the environmental disturbances and measures the glucose concentrations effectively and accurately has been presented [19]. A differential MEMS affinity glucose sensor which uses a bio compatible glucose responsive polymer is proposed. The design of the sensor is based on a sensor solution and a reference solution that are situated in different chambers. The sensing chamber is filled with a polymer solution and reference chamber with a polymer that does not bind with glucose. These two chambers are conserved with a semipermeable membrane. When glucose permeates through the membrane, the viscosity of the polymer solutions increases and diaphragm vibrates. The vibration of the diaphragm is detected by a capacitive technique and converted into a glucose level.

In paper [20], a prototype of a healthcare monitoring system which consists of two MEMS pressure sensors is reported. Each of these sensors is placed in adjacent points of various part of the body like wrist, neck etc. with a separation of 20 mm. Usually, the body area where the arteries are very close to the skin are selected. The blood pressure waveforms from these two sensors are used to detect the pulse wave velocity and derive the blood pressure more accurately. The data are sent to smartphones and laptops wirelessly. The design of the silicon coated MEMS sensor based on piezo resistive technique is presented in [20]. The prototype of the sensor is developed in dimensions 0.6 mm × 0.6 mm. In order to get the proper functioning, various layers of hard and soft silicon are used for the fabrication. Hard silicon is applied to protect the bond wires and soft silicon is applied to provide an efficient blood pressure waveform transmission path. The measured waveforms are recorded by a data functioning unit.

Flexible electronics is another field which helps to reduce the size of the RPMS. Design of flexible and stretchable sensors to monitor multiple parameters has been reported in [21]. The design of the fingertip as well as wrist based sensors is an ideal platform for the flexible electronics. Wearable devices with flexible sensors can act as an excellent terminal in the health care field to interact with the patient to collect the vital signs for remote monitoring. Furthermore, flexible electronics can make the wearable device very close to the skin and measure the parameters conservatively. Technology associated with flexible electronics makes the device thinner, lighter and flexible. Through the size miniaturization of this technology, power consumption of the device can be essentially reduced, thereby smoothing long term monitoring and simplifying its use.

In reference [22], the design and fabrication of a flexible wireless bandage using a custom oxygen sensor for the continuous monitoring of chronic wounds has been presented. Monitoring of oxygen levels is significant as it is a crucial factor for wound healing. The smart bandage is fabricated using a 3D printer. The 3D model of smart bandage is given [22]. Tango Plus FLX930 material is used for fabrication of the bandage. The oxygen sensor is placed on the bandage. In between, Hydrogel is used as an epidermal layer which allows the oxygen to easily diffuse and reach the oxygen sensor. The oxygen sensor is an electrochemical galvanic cell implemented on Parylene-C. Galvanic cell formation is by using silver and zinc electroplated electrodes and 0.1 M Potassium Hydroxide gel saturated on a filter paper electrolyte. A thin layer of PDMS is used as the oxygen solution membrane. Galvanic cell produces current proportional to the reduced oxygen at the cathode. The fabrication process of this oxygen sensor is also given in [22]. To acquire data from the sensor, an electronic read system has been provided. This system consists of programmable gain analog front end (LMP91000), which generates analog voltage from the oxygen sensor output, an Arduino Lilypad micro controller, which processes the output of analog front end and relayed to XBee radio through which the data sent to doctor's Personal Computer. These data also uploaded to a server for truly remote access by the doctor. The interaction between the patients in rural areas and doctors in the hospital are carried out by using different wireless technologies.

3 Wireless technologies

A lot of research has been developed in the area of RPMS using advanced telecommunication technologies. Wireless health monitoring requires a highly reliable network access at any time. For data communications, both short and long range wireless communication technologies are adopted [23]. RPMS usually use Blue tooth, Zigbee, Wi-Fi, and UWB technologies for short range communications and GSM, GPRS, CDMA, CDPD, and email based communication [24] for long range communications. In this section, the current technology and advances in short range communications using Bluetooth and Zigbee module are discussed.

3.1 RPMS based on bluetooth technology

Bluetooth is the most popular and widely used wireless technology. Incorporating Bluetooth technology in RPMS makes analyzing vital signs of a patient more convenient and easy. Advancements in Bluetooth technology like BLE is promising in RPMS which offers a much lower power consumption communication platform. Many useful and interesting Bluetooth enabled RPMS architectures and prototypes have been developed earlier and advanced research works are going on in developing new architectures and prototypes. This section presents some of the available architecture of Bluetooth enabled RPMS. General architecture of Bluetooth enabled patient monitoring system is shown in Fig. 2.

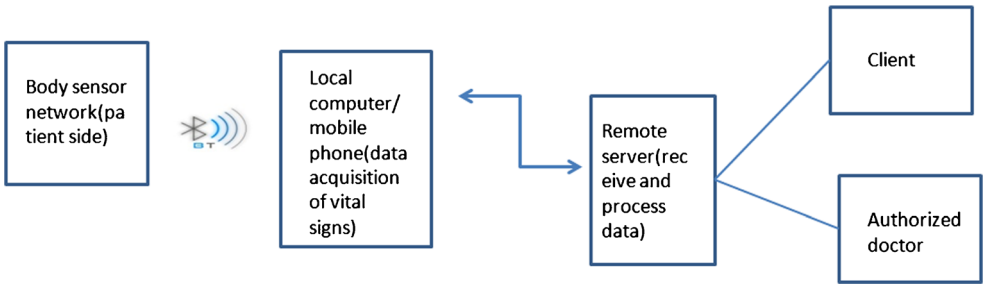

Fig. 2 General architecture of bluetooth enabled RPMS

The patient is surrounded by or attached with sensors to collect patient's vital information viz. blood pressure, SpO2, glucose level, heart rate, body temperature etc. Then it is send to local computer or mobile set via Bluetooth. This arrangement is convenient to patients so that they can do their daily activities with ease. A local computer or mobile upon receiving a request from a server (or automatically in case emergency) transfers data to a server that can be monitored by an authorized doctor through GSM, GPRS etc. Secure data transfers should be ensured for keeping the patient's data private.

Reference [25], describes a low cost, secure portable system with wireless transmission capabilities for the acquisition, processing, storing and real time visualization of the patient's vital health parameters **(**e.g**.** heart rate, oxygen saturation in blood) to a mobile phone or a PC. Here mobile is used to send real time secure data to server (emergency server in case of emergency) via Bluetooth. The server will process the data received. Security is ensured by encoding and decoding at the sender and receiver side respectively. Message integrity and confidentiality is maintained by using hashing function Hash Message Authentication Code (HMAC) and symmetric encryption authentication respectively. Reference [26] describes a two-way wireless communication system between patient and doctor. The system provides two approaches: one in which mobile phone is used to transfer vital signs to local computer via Bluetooth and other uses a Personal Digital Assistant (PDA). In the first approach, data is sent through internet and mobile phone technology (SMS) instead of internet which is used in second one.

The system not only allows the doctor to monitor patients but also to consult with other doctors. Drip infusion remote monitoring system implemented in the hospital in [27] serves to monitor the patients in the sick room continuously without continuous involvement of a doctor or a nurse. The system consists of infusion monitoring devices and a central computer. Each of the infusion monitoring devices records the count of drops, the infusion rate and the state of drip which are sent to the central computer upon request. The central computer displays data for monitoring by nurses or doctors. An embedded hardware solution model with two processors presented in [28] uses FPGA and Bluetooth as its principle component. The analogue ECG signal is handled by a 12 ADC with a 1KHz sampling rate which provides reliable copy of original ECG. The converted data is then stored in FPGA internal memory which responds to the Bluetooth module upon request. Incoming data from the Bluetooth module will be analyzed by a remote PC with simple software created in Lab Windows that controls the Bluetooth Data will subsequently be printed on a screen.

An improved and innovative version of a Bluetooth enabled patient monitoring system has been presented in [29] by the inclusion of Near Field Communication (NFC) technology. NFC technology transmits data at high speed of up to 424 kbps over very short distances of up to 10 cm. It enhances the user's experience of applications that use the Bluetooth technology. It also simplifies the discovery process by eliminating the Inquiry process by providing the Bluetooth address and other optional parameters related to a specific Bluetooth-enabled device for smooth wireless user experience. NFC can also simplify the process of authenticated pairing between two Bluetooth devices by exchanging authentication information over an NFC link. The architecture of the above system is shown in Fig. 3. Bluetooth Low Energy (BLE) is another promising technology for developing low power and secure patient monitoring systems. [30] describes the advantages of BLE technology over other available technologies. BLE seems to consume less power compared to other technologies like Zigbee, NFC etc. As Bluetooth finds many applications in patient monitoring systems, number of Bluetooth enabled products are now available in market recently. GlucoTel(Body Tel) is a Bluetooth 4.0 enabled blood glucose meter that transmits measured values to a smart phone or tablet(Android or iOS). Body Tel apps can receive measurements from connected vital sensors and provide an easy way to add additional information to the patient file. The Body Tel devices also include a blood glucose meter, a blood pressure meter, and scales with built-in Bluetooth modules that automatically send readings to the user's home base station or cell phone. The station then forwards the data to a secure online database using a protected internet connection. 9Solutions IPCS is another Bluetooth enabled device that enables real time tracking of patients. The device can also save personal activity profiles for each user and if any differ too much from the user's long-term activity, it can automatically send an alarm to caregivers.

Even though Bluetooth enabled patient healthcare devices are advantageous, some tradeoffs are associated with these

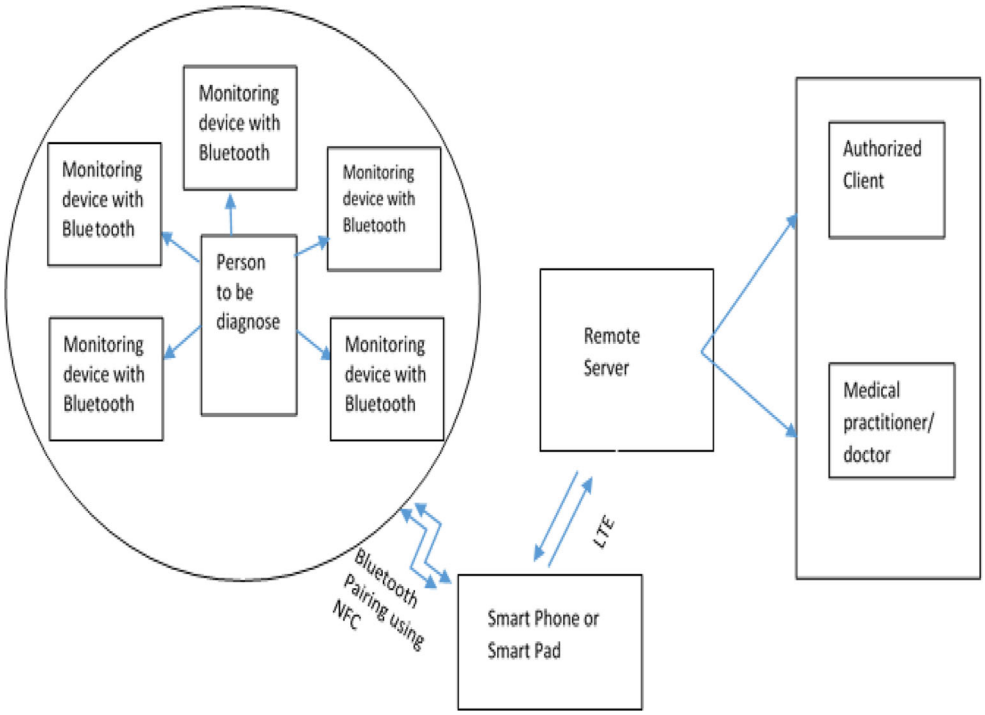

Fig. 3 u-Health environment

systems. One major issue is the electromagnetic compatibility problems that might arise between other medical equipment used today [31]. Also, the relatively short transmitting range (10 m) might be a problem if the patient moves. Since Bluetooth modules rate of transferring data is too slow, transferring large data might cause problems [31]. Another major issue is secure data transfer must be ensured since medical data is vital and any modification in data would produce disastrous results. Also, Bluetooth is vulnerable to interception to some extent [32]. Initial inquiry process is the weakest part since it takes place over an unencrypted link. Also, an attacker could assemble a list of commonly used BD_ADDR which allows the attacker to change the BD_ ADDR of Bluetooth module. [32] also describes some of the reported attacks on Bluetooth security: (1) MAC spoofing attack, (2) PIN cracking attack (3) Man in the Middle Attack, (4) Blue Jacking Attack, (5) Blue Snarfing Attack, (6) Blue Bugging Attack, (7) Blue Printing Attack, (8) Blue over Attack, (9) Off line PIN recovery Attack, (10) Brute Force Attack, (11) Reflection Attack, (12) Backdoor Attack, (13) DOS Attack, (14) Cabir Attack, (15) Skulls Worm Attack, & (16) Lasco Worm Attack

3.2 RPMS based on zigbee technology

Zibgee is another widely used wireless technology and finds applications in today's patient monitoring systems. Zigbee enabled patient monitoring systems follow similar architecture as shown in Fig. 2 and described in section 3.1. There will be an array of sensors attached to the patient's body to measure vital signs which will be transferred to a local computer through Zigbee. The local computer then transfers the data to the remote servers which can be then analyzed by an authorized doctor or client. ZigBee, [33], is an open standard technology to address the demands of low-cost, low-power WMNs via short range radio and targeted at RF applications that require a low data rate, long battery life, and secure networking. The ZigBee devices can be combined with WWANs to achieve a seamless platform of wireless patient monitoring.

Reference [33] describes a reliable, cheap, low powered, and accurate system that can be worn on a regular basis and monitors the vital signs based on Zigbee technology (IEEE 802.15.4). The system monitors the heart rate and temperature of a human body and also detects whether a patient is distressed or not while receiver units plot the graph of measured physiological parameters. This wireless body sensor network mainly utilizes temperature sensor, heart beat sensor to measure vital signs of patients in hospitals or in their homes and Matlab based window is used plot it graphically. Heartbeat is measured using a combination of high intensity type LED and photo-diode. The change in volume caused by the pressure pulse is detected by illuminating the fingertip's skin with the light from an LED using a photodiode sensor. A novel low cost patient monitoring system is implemented in [34] helps in detection of medical distress which does not necessitate pressing any panic button. The system which takes several inputs from the sensors are integrated and processed and are sent through the XBee Module to a host computer, which stores the data into an Access Database. Graphical User Interface (GUI) displays the values and an alarm may be generated if there is

medical distress. Beat per minute (BPM), body temperature, and impact (in both axes) are given on the display. The system proposed in [35] provides a continuous patient monitoring system that transmits the acquired data to a centralized ARM server using Wireless Sensor Networks. A Zigbee node which consumes very low power and is small in size is connected to every patient monitoring system. The data of all patients is stored in a common database and is accessible to doctors through a mobile device for convenience. In case of an emergency situation, such as falling or in an inactive state for more than the allotted time, the host computer automatically alerts the situation to the care staff by an alarm sound and sends a message to the doctor through a GSM module. Reference [36] proposes a similar mobile multi patient monitoring system for low power consumption with minimal circuit components intended for a small packet and long distance range applications that typically consist of a low power processor with minimal resources and interface capabilities. A conservative transceiver in the system is capable of transmitting 8 bytes of data at a time and has a moderate transmitting range of about 130 m. A temperature sensor, heart rate sensor, MEMs sensor and saline level sensor for measuring temperature, heart rate, detection of fall and the saline level are included in the system. [37] makes use of WBANs which promise to revolutionize health monitoring. The system uses medical sensors to collect physiological data from patients and transmit it to Intelligent Personal Digital Assistant (IPDA) using ZigBee/IEEE802.15.4 standard and to medical servers using 3G communications. The novelty of the system is the priority scheduling and data compression. Thus, transmission rates of critical physiological signals are increased which in turn improve the utilization of bandwidth and extends the life time of a hand-held personal server by reducing power consumption during transmission. The system proposes a networking solution in which a Medical Super Sensor (MSS) is used to collect multiple physiological signs sensed by each of the body sensors in WBAN and forward them to a personal server such as IPDA, to prioritize the transmission of collected data based on a patient's current condition and data content.

[37] presents advantages of Zigbee over other technologies. Compared to Bluetooth which supports a maximum of seven sensor nodes, Zigbee has a capability of handling large sensor networks up to 65,000 nodes. Zigbee provides low power consumption, low cost technology, supports a maximum of 250 kbps using Industrial, Scientific and Medical (ISM) free band i.e. 2.4 GHz and offers reliable data transfer. Therefore, ZigBee is adopted to transmit physiological signals from WBAN to the patient server. ZigBee provides a low power hardware encryption solution using Advanced Encryption Standard (AES 128) to encrypt data transmitted between MSS and a personal server since patient information is vital. Zigbee is highly scalable for many devices and provides interoperability between a variety of medical and non-medical devices.

The above advantages of Zigbee make it a favorable technology in patient monitoring systems and is used in many health care devices. IPCS ID-Badge, uTag, and Asset Tag of 9Solutions are Zigbee enabled devices are indoor positioning computing system, which can track and monitor locations of the wearer based on an array of wireless technologies such as Zigbee, Bluetooth etc. Zypad WL1500 is a Zigbee enabled wearable computer that gives the user access to instant computing capabilities without sacrificing mobility. It runs on Windows with a 128 GB hard drive and a Marvell PXA320 processor and has USB ports and Micro SD slots.

Some tradeoffs are also associated with Zigbee which make them inferior to other technologies. Since most of the handheld devices or mobiles do not support Zigbee, use of Zigbee is limited in many applications. Zigbee provides a low bandwidth of 250 kbps which results in four times the latency of BT-LE. Furthermore, low market penetration makes Zigbee inferior to BT-LE.

4 Conclusion

The paper is an overview of the literature reported on the technologies for Remote Patient Monitoring System (RPMS). These RPMS collect physiological parameters from the patient's body and send them to the smart phone of health care professionals. Research in this area has led to the development of many light weight, high efficiency, commercial products to monitor physiological body parameters. Current developments in the area of wearable sensors and wireless technologies have been reviewed in this paper. The challenges faced by the current system will be addressed in the future devices. The performance of the RPMS can be optimized using different wearable sensors and wireless methods for the improvement of the quality of human life.

Acknowledgements We are immensely grateful to our beloved Chancellor Shri. (Dr) Mata Amritanandamayi Devi for her inspiration and Motivation.

Compliance with ethical standards

Ethical approval This article does not contain any studies with human participants or animals performed by any of the authors.

Conflict of interest Author Sruthi k declares that she has no conflict of interest.

Author Kripesh E V declares that she has no conflict of interest.

Author K A Unnikrishna Menon declares that she has no conflict of interest.

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