# Monitoring of Vital Signs in the Home Environment: A Review of Current Technologies and Solutions

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Abstract: Vital signs measurement is key for monitoring and controlling the health of patients in the home environment. Parameters such as body temperature, heart rate, blood pressure, respiratory rate, oxygen saturation or blood glucose reflect the state of essential functions of the human body. Deviations of some of these parameters may indicate illness or worsening of the patient's condition. Nowadays there are different devices that allow the measurement of the main vital signs, in this article the measurement technologies as well as the main medical devices are reviewed. Many of these devices are not suitable for simultaneous monitoring of several vital signs so the patient is required to handle a multitude of devices. Therefore, a review of new monitoring device concepts that combine more than one vital sign and do not interfere with the day-to-day life of patients is carried out.

## 1 INTRODUCTION

This article aims to review the current state of sensorisation and monitoring technologies used in biomedical applications for the diagnosis and treatment of patients at home. To this end, firstly, the monitoring of the patient's vital signs has been addressed. Then, the monitored physiological characteristics have been defined and the technologies and medical equipment established or likely to be used in their measurement/monitoring have been summarised.

This review has shown how advances in microelectronics, communications, sensors and data processing have led to the development of wearable sensors for monitoring, both at research and commercial levels. Despite this, there are still challenges of adapted functionality and usability to bring together in a single device all the parameters for comprehensive care, such as the need for multiple sensors in different areas of the body or accuracy limitations for healthcare use.

In this sense, existing commercial developments have been presented and the advantages and limitations of their operation have been shown. Finally, a review of portable developments in the literature for monitoring vital signs at home has been made.

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## 2 MONITORING OF VITAL SIGNS

Monitoring systems aim to obtain continuous information on the state of a patient to enable diagnosis and treatment. Theses systems can be use in a home context to achieve detailed characterization of the patient status. Typically, the indicators measured for this are vital signs.

Vital signs are a series of parameters that show body's most basic functions such as the haemodynamic status of a patient. They reflect the state of the organism and are the first sign of alarm in the event of a malfunction or defect in the organism. There are four main vital signs that physicians and other health professionals routinely examine in clinical practice (Rose and Clarke, 2010), (Lockwood et al., 2004): body temperature, heart rate, blood pressure and respiratory rate.

In this context, two groups of potential patient monitoring solutions can be identified. On the one hand, there are non-intrusive sensing solutions in the patient's home environment. On the other hand, solutions based on highly portable devices, wearables. Currently, technology allows the integration of several sensors together with the information processing units, which makes it possible to build very compact and accurate wearables.

In an ageing society with the increasing prevalence of chronic diseases such as neurological dis-



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eases, cardiovascular diseases, diabetes, respiratory disorders... the demand for continuous monitoring will lead to a growing sector of wearable devices. This will provide greater patient comfort and more meaningful data to perform diagnostics. As an indication of the financial size of the wearable health market, in the US it accounted for spending in the years 2017, 2018 and 2019 of $7 billion, $10 billion and $25 billion, respectively. In other words, spending has almost quadrupled in two years (Fortune Business Insights, 2020).

## 2.1 Body Temperature

Body temperature is a measure of the body's ability to generate and eliminate heat. Depending on where it is measured, three types of temperature can be distinguished. Core body temperature, when measured rectally, orally or tympanically. Proximal skin temperature if taken near the central axis of the body such as the groin or armpit. And distal skin temperature when measured in the regions furthest from the central axis of the body, typically the hands and legs.

Depending on the place where the measurement is taken, different results are obtained. Likewise, aspects such as stress can vary body temperature. In (Vinkers et al., 2013), the author states that stress causes a decrease in body and distal temperature, but an increase in proximal temperature. Likewise, (Coiffard et al., 2021) shows how the body temperature presents a circadian rhythm, increasing its value during the day and decreasing during the night. In addition, age, sex of the patient or different diseases can also affect the measurement. In Alzheimer's patients the core body temperature rises by up to 0.2 degrees Celsius (Sixsmith et al., 2005). A rise in body temperature is the first symptom of infection or inflammation somewhere in the body. When the proximal skin temperature value is below 35.8ºC, it is called hypothermia. If the value is high, it is called febrile (up to 37.5ºC) or fever (above 38ºC) (Marion, 2003).

Table 1: Normal body temperature ranges according to reading type and gender.

| Type of reading | Female | Male |
|---|---|---|
| Oral | 33,2 – 38,1 ºC | 35,7 – 37,7 ºC |
| Rectal | 36,8 – 37,1 ºC | 36,7 – 37,5 ºC |
| Tympanic | 35,7 – 37,8 ºC | 35,5 – 37,8 ºC |

## 2.2 Pulse or Heart Rate

It refers to the number of heart beats or contractions per minute. It can change throughout the day or in a given situation. However, it is quickly reversed in the event of a specific triggering situation. The standard values are considered between 60 and 100 beats per minute (bpm). Tachycardia is defined as a state when the heartbeat is greater than 100 bpm and bradycardia when it is less than 60 bpm. The heartbeat is also subjected to natural variations that show how our nervous system adapts to sudden challenges (Spodick et al., 1992).

## 2.3 Blood Pressure

Blood pressure is the force applied against the walls of the arteries when the heart pumps blood through the body. It is a parameter that can change throughout the day. It is measured in millimetres of mercury (mmHg). Two different blood pressure values can be distinguished, Systolic blood pressure (SBP) and Diastolic blood pressure (DBT). SBP reflects the pressure in blood vessels when heart contracts (standard values between 110 and 140 mmHg). DBT is the pressure of the blood on the walls of the arteries when the heart rests between beats (standard values are between 70 and 90 mmHg). A patient is said to be hypertensive when their SBP is above 140 mmHg and their DBT is above 90 mmHg (Organization, 2022).

## 2.4 Respiratory Rate

It quantifies the number of breaths taken in a specified period of time, usually one minute. In adults, 12 to 20 breaths per minute is considered a standard value. When the value is higher, the patient has lack of oxygen, this status is called tachypnoea. If it is less, it is bradypnea (Lovett et al., 2005).

## 2.5 Non-Universal Vital Signs

Several additional vital signs have been proposed, although they have not been officially or universally adopted. These additional parameters include the oxygen saturation and blood glucose.

### 2.5.1 Oxygen Saturation

Oxygen saturation, reflects the amount of oxygen available in the blood; a critical parameter in patients with respiratory pathology. The standard oxygen saturation value is between 95% and 100% and indicates that cells are receiving enough oxygen to preserve their function. A saturation value below 90%, called hypoxaemia, is considered insufficient and is manifested by shortness of breath and a compensatory increase in respiratory rate. Values below 80% are considered severe hypoxaemias (Subhi et al., 2009).

#### 2.5.2 Blood Glucose

The sugar ingested with food is converted by metabolism into glucose, which travels through the bloodstream to reach cells of different tissue types providing the energy they need to function. Blood glucose levels, clinically referred to as blood glucose, vary throughout the day. When insulin metabolism is not working properly, glucose is no longer properly assimilated by tissue cells, and it is accumulated in the blood. The standard value of glucose before eating are between 70 - 100 mg/dl (Gunst and Van den Berghe, 2010).

## 3 MEASUREMENT TECHNOLOGIES AND PRINCIPLES

This section reviews the specific medical technologies and equipment already established for the measurement of vital signs. Although in certain cases there may be variants based on more precise methods, this summary prioritises those devices that can carry out the measurement in a automated non-invasive way.

### 3.1 Clinical Thermometers

They are used to measure body temperature. There is a wide variety, and they can be classified according to the area of the body where they are designed to measure (oral, axillary, rectal, tympanic or temporal) or the type of technology on which they are based. In terms of technology they use, the most common clinical thermometers are those based on liquid, liquid crystal, electronic contact and infrared.

#### 3.1.1 Liquid Thermometers

Liquid thermometers are based on the thermal expansion of a liquid inside a graduated glass tube. The traditional solution used mercury, although it is no longer used due to its toxicity. Now, coloured alcohol or gallium is used as an alternative. Due to their operation principle, it is necessary to wait for about 3 to 10 minutes (depending on the area of the body) so that the device can perform a reliable measurement. They are commonly used for measurements in the armpit, mouth or rectum. Due to their fragility, measurement time and the ban on mercury variants, their use has been largely displaced by digital alternatives, especially outside the hospital environment.

In addition, there are liquid crystal thermometers, It consists of heat-sensitive liquid crystals that are integrated in a plastic strip. These crystals change their colour to indicate different temperatures. They are usually placed on the forehead and are disposable (Rodríguez et al., 2008).

#### 3.1.2 Electronic Contact Thermometers

They are made up of temperature dependent transducers that vary the output voltage depending on the temperature of the patient. This voltage variation is translated into degrees and displayed on a small screen. Some of their advantages are that they are easy to read and quick to respond, so their use has spread both inside and outside the hospital setting. Many of them employ predictive algorithms to provide a reading in a few seconds rather than a minute. They are commonly used for measurement in the armpit, mouth, rectum or ear. In the case of predictive devices, the algorithms used must take into account the area of placement in order to provide an accurate temperature reading (Habibian et al., 2009).

#### 3.1.3 Infrared Thermometers

They do not require physical contact to carry out the measurement and it is usually performed on the forehead, although there are specific developments for ear measurements. As they do not require contact, they can reduce the risk of infection transmission. Measurement times are low, in the order of seconds. As these devices are based on optical sensors, readings can be affected by the state of the surface on which the measurement is made (cleanliness, humidity, position, movement, etc.). Also, the level of ambient light, external heat sources or the use of clothing or cosmetic products can vary the measurement. Therefore, it is more prone to measurement errors than contact alternatives (Khan et al., 2021).

### 3.2 Heart Rate Monitor

Heart rate monitor allows real-time measurement of a patient's heart rate. Modern wearable devices typically use electrocardiography or photoplethysmography method to record heart rate signals.

#### 3.2.1 Electrocardiograph

Electrocardiograph or ECG electrical can record the electrical activity of the heart. That is, the biopotential generated by the electrical signals that control the expansion and contraction of the heart. In other words, it captures, records, and magnifies the electrical activity of the heart. Different types of ECGs can be distinguished according to the number of used electrodes: 1, 2, 6 or 12 leads or channels, where each lead will measure the electrical potential difference between two electrodes. A 1-lead ECG provides only basic monitoring of the heart. In contrast, a 12-lead ECG provides a complete picture of cardiac activity. ECG is widely used to detect almost any cardiac pathology (Bansal and Joshi, 2018).

There are different algorithms to extract the pulse from the ECG. The basis of this measurement is the detection of QRS complex. This parameter is formed by three vectors: the Q wave, the first wave of the complex with negative values; the R wave, which follows the Q wave, is positive and the largest one; and finally, the S wave, any negative wave that follows the R wave. Based on the duration, amplitude and shape of QRS complex it is possible to detect heart rate, arrhythmia, infarcts and other disorders. In (Parak and Havlik, 2011) authors discuss different algorithms and methods of heart rate frequency estimation based on auto-correlation of energy signal, thresholding of energy signal and peak detection in energy signal envelope.

#### 3.2.2 Photoplethysmography

Photoplethysmography or PPG optical determines the heart rate using a light source of a specific length that emits a beam on the skin to illuminate the subcutaneous vessels. The subcutaneous vessels reflect part of the beam depending on the amount of red blood cells they contain. (Saquib et al., 2015) The reflected light hits on a photosensor which converts it into an equivalent voltage. The cardiac cycle can be obtained by measuring the interval between each voltage peak. Its principle of operation is the same as that of the oximeter, hence there are pulse oximeters that offer both measurements.

### 3.3 Blood Pressure Monitor

It is a medical device used for indirect measurement of blood pressure through SBP and DBT values. It consists of a manometer and a cuff that is inflated until it squeezes the measurement area so that, by occlusion, the transit of blood is temporarily stopped for measurement. It is used in conjunction with a stethoscope to auscultate the audible intervals of the Korotkoff arterial sounds while the cuff is being deflated in a controlled manner.

For home use the digital ones are the most appropriate as the whole process to be automatic, including inflation. However, they require periodic calibration as they use sensors placed in the cuff to detect Korotkoff sounds (Babbs, 2015). These sensors can be auscultatory or oscillometric. The auscultation is based on microphones capable of interpreting the sounds of the measurement process (Beevers et al., 2001). The Oscillometer relies on deformable membranes whose variation in piezo-resistance or capacitance allows the analysis of the vibration transmission of the arterial wall (Mostafa et al., 2021). Most vendors use the oscillometric procedure, displacing the auscultatory procedure, which makes these devices particularly suitable for noisy environments.

### 3.4 Respiratory Rate Monitor

Respiratory rate is usually measured manually by observation, palpation or using a stethoscope. There is, however, equipment for automatic monitoring. For example, fibre optic sensors can be used during Magnetic Resonance Imaging (MRI) scans to monitor respiratory rate (Nedoma et al., 2018).

#### 3.4.1 Respiratory Inductance Plethysmography

This is a device that records respiratory movements using an inflatable coil that surrounds the thorax. These signals are connected to a monitoring device that transforms the inductance of these coils into signals relative to the rib cabe and abdomen strains (Massaroni et al., 2021). This measurement technique is widely used in the hospital environment.

#### 3.4.2 Impedance Pneumography

Another technique is based on impedance pneumography. This is done by using 2 or 4 electrodes on the thorax. A high-frequency, low-amplitude current is flowed through the chest cavity and the variation in resistance is used to estimate respiratory rate (Charlton et al., 2021). The variation in resistance is due to the impedance of the body and its respiratory cycle.

#### 3.4.3 Spirometry

By using spirometers it is also possible to record the amount of inhaled and exhaled air during a certain time. Modern spirometers are able to graphically represent these curves. Based on a test of at least 60 seconds, it is possible to measure the breathing rate. To do this, it is sufficient to count the number of peaks or troughs that are represented on the breathing graph (Miller et al., 2005).

#### 3.4.4 Capnography

Capnography is used to measure the concentration of carbon dioxide in the airway of a patient during the respiratory cycle. From the time evolution of this concentration, it is possible to determine the value of the respiratory rate. Their operation is generally based on the principle of absorption of infrared light by carbon dioxide (Bergese et al., 2017).

### 3.5 Pulse Oximeter

This is a medical device that can determine the percentage of oxygen saturation of haemoglobin using photoelectric methods in a non-intrusive manner. The pulse oximeter is placed on a part of the body that is relatively translucent and has good blood flow: the fingers, toes, earlobe or wrist. The equipment emits light at specific wavelengths (green/red/infrared) which pass sequentially from an emitter to a photodetector through the patient (Moço and Verkruysse, 2021). The absorbance of each wavelength caused by arterial blood (pulsatile component) is measured, excluding venous blood, skin, bone, muscle, fat. With this data it is possible to calculate the blood oxygen saturation.

### 3.6 Glucometer

It is a device in which a test strip impregnated with a drop of blood. It provides the result of the patient's blood glucose levels automatically in just a few seconds and its use is not complex for the patient himself. However, it is an invasive method (Wang, 2008). As an alternative, there are developments aimed at achieving continuous monitoring of glucose concentration, usually in interstitial or tissue fluid (McKinlay et al., 2017).

## 4 MULTI-MONITORING SOLUTIONS

The current scenario of technology applied to health services does not free us from a series of challenges that arise when considering the possibility, and even the need, to use technologies suitable for home use. The technologies required for this are evolving and are making remarkable advances, such as developments in micro and nano electronics and SoC (System on Chip) integration. As these developments are programmable and have a large memory capacity, they have created the basis for very small systems with various integrated sensors and a large information processing capacity. This, together with the constant evolution in the field of electronic communications, makes it possible for these systems to be connected to distant information repositories, or even to be interconnected with each other.

This scenario is perfectly compatible with the introduction and use of highly portable, increasingly usable and interconnected devices in the field of health and personal care. These principles tie in with concepts that are at the epicentre of the evolution: eHealth, Internet of Things (IoT) and its combination IomT (Internet of Medical Things) (Sudana and Emanuel, 2019).

Thus, advances in microelectronics, communications, sensors and data processing have made possible a great scope in the development of new technologies and devices to support healthcare. Wearable sensor devices for monitoring are an example of these advances (Li et al., 2018). There are a large number of wearable devices that, due to their design and built-in sensors, are functionally adapted to obtain health-related information from non-hospital settings. They can enable continuous monitoring of parameters such as body temperature, position or bio-electrical signals (García et al., 2019).

However, the development of wearable devices, with high usability and medical use, still offer a number of challenges. Despite major developments, it is still not possible to bring together in a single device the ability to monitor all the parameters necessary for comprehensive care. The proper placement of the sensors, as part of the wearables, is a critical point for the correct functioning and obtaining the measurement of the corresponding vital sign.

There is a wide variety of systems proposed in the literature for monitoring patients' vital signs at home (Lin et al., 2017), (Rashidi and Mihailidis, 2013). However, many of these monitoring systems are designed to monitor one or two specific parameters only (Shivakumar and Sasikala, 2014). Among the multi-measurement systems, the most important ones include smartwatch-based systems, smart furniture, and textiles with integrated sensors.

### 4.1 Smartwatches

The role played by smartwatches and their use should also be mentioned. Some of them, at the high end of the price range, are starting to offer quite advanced monitoring of health parameters, including ECG-correlated measurements. However, these smartwatches must be certified as medical devices to be used for this intended use. The regulatory barrier limits their availability in certain markets.

A representative example is the Apple Watch, the first smartwatch approved by the US Food and Drug Administration (FDA) for the incorporation of algorithms for detecting atrial fibrillation and performing ECGs (Isakadze and Martin, 2020). A similar authorisation was granted by the European Commission in 2019 for 19 countries. For this purpose, the watch incorporates electrodes on its back and crown. Placing a finger on the crown closes the circuit with the back electrodes providing data to the ECG application. A measurement takes about 30 seconds and offers the option of four possible results: sinus rhythm, atrial fibrillation, high or low heart rate or inconclusive. However, it is necessary to remark the limitations of the Apple Watch's single-lead system compared to a traditional holter, a small electronic device that records and stores the patient's electrocardiogram for at least 24 hours on an ambulatory basis (De Asmundis et al., 2014). This limitation makes the Apple smartwatch unable to detect heart attacks, cardiovascular accidents or other heart conditions.

In the case of other vital signs, the technology available for wearables is still far from the healthcare related purposes. For example, several smartwatch manufacturers such as Apple, Samsung or Amazfit are planning to incorporate in their products the possibility of estimate blood pressure using different algorithms. This is possible due to the optical sensors that watches incorporate for heart rate measurement. As with the Apple Watch ECG, such capabilities require the approval of specific regulatory affairs. In terms of blood pressure monitoring, the Omron Heartguide wristband (Liang and Chapa-Martell, 2021), is the only smartwatch with FDA clearance. This device is an ultra-portable wrist sphygmomanometer.

Likewise, there are more and more references in which different smartbands or smartwatches are used to estimate body temperature. For example, (Kwak et al., 2019) presents a statistical approach to estimate body temperature based on skin temperature measured with a smartband.

## 4.2 Smart Furniture

Smart beds or chairs equipped with vital signs sensors, can also be an interesting option for non-intrusive monitoring of various vital signs.

In (Popescu and Mahnot, 2012) a set of pneumatic sensors placed on a bed is presented to carry out heart rate and respiratory rate measurements. In (Klack et al., 2011), temperature measurement is carried out using a high-precision IR camera. (Grace et al., 2017) use different types of external sensors to measure respiratory rate in bed by integrating accelerometers in the blanket, heart rate while sitting or standing using electrodes on the floor in contact with the feet. The use of a ballistocardiograph using pressure sensors installed on chairs or on the bed to estimate blood pressure is also tested.

## 4.3 Textiles with Sensors

Another alternative is to incorporate monitoring capabilities into everyday items or accessories that the patient carries with them on a regular basis, such as socks, shoes, T-shirts, waistcoats, wristbands (Avgerinakis et al., 2013)... One example is the Smart Vest, a wearable monitoring system for parameters such as heart rate, blood pressure, axillary temperature and ECG (Pandian et al., 2008). There are other experimental designs with promising preliminary results that incorporate measurement capabilities (heart rate, respiratory rate) into conventional T-shirts rather than more bulky garments (Sardini and Serpelloni, 2014).

(Pigini et al., 2017) describe the pilot development of a commercial home telemonitoring system. The system is capable of performing ECG measurements (1-lead) by means of a smart patch that can be placed as a stand-alone sticker on the chest or can be integrated into a garment or an elastic band. The system also employs a commercial multi-purpose non-wearable device to measure several constants: Heart rate, blood pressure, and blood oxygen saturation. The same system also performs a glycaemia measurement.

(Pham et al., 2016) describe a system that uses a smart garment with ECG textile electrodes and a chest strap to measure respiration using an inductive transducer that measures changes in chest or abdominal circumference.

An example of a commercial development of a wearable for vital signs monitoring is the Hexoskin smart garment (Villar et al., 2015). It is an elastic T-shirt that provides, among other data, continuous information on heart and lung activity: ECG (1-lead), heart rate, heart rhythm, breathing rate, etc. Another example is the Philips wearable biosensor (Li et al., 2019) in the form of a patch with, among other things, a temperature sensor (thermistor) and ECG (1-lead).

# 5 CONCLUSIONS

This article reviews vital signs, measurement technologies and principles, and monitoring systems. The review shows the limited number of wearable devices that can be considered medical devices and highlights their drawbacks for diagnosis. That is, wearables that have been certified according to medical device regulations. There is also a lack of wearables capable of simultaneously monitoring several vital signs at home environment.

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