REVIEW OF SENSORS FOR REMOTE PATIENT MONITORING

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ABSTRACT
Remote patient monitoring (RPM) of physiological measurements can provide an efficient method and high quality care to patients. The physiological signals measurement is the initial and the most important factor in RPM. This paper discusses the characteristics of the most popular sensors, which are used to obtain vital clinical signals in prevalent RPM systems.

The sensors discussed in this paper are used to measure ECG, heart sound, pulse rate, oxygen saturation, blood pressure and respiration rate, which are treated as the most important vital data in patient monitoring and medical examination.

KEY WORDS
Bio-sensors, Remote patient monitoring, Physiological measurement

1. Introduction

The application of Remote Patient Monitoring (RPM) technology enables healthcare organizations to remotely monitor and manage the elderly and patients injured or with chronic diseases such as congestive heart failure, diabetes, chronic pulmonary disease and asthma [1]. With RPM, healthcare organizations can reduce costs, improve patient care, and increase access to patients living in remote areas.

Generally, a monitoring process may be divided into three parts, namely measurement, analysis and interventions [2]. This review will focus on the first part, measurement, and evaluate common sensors, which are used for gathering information for remote patient monitoring.

Many type of sensors have been developed, which can measure a variety of bio-signals. For example, electroencephalograms (ECG), pulse rate, body temperature, blood pressure, oxygen saturation, respiration rate, pain scale, glucose, intracranial pressure and so on. This paper will only focus on the development and characteristics of sensors used to measure heart rate (pulse rate), blood pressure, oxygen saturation and respiration rate and evaluate their capabilities in measuring physiological signals to support remote patient monitoring.

It should be mentioned that some of tables in this paper indicate the characteristics of the sensors as well as the parameters that they can measure. Due to the variety of the sensors produced by different manufacturers the tables show the range of measurements which could be extracted from their data sheets.

2. Heart Monitoring Sensors

In September 2005, WHO (World Health Organization) warned that about seventeen million people died in heart disease around the world [3]. It is obvious that heart monitoring is one of the extreme important elements in patient monitoring in order to save people.

In traditional medicine, heart examination and monitoring is carried out by a stethoscope, through which medical personnel may listen and examine patients' hearts and make decision based on his/her experience.

However, in 2003, Budinger [4] expressed that heart rate may be measured by electrical waveform, pulse oximeter, heart-rate chest strap, ultrasound doppler, pulse pressure detection, and electromagnetic flow. This paper will only focus on the most four popular methods, ECG, heart-rate chest strap, heart sound measurement and oximeter, since these widely used in RPM.

2.1 Electrocardiograph (ECG)

ECG is primarily a tool for evaluating the electrical events in a heart [5]. It is an electrical recording of the heart and is used in the investigation of heart disease. Shnayder *et. al.* [6] indicated in their paper that the most prevalent ECG type involves the connection of 12 leads to a patient's chest, arms and right leg via adhesive foam pads. The device records a short sampling (not more than thirty seconds) of the heart's electrical activity between different pairs of electrodes (normally 3 to 10). Each pair of leads provides a unique and detailed picture of the cardiac rhythm by detect the change of electrical energy and referenced to a ground signal.

The electrode patches, which can be treated as sensors, are a solid silver/silver chloride gel on a foil backing, which enable the electrode to stick to the skin surface. A minimum of three electrode patches is required for each test subject and the position on arm, leg or ankle. After connection, a range of -200uV—1800uV waveform can be shown on the linked PC or electrocardiograph. Typically, ECG signals detected by the electrode are very weak with amplitude of about 1 to 3 mV and a frequency spectrum of 0.05 Hz to 150 Hz.

By analysing signals from an ECG, an experienced cardiologist can diagnose a wide range of cardiac disease. However, Shnayder *et. al.* [6] indicated that in order to overcome the shortcoming of standard ECG traces, which only represents a short sampling of patient data, irregular or intermittent cardiac conditions, continuous ECG telemetry is employed in intensive care in some hospitals.

In 1999, researchers from Texas [7] show that 12-lead ECGs transmitted via wireless technology to hand-held computers is feasible and can be interpreted reliably by cardiologists.

Kho, *et. al.* [8] indicated that a full-lead ECG records is formed by 12 leads which are derived from 10 electrode locations. However, in some situations that do not need as much data recording, subsets of 12 leads ECG are used. For example, 2-leads ambulatory ECG and 1 or 2 leads intensive care at the bedside are also used in hospitals.

In term of building remote patients monitoring system, 1 or 2 leads are usually employed in order to reduce the cost of data transmission and increase flexibility. For example, Kho *et. al.* [8] employed only 2 leads ECG in their project named 'Bluetooth-enabled ECG Monitoring System' because of the accuracy and portability factors. Additionally, Lin *et. al.* [9] combined a two leads ECG with a PDA to build a PDA-based physiological monitoring system for patient transport and Yu *et. al.* [10] introduced another wireless physiological signal monitoring system, which include a one-lead ECG to acquire ECG signals.

However, in 1995, Haghighi-Mood and Torry [11] indicated a major disadvantage of using the ECG is that the timing between electrical and mechanical activities in a cardiac cycle is not exactly constant for all patients due to a variety of pathological conditions. Moreover, "the presence of a reference signal requires additional hardware that might not be readily available" [12].

2.2 Heart-rate chest strap

In addition to the patients who are in critical conditions, other categories of people may also require remote monitoring. For example, people with some degree of chronic disease may require regular exercises and monitoring. In 2005, Barrett [13] introduced a chest-strap monitor, which is now one of the most frequently used method by athletes and individuals in exercise conditioning programs, in his overview of patient self-management.

A chest-strap transmits heart rate signals collected from across the chest by an electrode that picks up the potential differences. The signal is then detected by a wrist-mounted device as well as electronic receivers in exercise equipment (e.g., treadmills, bicycles). Some of the models can upload reading into laptops or PCs for longitudinal record-keeping and cardiac health analysis. The chest strap is always used by heart diseased patients who need to control their weights and have to do exercises [13]. Therefore, it qualifies as self-management tool.

A common heart-rate chest strap monitor has the maximum receiver distance limit of 200cm [4] and the transmitter works in the range of 4.8-5.6 KHz. Since normal heart rates vary according to people's age (for example, typically Max=202 beats/min for a 12 years boy and Max=198 beats/min for a 18 years old man), the monitor normally outputs a figure to indicate the maximum heart beat and a safe heart beat for different ages or may display percentages of maximum heart rates.

Using similar fundamentals of heart-rate chest straps, piezoelectric sensors have been integrated into wrist straps or watch to monitor patient's pulse rates. This increases the mobility of patients.

2.3 Heart Sound Measurement

A study by Anand [14] showed that diagnosing heart disorders on the basis of heart sound has a long history. However, the study showed that the application of cardiac sound analysis rapidly decreased since the 1970s. This is due to the development of the techniques on the cardiologic echocardiography and cardiac catheterization or percutaneous coronary intervention, which provide a closer and accurate examination. However, the interpretation of the heart sound is always thought to be subjective. The interpretations of heart sound heard by the doctors have been different from one doctor to another and this is mainly based on one's expertise and experience.

In recent years, the development of computer hardware and digital signals processing techniques has made it possible for the cardiac sounds to be easily recorded and analysed. Hence, many researches concentrated on how to help the cardiologist to improve accuracy of diagnosis. Most of these researchers [15][16][17][18] concentrated on using frequency analysis method to extract heart sound characteristics. Others researchers [19] focused on noise cancellation by employing adaptive filters to extract a more accurate and clear heart sound.

In heart sound monitoring, the heart sound is first acquired and recorded using an electronic stethoscope or microphone, which has the capability of transferring these signals to the nearby workstation. The signals are then analyzed by a computer. Javed *et. al.* [20] presented a signal-processing module for the analysis of heart sounds, which segments the received signals into individual cycles and components using spectral analysis of heart without using any reference signal like ECG.

Oximeters can also be used to monitor heart by measuring pulse rates. However, the main function of an oximeter is to measure oxygen saturation, therefore it will be discussed in a later section. Moreover, due to the large variety of heart monitoring sensors, only the most popular types are discussed. More information about relevant sensors could be found in the book: Biomedical Engineering Handbook [21].

3. Oximeter

Oxygen saturation is normally reflected in the amount of oxyhemoglobin in the circulating blood. Oxygen level is a variable of major importance for acute patient monitoring in hospitals, at the scene of accidents, and in effective sub acute monitoring for home care [4]. The simplest method to measure oxygen saturation is pulse oximeter, which involves the projection of infrared and near infrared light through blood vessels near the skin.

Pulse oximeter has been in use as a medical diagnostic technique since its invention in the early 1970s [22]. This non-invasive technology is used to reliably examine two key patient health metrics: heart rate and blood oxygen saturation. These parameters yield critical information, particularly in emergencies when a sudden change in the heart rate or reduction in blood oxygen saturation can indicate a need for urgent medical intervention. With the advance warning, patients could get treatments to avoid hypoxemia before they manifests physical symptoms [6].

Pulse oximeters typically incorporate a plastic housing, which contains an array of LEDs and an optoelectronic sensor opposite. By detecting the amount of light absorbed by haemoglobin in the blood at two different wavelengths (typically 650nm and 805nm), the level of oxygen saturation can be measured. In addition, heart rate can be determined from the pattern of light absorption over time, since blood vessels contract and expand with the patient's pulse. Computation of heart rate and SpO2 from the light transmission waveforms can be performed using standard digital signal processing techniques.

In clinical situations, highly precise arterial oxygen saturation (SpO2) measurements are commonly obtained using transmittance pulse oximeters [23]. However, the application site of them is limited mainly to the peripheral tissue, such as the fingertip, ear lobe, or toe. Alternately, a reflectance oximeter can measure SpO2 from various parts of the body, especially from other body regions such as the forehead, cheek, wrist, etc [4]. In 1998, Nogawa *et. al.* [24] conducted an experiment on a reflectance oximeter and concluded that there was a linear relationship between the reflectance ratio and SpO2. The reflection pulse oximeter can be applied to various locations of the body in the hospital and home care scenarios to aid in the early diagnosis of cardiopulmonary as well as peripheral circulatory disorders.

Recently some PDA-based oximeters [9] became available for emergency care. Some self-displayed pulse oximeters have also been developed for patients' self-management. These devices can measure and displayed heart beat and oxygen saturation. The following table shows the capabilities of both self-displayed oximeter and cable-based types (including PC, PDA and special device-based oximeters).

Type	Self-display	Cable-based
Parameters	Oxygen saturation (SpO2) and Heart hate (beat/min)	
Output method	Self-display	Display on the adjacent Device
SpO2 Range	Reliable : 70 to 99% (Typically)	
	Normal condition: 97% -99%	
Pulse Rate Range	30—235 beats/min (Typical)	
Continuous monitoring	Depend on batteries' life	Yes
Condition analysis capability	Poor	Powerful
Suitable application	Normal condition self examine	Long period patient monitoring
Factors that affect validity	Environment temperature, motion, dirty sensor, nail polish, low blood pressure etc.	

Table 1 - Capabilities of Oximeter [22][23][24][25]

However some pulse oximeter sensors cannot function on patients with finger nail polish or nail fungus. Additionally, Gao *et. al.* [25] indicated that in cold temperatures and/or high altitudes, the body often responds through vasoconstriction in the peripherals. In this case, blood flow to the fingers is restricted and pulse oximeter may not provide accurate readings. Furthermore, Hakemi *et. al.* [26] indicated that hypotensive systolic blood pressure readings of less than 80 mmHg may cause inaccurate and unreliable pulse oximeter readings.

ECG, heart rate chest strap, heart sound sensor and oximeter are four types of prevalent devices which are currently used to measure heart signals. The heart rate chest strap and oximeter measure and display hear beat, whereas ECG and heart sound sensor can provide more information about the heart condition.

Table 2 provides a comparison of characteristic of these sensors in respect of RPM systems.

Sensors	Advantages	Disadvantages
ECG	More information about heart activities provided for analyse	Reference signal might not be readily available [12], operation skill needed
Heart Rate Chest Strap	Once on, less bothersome. Flexible, comfortable [13]	Can be affected by interference from electromagnetic radiation
Heart sound sensor	Traditional, reliable	Difficult to cancel noise caused by various reasons
Oximeter	More parameters output Easy fixed	Decreased perfusion causes error result. Effected by blood pressure, bright light, temperature [25]

Table 2 Comparisons heart monitoring sensors

In respect of accuracy, convenience and the operation skills required, it can be concluded that ECG and heart sound sensor suit patients in hospitals or ambulances who need long period of healthcare and monitoring. Oximeter could be utilised in homecare or self examination. Heart rate chest straps would be more suitable for patients with some flexibility in movement while being monitored.

4. Blood Pressure Sensor

In 2003, Hajjar and Kotchen [27] stated that an estimated 50 million Americans, which is about 25% of all adults, have high blood pressure. In addition, a worldwide prevalence estimated from WHO in 2002 pointed out that there may be as much as 1 billion individuals suffer from hypertension, and approximately 7.1 million deaths per year may be attributable to hypertension. Therefore, blood pressure is another vital clinical parameter, which usually been used in patient monitoring.

In 2003, Budinger [4] have expressed five non-invasive methods for measuring blood pressure: auscultation, palpation, flush, oscillation, and transcutaneous doppler. It was also suggested that among these five methods, only the oscillometric and transcutaneous doppler can be adopted in remote monitoring by incorporation of sensors for pressure oscillations or doppler shift in the pressure cuff around the wrist or finger.

General blood pressure sensors used in clinical are designed to measure systolic and diastolic blood pressures utilizing the oscillometric technique. A typical sensor includes a standard adult size adjustable cuff (typically 25 to 40 cm), a pump bulb and a pressure transducer.

Brachial artery blood pressure monitoring devices using wireless telemetry have also become available for remote monitoring [4]. However, lightweight sensors should be considered to increase mobility and comfort for long-time monitoring.

In current market, wrist or finger- applied blood pressure monitor, which are portable and user-friendly, are provided. These devices include a memory storage that makes recording measurements easy. While working, the wrist cuff inflates and deflates automatically. More relevant information about these kinds of products could be found in [4]. Although these devices have been proven clinically accurate, they do not include communication capability.

In 2004, IBM researchers working with medical devices and mobile-phone handset manufacturers have created prototype track blood pressure. These new prototypes build on the existing devices resemble large wristwatch to measure blood pressure, then transmit data via Bluetooth to a mobile phone through which to an Internet portal, and so to the medical personnel monitoring the patient [28].

Although, the prototype hasn’t brought up products to the market yet, it could be argued that the home-care potential of these devices will increase when the information can be recorded remotely and transmitted to caregivers through some communication systems.

Table 3 shows the specifications of typical blood pressure sensors. The data, which show main capabilities of blood pressure sensors, is extracted from several manufacturers’ data sheets.

Calibration (mm Hg)	Slope 56.11 (mm Hg/V) Intercept 0.00 (mm Hg)
Pressure range	0 mm Hg to 250 mm Hg
Maximum pressure without permanent damage	1030 mm Hg
Typical accuracy	± 3 mm Hg
Temperature Compensated	0°C to 50°C
Combined linearity and hysteresis	Typical ±0.2% full scale
Response time	100 microseconds

Table 3 Blood Pressure Sensor Specifications

5. Respiration Rate Sensor

Respiration is one of the most valuable signals for patient monitoring, while the importance of it in the assessment of a patient’s condition has been, until recently, largely under emphasized [29].

In 1973, Cooley and Moser [30] pointed out that monitoring respiratory rates is ostensibly a simple task. The sensor needs to be neither linear nor accurate, but rather merely capable of recognizing respiration as such.

The following provides information on respiratory rates and some of the sensors currently used for their measurement:

1. Brady *et. al.* [31] stated that a pneumotachograph can be used to measure respiratory rates by detecting the rate of airflow to and from the lung. While using this clinical apparatus, the patients need to wear a head-mounted breathing tube. This type of sensor has an advantage that it can provide detailed information on volume and direction of breath. However, it is too big to be employed in a portable RPM system.

2. A plethysmograph was also introduced by Brady *et. al.* [32], which can be used to record breathing rates by measuring volume changes around the chest to determine lung capacity. However, though sophisticated, these devices require hard-wired interconnections to external equipment and cannot be used outside a specialized clinical environment.

3. In order to provide comfortable measurement, some researchers [31][32][33] investigated a wearable sensor, which is used to measure breathing rate by combining wireless with wearable technology. It is a foam-based polypyrrole sensor. The sensor responds to compression of the foam substrate through increases in conductivity. Compression and relaxation of the foam sensor occurs repeatedly due to the movement (expansion and collapse) of the chest wall during respiration. The sensor was tested with a range of 10-40 breathes per minutes and shown a satisfied performance.

However, this kind of wearable sensor has some limitations. One is that the careful sensor placement is important for the quality of data gathered, since the position is crucial to their sensitivity. Additionally, the presence of movement during the monitoring phase may insurer incorrect result [33]. But the potential of this kind of sensor should be realized, since it is wearable, mobile, and offer user much personal convenience [32].

4. Another approach was proposed by Johnston and Mendelson [34] in 2004, for extracting breathing rate information from a wearable reflectance pulse oximeter sensor. The feasibility of extracting accurate breathing rate information from a photoplethysmographic signal was demonstrated. A pulse oximeter sensor mounted on the forehead is used to record photoplethysmographic signal. The signal can then be processed by a simple time domain filtering and frequency domain Fourier analysis in order to extract breathing rate.

As it was mentioned earlier, respiration rate is one of the most valuable signals for patient monitoring. Though there is not enough attention has been paid on that while developing RPM technology. The reason may be the devices for measuring respiration rate has no satisfied motilities. While if the outcome of research on extracting breathing rate information from a wearable reflectance pulse oximeter sensor could be demonstrated reliably, it will surely bring out many benefits. It is worth pointing out that an oximeter can measure three parameters, namely, oxygen saturation, pulse rate and respiration rate.

6. Conclusion

Remote patient monitoring (RPM) has the potential to reduce the cost of caring for patients while enhancing healthcare quality. Accurate and timely measurement and analysis of clinical parameters such as heart rate, oxygen saturation, blood pressure and respiration rate are vitally important in remote patient monitoring. Popular sensors used to obtain this information have been discussed and evaluated in this review.

The sensors discussed can be used to monitor patients' heart, capture oxygen saturation, blood pressure and respiration rate.

In respect of heart monitoring, ECG, heart-rate chest strap, heart sound sensor and pulse oximeter are the most prevalent sensors. Characters and limitations of these sensors were discussed. Amongst these sensors, oximeters are capable of providing two types clinical information: pulse rates as well as oxygen saturation. Two types of oximeters, namely self-display and cable-based, were compared and evaluated. In addition, a recently developed blood pressure sensor was also discussed. Finally, to measure respiration rates a foam-based polypyrrole sensor system was discussed. A possible approach for extracting breathing rate from pulse rate using a pulse oximeter was also explored.

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