# Wearable and Implantable Sensors for Cardiovascular Monitoring: A Review

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**Summary**
The cardiovascular syndrome is the dominant reason for death and the number of deaths due to this syndrome has greatly increased recently. Regular cardiac monitoring is crucial in controlling heart parameters, particularly for initial examination and precautions. The quantity of cardiac patients is rising each day and it would increase the load of work for doctors/nurses in handling the patients' situation. Hence, it needed a solution that might benefit doctors/nurses in monitoring the improvement of the health condition of patients in real-time and likewise assure decreasing medical treatment expenses. Regular heart monitoring via wireless body area networks (WBANs) including implantable and wearable medical devices is contemplated as a life-changing technique for medical assistance. This article focuses on the latest development in wearable and implantable devices for cardiovascular monitoring. First, we go through the wearable devices for the electrocardiogram (ECG) monitoring. Then, we reviewed the implantable devices for Blood Pressure (BP) monitoring. Subsequently, the evaluation of leading wearable and implantable sensors for heart monitoring mentioned over the previous six years, the current article provides uncertain direction concerning the description of diagnostic effectiveness, thus intending on making discussion in the technical communal to permit aimed at the formation of well-designed techniques. The article is concluded by debating several technical issues in wearable and implantable technology and their possible potential solutions for conquering these challenges.
***Keywords:***
*Wireless body area network, cardiovascular monitoring, healthcare, wearable sensors, implantable sensors*

## 1. Introduction

The heart is an essential organ that supplies blood through veins called blood vessels to give oxygen (O2) and supplements all through the whole body and pull out carbon dioxide (CO2) and also metabolic waste away from the human body. The WHO (World Health Organization) make estimates that up to 30% of people dying worldwide overall in number due to cardiovascular disorder, i.e., heart and vein (blood vessels) ailments [1]. This type of disease becomes a lot simpler to control when recognized right on time, there is an increase in the demand for constant monitoring of cardiovascular [2]. Such as multiple cardiovascular infections can be shown by understanding the model of electrocardiograms (ECGs) [3]. At the same time, because of the high BP is unit of the highly crucial risk factors in this cardiovascular disease, so that the blood oxygen saturation and blood pressure are also observing on daily basis [4]. At the point, when a cardiac arrest or usual heart rhythms is recognized, convenient and precise treatment is essential. Therefore, there are huge requirements for innovative work about cardiovascular monitoring gadgets, which must be empowered by the new design, material, and plan developments.

Heart patients are increasing in number, and the limited capacity of medical personnel is one of the main problems occurring, the pressure of work on doctors will also increase in handling the health condition of patients. As well as, the equipment they used for monitoring the heartbeat of patients is not convenient, still using a wire connected to a computer. For this reason, we need a proper solution that could assist medical staff in real-time for monitoring the health of patients [5].
These implantable and wearable devices are entered in the field of technology known as digital health, in several medical applications compromising monitoring, and recording the crucial signs of patients to improve and get better results of their health as well as of their family. A few of these technologies such as smart watches, glasses, and armbands have now become a part of everyone's life in the type of accessories [6].

We present the current and novel approaches in wearable, implantable, and established medical devices in this article, particularly built for heart monitoring. The review begins with emphasizing the significance and value of these devices in cardiac monitoring i.e. wearable and implantable. In section II, we evaluate the comparison of different wearable devices for ECG monitoring and also discuss some FDA approved commercial wearable ECG monitoring devices. Section III comprises the comparison of implantable devices for blood pressure monitoring. Section IV consists of some challenges based on technology associated with these devices and future developments. At last, Section V relies on the conclusion. The responsive and easy-going application for cardiac devices has improved the quality and potential of the cardiac monitoring system and has given numerous future chances and opportunities for further development.

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## 2. Wearable Cardiovascular Monitoring Devices

Wireless and wearable sensors aids in 24-hour care of patients with cardiac disease or at the possibility of evolving heart problems. The portable and lightweight characteristics of a wearable is attractive to patients who do not prefer to be stuck by their observing equipment [7]. Byeong Wan An et al. says that wearable automated devices offer real-time uninterrupted information gaining for difficult well-being situations, and can enhance the duration and excellence of life of the world's old inhabitants [8].

The use of a medicinal wearable device in heart monitoring comprises of numerous stages. Initially, the wearable is incorporated with the patient through a strap, smartwatch, clothing, or other forms of settlement. Next, the sensor of the wearable device processes the important heart parameters. In cardiac monitoring, wearable sensors are capable of collecting beneficial data about heart parameters comprises of electrocardiogram (ECG), blood oxygen saturation, heart rate variability, blood pressure, etc. [9]. The data obtained through wearable is then interpreted from the front-end sensor in such a way that it can be presented to the patient. Lastly, the recorded data is regularly shared with the cardiologist of the patient as an electronic health report through a mobile application or cloud-based server [10].

Presently on the market, there is a collection of wearable devices that use sensors to observe vulnerable heart patients. The next section comprises up-to-date technologies through accessible wearable devices and their efficiency at observing cardiac syndromes. The capabilities of ambulatory cardiovascular monitoring and kind of devices that can be used for such monitoring is depicted in figure 1.

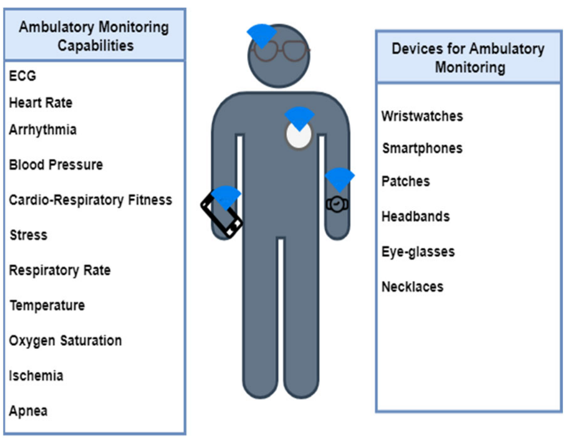


Fig. 1 Ambulatory Monitoring Capabilities and Devices

### 2.1 Different Wearable Electrocardiogram (ECG) Monitoring Devices

Electrocardiography (ECG) is an uncomplicated process of measuring the activity of the heart rate electrically and gives a detailed report of the heart condition. It is used in common and also the most basic diagnostic apparatus for unusual cardiac oscillations. An electrical pulse or "wave" goes throughout the heart with each rhythm. That wave provokes the muscle to-compress and pumps out blood through the heart. An average heart-beat on ECG would display the rhythms, upper and bottom chambers.

The right and left atrium or top chambers form a first wave, which is known as "P wave" and by a horizontal line when the electrical signal or pulse goes toward bottom chambers. The left and right ventricles or bottom chambers create a next wave known as "QRS complex." The last and third wave called a "T wave" illustrates the resting state of ventricles [11].

You might necessitate an ECG to inspect signs of a probable cardiac problem, such as chest pain, palpitations (suddenly noticeable heartbeats), rapid pulse, dizziness and shortness of breath. Your cardiologist will use the data recorded by the ECG machine to determine complications with your heart, comprising: heart attack, coronary heart disease, heart rate, arrhythmias heart rhythm, cardiomyopathy, insufficient blood and oxygen supply to the heart, structural irregularities.

There are three major categories of ECG: an ambulatory ECG, a stress/exercise ECG, a resting ECG. That sort of ECG we use will depend upon your symptoms as well as presumed heart problems. In ambulatory ECG type, an ECG machine would save the information electronically about your heart that can be available by the physician when the whole checkup is complete [12].

The monitoring occurs by attaching more than a few small, sticky type sensors called "electrodes". Each time when your heart beats, it generates electrical signals. These sensors are attached to the skin (arms, chest, limbs, and legs) and are used to detect these signals. These also have connections with a recording machine (ECG) by wires and recorded signals by this machine, which gives us output in the form of graphs or waves on a monitor/paper of your heart rate and electrical pulses. ECG sensors (electrodes) perceive the tiny-scale electrical charge or energy of the heart-beat emerging from among skin. A complete view of the cardiac activity might be obtained by putting these sticky sensors/electrodes in various areas of the patient's body. i.e. 10 electrodes are around here in "12 lead ECG" that present 12 positions of the cardiac functions using different angles between frontal planes, described as "V1, V2, V3, aVR, aVL, aVF, V1, V2, V3, V4, V5, and V6" [13].

Conventional ECG of a healthy person is shown by a schematic diagram i.e. Figure 2, This provides useful information about heart action if it is slow, too slow, irregular, fast, or heart muscles are overlooked.

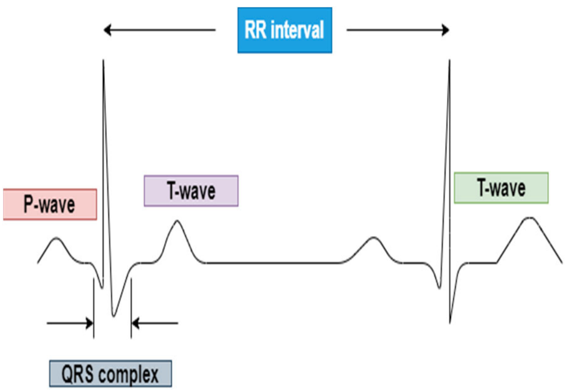


Fig. 2 Illustration of healthy ECG of heart in normal sinus rhythm

The core objective of ECG (wearable devices) is to assist in tracking activeness of the heart beyond the medical practice. Besides, it provides constant tracking or monitoring of cardiovascular fitness. So that, diagnosis and detection at their early stages of every heart-related issue. The wearable ECG systems are compact and small in size as opposed to 10-electrode medical ECG systems along with characteristics of handheld, usually use 2 to 3 electrodes to evaluate, measure and note indications in electrical form. Many systems even integrate wireless communication technology-based such as ZigBee, Bluetooth, and Bluetooth low energy (BLE) to promote real-time data communication. This type of ECG system with native wireless communication capacity could play an important role in monitoring the condition of cardiovascular without having an impact on daily bases routine and user's comfort [14]. A general architecture of wearable ECG monitoring system is shown in Figure 3.

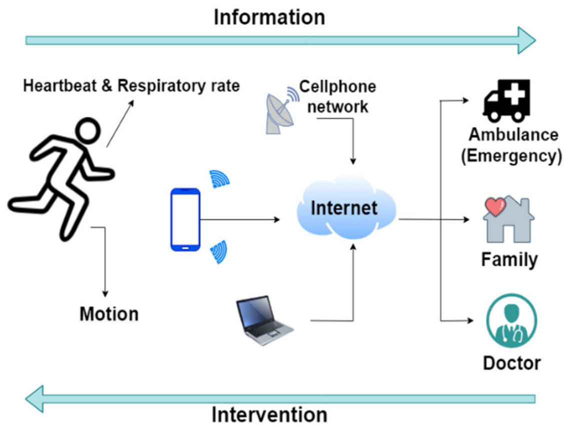


Fig. 3 General Architecture of Wearable ECG Monitoring System

Many different designs and models of wearable ECG devices were produced as an alternative to standard 12 Lead ECG. These designs mainly focus on capability, portability, and ease of use, while retaining signal coherence and maintaining lower power utilization. Table 1 & 2 presents a comparison of different wearable ECG monitoring devices based on specifications and signal acquisition module respectively.

#### 2.1.1 *Low power wearable for multiple patient ECG monitoring*

In this research, a low power wearable is implemented as a single mainstream to assist several monitoring systems for ECG, so that it would make possible for management and also monitoring of many users at very low cost. This device permits the monitoring of patients in a quite large domestic place (building, home, nursing area, etc.) [15].

#### 2.1.2 *Wearable ECG system with flexible PCB*

Wearable ECG monitoring systems produced completely from distinct electronic elements and a flexible PCB. This system or device removes whole loose wires through the network and reduces the track of the user [16].

#### 2.1.3 *Wearable mobile ECG monitoring system using dry foam electrode*

In this study, to monitor ECG a "wearable mobile electrocardiogram monitoring system" (WMEMS) has been proposed. It includes a wearable ECG acquisition device, a healthcare server, and a mobile phone platform in particular. Using a novel dry foam electrode is inherent in the wearable ECG acquisition device. It is a good conductor for acquiring ECG successfully without product. Besides, with the use of mobile phones, WMEMS could track the ECG state of the user continuously worldwide if they're under the scope of the

"Global System for Mobile communications" (GSM) mobile network [17].

*2.1.4 Wireless ECG sensor with multi-ring electrode*

It carries on a finger-like an ordinary ring and connects with a mobile application by wireless connection i.e. Bluetooth to monitor ECG values and if an abnormal heartbeat is identified, it gives alarm to patients. It uses a wireless sensor with a multi-ring electrode. It can be easily worn on finger like a ring, this feature and its small size makes it very feasible for users [18].

*2.1.5 Wearable capacitive ECG sensor*

This sensor device connected a wireless protocol for Datacom with a capacitive ECG sensor. The ANT protocol is used as a wireless module to lessen the power intake and sensor size. Moreover, a capacitive ECG sensor avoids contact with the skin directly and offers maximum ease to the consumer. In this work, tiny capacitive electrodes are integrated with a cotton T-shirt and transmit into a two-layer circuit board design [19].

*2.1.6 Wearable ECG using Impulse radio type HBC*

The physical body has been used as the communication channel to transfer the ECG signals i.e. HBC technology. The HBC carrier generates a force electric field near the body via capacitive coupling. Therefore, HBC provides minimal intervention with other wireless devices along with data security. The ECG data could be easily transferred by touching the receiver to a computer. Once ECG data received by connecting with computer, the software then immediately save and display the outcome in real-time [20].

*2.1.7 Common Electrode-Free ECG monitoring System*

This device is based upon remotely coupled electrodes without contact to the body of the patient electrically and thereby avoiding the common electrode. Assessments are carried out under actual situation prove that there is a possibility to obtain ECG signals without having common electrode while the patient is lying, sitting and also during walking, it will still give the better ECG results [21].

*2.1.8 Bio-potential ECG system with PDMS dry electrode*

This work implies a Bio-potential ECG system in favor of portable healthcare apps using "flexible polydimethylsiloxane dry electrodes" (FPDEs) and a recording circuit. This innovative FPDE using Au in terms of the contact layer that was made up of CO2 laser as well as replica methodology. The FPDE has now altered from a bio-potential electrode, with the use of dry electrodes comparatively wet ones that are reliable support for measurement and made it wearable by attaching hooks and loops on the wrist [22].

*2.1.9 Exercise ECG monitoring using H-shirt*

Another customized Health shirt (H-shirt) merged with conductive stuff ECG electrodes allowing ECG to monitor during physical activity. The H-shirt system contains a cell phone application, which could identify six types of abnormal ECG. Including trigeminy, bradycardia, premature beat, a dropped beat, bigeminy, and tachycardia [23].

2.1.10 *ECG monitoring system using dynamic power regulation*

A wireless ECG monitoring device based on a novel approach i.e. 3-Lead electrode. On the basis of this new electrode, a tiny size detector node is developed to detect, intensify, transmit, and filter the ECG signals. The coordinator collects the data and transfers it to the PC. Lastly, then signals are represented on the GUI. Also, the researchers in [49] made a power allowance method to maximize the power usage of the sender by evaluating the distance between the sender and the receiver [24].

*2.1.11 Wireless Armband for mobile ECG monitoring*

A strap was chosen as a replacement in former wearable devices that are bound to a patient's chest, which becomes awkward for many users. This system uses capacitive-coupled electrodes technology. The capacitive coupled electrodes allow the system to evaluate bio-signals via the clothes. So that the deficiencies from wet and dry electrodes could be declined [25].

*2.1.12 ECG monitoring system using mobile cloud computing*

The researchers have developed a mobile app for an ECG monitoring device that is able to summarize, examine, and monitor the status of a user's health. It can do interaction and share resources using a web-based cloud computing (, a common server) with the health-care professional. The web server operates an algorithm which measures and improves the quality of ECG, also analyzes and displays ECG signal in real-time [26].

*2.1.13 ECG monitoring system using novel non-contact electrode*

Furthermore, the researchers embed an alert device in their app. The system is able to detect irregular heartbeat with high sensitivity and precision. It can notify the user by text/email messages. In this study, a simple contactless electrode circuit has been proposed. The proposed contactless electrode can evaluate bio-potentials over thin clothing, embedded in a person's clothing to observe ECG in daily routine. [27]

Table 1: Specifications comparison of ECG monitoring devices

| **ECG Monitoring System** | **Data Transmission** | **Attachment Method** | **Electrode Type** | **Electrode Size** | **Active Material** |
|---|---|---|---|---|---|
| Low power wearable for multiple patient ECG monitoring [15] | ZigBee | Snap buttons to attach the strip | Dry plastic electrodes | - | Conductive rubber |
| Wearable ECG system with flexible PCB [16] | Bluetooth | On back of PCB with metal buttons | 4M 1540 red dot wet ECG electrodes | 1.5 inch diameter (4.9cm diameter) | - |
| Wearable mobile ECG monitoring system using dry foam electrode [17] | Bluetooth v2.0, and GSM | Fixed into short cases in the shirt | Dry foam electrode | 15 mm × 7 mm × 7 mm | Ni/Cu covered compacted urethane polymer foam |
| Wireless ECG sensor with multi-ring electrode [18] | Bluetooth | Fits on finger of Patient | Dry multi-ring electrode | Dia: 35 mm, 44mm | Hook-shaped Ag on polyester film |
| Wearable capacitive ECG sensor [19] | ANT | Knitted below a stretchable strap | Capacitive electrode with cotton insulator | 22 mm × 22 mm × 3 mm | - |
| Wearable ECG using Impulse radio type HBC [20] | Human body communication and USB | Directly attached to the chest | Two Sensing Electrodes | 2.5 cm × 2.5 cm | Copper plates |
| Common Electrode-Free ECG monitoring system [21] | - | Sticky tape | Active capacitive electrodes | 4 cm × 2 cm | Copper layer |
| Bio-potential ECG system with PDMS dry electrode [22] | - | Conductive snap | Dry PDMS electrode | contact area:26.3 $mm^2$ | Ti and Au on PDMS |
| Exercise ECG monitoring using H-shirt [23] | Bluetooth LE | Incorporated in the shirt with hot pressure welding | Conductive fabric electrode | 34 mm × 40 mm × | Gel-type silver/silver chloride |
| ECG monitoring system using dynamic power regulation [24] | ZigBee | Snap buttons to attach the sensor node | 3-lead electrode | 4.5cm ×3.5cm | - |
| Wireless Armband for mobile ECG monitoring [25] | Bluetooth LE | Stitched into the armband | Dry capacitive electrode | 2.5 cm × 2.5 cm | Silver-plated polyester |
| ECG monitoring system using mobile cloud computing [26] | Bluetooth | Connected at the backrest of the chair | Capacitive textile electrode | 3cm × 3cm | Super absorbent polymer layer |
| ECG monitoring system using novel non-contact electrode | Bluetooth | Velcro used to connect the electrode to fabric | Dry non-contact electrode | Dia: 3 cm | Copper plate PCB |

| | | | | | |
|---|---|---|---|---|---|
| [27] | | | | | |

| ECG Monitoring Systems | Weight | Battery Life, Power | Frequency | A/D | CMRR | Input Noise | Size | Performance |
|---|---|---|---|---|---|---|---|---|
| Low-power wearable for multiple-patient ECG monitoring [15] | 15g | 6-7 days, 5.95 mA from 590 mAh 4V Li battery | 500 Hz | 22 bit | 132 | 0.48 µVrms | 65 × 34× 17 $mm^3$ | Clearly identify the QRS complex. Morphologically similar to conventional ECG. |
| Wearable ECG system with flexible PCB [16] | 29g | 29 d, 0.8 mA from 160 mAh 4.9 V Li battery (with 12-bit ADC) | 250 Hz | 10 bit | 40 | -- | 115× 115 $mm^2$ | QRS positive predictively and sensitivity: 88.32%, 99.72% |
| Wearable mobile ecg monitoring system using dry foam electrode [17] | -- | 40 h, 1100 mAh Li-ion battery | 512 Hz | 12 bit | -- | -- | 3 × 3.4 × 0.7 $cm^3$ | 98.23 % QRS detection accuracy, 99.62% compared to recorded ECG |
| Wireless ECG sensor with multi-ring electrode [18] | 17.9g | 11.3mA(standby), 58.2mA(transmission) and 32.8 mA (data storing | 1000Hz | 24-bit | 130 | 0.28µ Vrms | 70× 35× 12 $mm^3$ | Simultaneous recoding of three BC-ECG signals. SNR: 13-21 dB, SNR improves with ring size. |
| Wearable capacitive ECG sensor [19] | -- | 16 h with 243 mAh 4 V Li battery | 500 Hz | 12-bit | -- | -- | 44 × 50 × 8 $mm^3$ | Lowest power consumption - 1mA, (lowest compared to others). CC-ECG resulted in good quality signals |
| wearable ECG using Impulse radio type HBC [20] | -- | -- | 512 Hz | 10-bit | 80 | -- | -- | Not only the QRS wave but also the P&T wave can be clearly observed. Compared to Holter ECG and 97 % correlation. |
| Common Electrode-Free ECG monitoring System [21] | -- | -- | 250 Hz | 12 bit | 130 | -- | -- | QRS complex is noticeable. ECG was effectively acquired also during walking. |
| Bio-potential ecg system with PDMS dry electrode [22] | 40g | 4 days with two 2500 mAh batteries, 88.74 mW | 200 Hz | -- | 102 | 0.45 µVrms | 4.7 × 4.0 × 0.5 $cm^3$ | Morphologically comparable to conventioal ECG |
| Exercise ecg monitoring using H-shirt [23] | 11g | 25 h, 150 mAh 4.1 V Li battery | 250 Hz | -- | 40 | -- | 16 × 40 × 1.6 $mm^3$ | QRS sensitivity: 96.33% (at rest), 90.16% (running) |
| ECG monitoring system using dynamic power regulation [24] | -- | | 512 Hz | -- | -- | 0.60µ Vrms | 4.6 × 3.4 $cm^2$ | QRS sensitivity: 98.33% (at rest) 92.36% (running) |
| Wireless Armband for mobile ECG monitoring [25] | -- | -- | 40Hz | -- | -- | -- | Dia: 39 mm | QRS wave is quite clear. Error rate is less than 10% compared with standard lead 2 wet-electrode system |
| ECG monitoring system using mobile cloud computing [26] | -- | -- | -- | -- | -- | 0.50 µVrms | -- | Compared by graphic review, lesser QRS amplitude |
| ECG monitoring system using novel non-contact electrode [27] | -- | 36 h, 30 mA from 2100 mAh 4.8 V Li battery | 512 Hz | 12 bit | -- | 0.39 | 6.5 × 4.5 $cm^2$ | Provide better signal-to-noise ratio (SNR). ~97% correlation with standard system |

Table 2: Comparison of ECG monitoring devices based on signal acquisition module.

Most of the time researchers used textile [23] and polymer [17], [18], [15]-[22] based electrodes, flexible in nature to figure out the sensor part of a wearable ECG system. The capacitive electrodes are good for sensing bio-potential through the cloth without any contact into the skin. Such contactless electrodes are planted in chairs [27] or under bed covers to evaluate ECG during sleep or rest position by using Velcro [27], snap buttons [15],[22]-[24] and by zigzagged, traditional sewing or packaging methods [25], [26]-[19].

The sensor-based bio-potential is supplied to the analog-front-end (AFE), which enhances and filters the ECG signal. The fuss/noise in a battery-driven immobile ECG system is basically due to the body's activity. These flexible electrodes can considerably lessen the motion-artifacts (MA) because of their huge adaptability to the skin. That noise can be lowered furthermore by scheming the AFE with a high common-mode rejection ratio (CMRR) and high input impedance.

It is possible to enhance the input impedance of AFE with the help of resistors [19] or biasing with two anti-parallel diodes [27], [21]. Although, these diodes are preferable because of their fastest recovery time and low thermal noise. Researchers also used advanced amplifier layouts i.e. "Differential Difference Amplifier" (DDA) [22] to attain high-CMRR, high-impedance, low-noise, and low-power achievement. Later, the filtered ECG signal converted into digital format that could be easily stored within the SD card or transferred to a computing program such as PC, smart-phones, tablets, and over wireless media.

One more important issue is attaining low power usage and high energy efficiency for the ambulatory ECG monitoring systems. Lower power usage expands the battery duration, which is crucial for long-lasting monitoring devices. Power convention can be reduced with the use of low power electronic factors [15] or/and wireless communication tech i.e. ZigBee [15], [24], Bluetooth LE [23], [25], Bluetooth [17], [18], [26]-[27] and ANT [19].

To further minimize the noise and to make SNR better, the system in [20] owns high SNR as well as uses the signal processing methods such as wavelet decomposition [29], empirical mode decomposition, and adaptive filtering [28], [30]-[31]. This platform also uses artificial intelligence (AI) techniques i.e. neural networks, machine learning, and deep learning to find out and access the status of user's health.

The researchers in [27], embedded an alert tool in systems application as well. The system can detect abnormal heart-beat with high precision plus high sensitivity and also notify the consumers by a simple text message. Many researchers use a cloud-computing manifesto to achieve consistent monitoring of the vascular system through a distinct facility [26].

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## 2.2 Different Commercial Wearable ECG Monitoring Devices

The 12-lead clinical ECG devices are available at a very high cost, they are not portable and need to have a proper learned staff to make this system work, making it unable to be used at home. Technology is getting enhanced day by day, all these devices which are unable to use are left behind by home-based devices such as smartphones, laptops, and other portable devices, and giving a boost to medical industries. This assures home-based all-time monitoring. These systems are available in the market, but one may need permission from the doctor to buy those.

Only with the support of two to three electrodes, these portable and cost-effective devices can measure the needed data [33], [35]-[37]. Few of these devices can record the data for a little period e.g. half a minute, while few can record continuously [32]. The data is stored within the device [33], [36] or any additional apparatus attached 32], [35], [37], [39]-[40] or special storage system [38].

While it can be used and reviewed by getting transferred to the monitor or USB [36], few of these devices includes low-power wireless updates, like Bluetooth, BLE to manage the system to run at real-time [32],[33],[37],[38],[39]-[40].
In table 3, we presented the comparison of FDA approved commercial wearable devices for ECG monitoring.

### *2.2.1 QardioCore*

The medical-grade wearable which is used for all time monitoring of single-channel ECG, heart rate, skin temperature as well as respiratory rate is called QardioCore. Unlike a Holter monitor, it does not have external wires. It is a clinical-quality wearable electrocardiogram recorder. Silver-plated electrode make the front of the device. It records the physical activity as well as an electrocardiogram (ECG/EKG). The device monitor is a smartphone/tablet enabled device, programed is to record and transmit a single-channel electrocardiogram (ECG) [32].

### *2.2.2 iRhythm Zio Patch*

This device is to be sent to the patient's home in a packet and send back for analysis. It does not have wires, and its simple design does not interfere in the patient's daily chores. Same as other cardiac monitors, it does not need additional power, as resistant to water, and due to no extra need of a battery, it works for a long time. It can be recharged. It includes the additional feature to record the symptoms. [34] Recent experiments show that it is 57% more effective than traditional monitors like the Holter monitor. For instance, as compared to a Holter monitor's 61 events, it detected 96 arrhythmia events [33].

### *2.2.3 AliveCor's Kardia Mobile*

ECG recording in this one starts with a single click of a finger.it takes 30 seconds to display the single-channel ECG on screen for a specified duration, same as the few wearable devices in the market. AliveCor's Kardia Mobile smartphone-based ECG event recorder. It mixes up the ECG leads with the smartphone and get started the recording of cardiac rhythms with respective recording, with health care providers [35].

### *2.2.4 AfibAlert*

This monitor uses a proprietary computer algorithm to work, with the help of atrial fibrillation. To make this apparatus work, the small machine is held by a hand, and touching the thumb on a specified space. The complete procedure takes 45 seconds and records. The green or red light shows the results [36].

### *2.2.5 BioStamp*

BioStamp is used to check the movement as changes, to check out the heart acts as a whole, with the help of a 3-axis accelerometer. This device is not thick like other devices, and actually a bit stretchable, and has a single-Lead sensor. Its design makes it stretchable. The cell phone is approached by near field communication (NFC) capability into the platform which activates the ECG [37].

### *2.2.6 NUVANT MCT*

An additional device named NUVANT mobile cardiac telemetry (MCT) is responsible for the monitoring and analysis of arrhythmia when the Zio patch performs its part for the long term. These apparatus have portable features for transmission and a monitor, which present the real-time transmissions, but the data isn't available in real-time, meaning it doesn't really store the data, unlike Zio Patch. While working, the sensor gets activated automatically, transmitting ECGs, and then transmitted ultimately to the cloud-based application for analysis [38].

### *2.2.7 ECG CHECK*

This provides automatic analysis and report, by turning the smartphone into a monitoring apparatus. It also works on the touch of a finger, and the monitor is at the back of the smartphone, and produce a report for single-lead ECG. The display of the smartphone shows the result right away and analyzes that. It can also be saved unlike the data in NUVANT MCT, the documents can be reviewed in PDF layout. There are various settings involve4din this simple monitor like the way of presenting and reviewing as well as a screening of atrial fibrillation [39].

### *2.2.8 Apple Watch Series 4*

Apple watch series 4 is another monitor in this context, this system requires double handling and the ECG recording is across the heart. Additional tool required here is electrodes, set up at chest for hands-free ECG measuring. A software update is responsible for working on this system in the apple series. The upper and lower parts of apple watch help in the process acting as censors to calculate the heartbeat and produce the needed results [40].

Table 3: Comparison of FDA approved commercial wearable devices for ECG monitoring

| Device Name | Attachment | Data Transmission | Real-time transmission | Recording Duration | Battery Life | Continuous Recording | Memory Type | Size | Performance |
|---|---|---|---|---|---|---|---|---|---|
| QARDIOcore [32] | Strap- wraps around chest directly on skin under sternum | Bluetooth | yes | up to 1 day | 1 day | yes | Smart phone memory | 185mm × 87mm × 9mm | ECG, respiratory rate, HR, HRV activity and skin temperature |
| iRhythm Zio Patch [33.34] | Patch - device attaches to left side of user's chest | - | no | 90s | 14 days | yes | Embedded | 123mm × 53mm × 10.7mm | Greater performance than Holter monitor (Total diagnostic yield of 64.5) |
| AliveCor's Kardia Mobile [35] | Smartphone case – the device hardware attaches to back of a smartphone | Bluetooth | yes | 30s | 200 hours (12 months typically) | no | Smart phone memory | 81mm× 35.5mm × 5mm | 100% diagnostic yield is compared to 75.6% with ECG |
| AfibAlert [36] | Hand-held device | USB | no | 45s | 27 days | no | Embedded | 149.5mm ×70mm ×28mm | Clinical-grade ECG, ECG measurement with 94.7% accuracy, medical management use |
| BioStamp [37] | Patch- applied to skin like band-Aid around the chest | Bluetooth | yes | 1 min | 36 hours | yes | Smart phone memory | 6.6 ×3.4 ×0.3 cm | ECG signals that match the measurement of Holter device, with higher comfort result |
| NUVANT MCT [38] | Patch – applied to upper left of quadrant of chest | Bluetooth | yes | - | 7.5 days | yes | Cloud-based | 160mm ×60mm ×15mm | Compared to Holter monitor, 81% preference over the Holter monitor |
| ECG CHECK [39] | Smartphone case – the device hardware attaches to back of a smartphone | Bluetooth | yes | 30s | 8 hours | no | Smart phone memory | 118mm ×62mm ×17mm | Ventricular escape beat detection sensitivity of 94.5% and predictability of 95.6% |
| Apple Watch Series 4 [40] | Wrist watch | Wi-Fi, Bluetooth | no | 30s | 18 hours | no | Smart phone memory | 44mm ×38mm ×10.7mm | Sensitivity of 88% and specificity 98% in atrial fibrillation identifying patients with silent atrial fibrillation |

## 3. Implantable Cardiovascular Monitoring Devices

The biological sensors are weak, and they need interaction with the patient's body. Devices that are used to monitor ECG are mostly developed as patch types [41, 42]. Some evolving sensors (i.e. chemical, optical, electrical) have been lately presented that can detect several biological indications on the epidemics [43]. The problem in current patch-type devices is that they need to interact with the body which is very disturbing for some people. To tackle this problem, the biological sensors have upgraded into implant sensors, by radar technology, which can effectively detect heart rhythm [44, 45]. While the implantable devices can detect biological signals from the patient's body internally and send the detected signals to an external device. The implantable devices are primarily mechanized through prime cells of the body, but these cells have very little life-time and they regularly need an operation to substitute these deceased cells. To overcome this problem, wireless power transfer (WPT) technology is inserted into thin-surfaced body parts by skin [46-52].
Implantable devices can be categorized into three main groups: 1) Monitoring, 2) Therapy, and 3) Assistant. Firstly, implantable devices that have monitoring functionality detect the important parameters of the patient's heart [45, 46], like a loop recorder for recording heart rhythms. Implantable devices for heart therapy promptly send an electronic stimulus to nerve or heart. For example, dorsal stimuli and pacemakers [47-49]. The third category of implantable devices that have assistant functionality, change light or sound externally and convert them into an electronic signal and then send the converted signal to the optic or auditory nerves [51, 52]. For example, retinal or cochlear implants. Such devices are very useful for patients who lack instantaneous medical facilities. The architecture of implantable devices for cardiovascular monitoring is illustrated in figure 4.

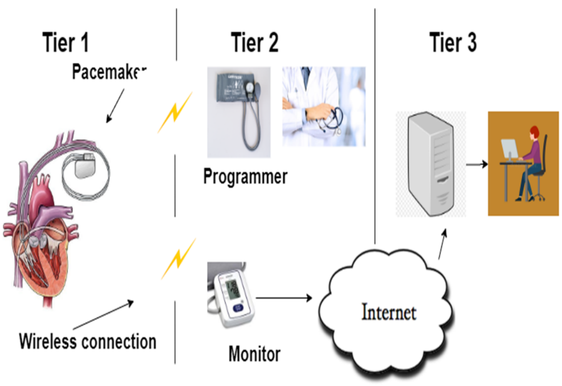


Fig. 4 General Architecture of Implantable Devices for Cardiovascular Monitoring

### 3.1 Different Implantable Blood Pressure Monitoring Devices

Other than ECG, BP is similarly an essential indicator tool for monitoring cardiovascular health. The ECG examines electrical pulses of heart, which is tested by examining the magnitudes, time intervals, and waveforms. These measurements give understanding about rhythm of a heart-beat such as how far a signal requires to move over the chambers? Magnitude of heart? etc. On the contrary, BP has closely linked toward dynamics of blood flow. Functional integrity of the circulatory system is influenced by blood flow resistance, blood viscosity, arterial rigidity and cardiac power. Therefore, for this purpose BP figures in the vascular system ("central/peripheral") and in multiple chambers of the heart ("left/right") assist the surgeon to determine it. The pressures produced by the left side ("arterial pressure") and right ("venous pressure") side of the heart vary in apex values and pulse waveform. It is essential to review these variations and to control small changes constantly [53].

Devices of second-generation use downsize and high-frequency sensors that are entirely enclosed within a chamber or vessel. Using high-frequency radio, these are received their power from external sources wirelessly and similarly their data is sent back. Presently, four kinds of devices exist (Table 4); three devices use a micro electro-mechanical system (MEMS) and one utilizes surface acoustic-wave (SAW) methodology. At this moment, CardioMEMS is the main monitoring sensor (implantable) that passed by the FDA, after the outcome of the CHAMPION experiment.

#### 3.1.1 *The CardioMEMS Device*

During CHAMPION trial60, the device was under observation for 18s by the patient each morning while lie flat across the external transmitting aerial and the assessments of the diastolic, systolic and mean arterial pressures were noted and submitted to the health professionals for clinical evaluations and to conduct alternative/medicinal change. This has proved a remarkable decline by 37% in hospital re admittance with 98.3% release from system-related or device-related complexities during the early six months after randomizing. Patients are mandated to take measuring values of pressure daily at home. Data or values transfer via the monitoring system to the database instantly and are accessible for physicians to examine [54].

#### 3.1.2 *The Titan device*

One more second-generation device is made by Integrated Sensing-Systems (ISS) using MEMS technique, especially to monitor heart pressures. After non-clinical testing performed on animal models, the device has now been implanted within four patients under open-heart

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surgery. During that early stage of patients, the injected device is examined once a day using an extra-corporeal aerial and recording unit for home-examination using a tablet PC. After that reading is stored either by a patient or medical-care professional. Three times device failure happened due to many reasons [55].

#### 3.1.3 *The Endotronix device*

The Endotronix sensor is the same as the CardioMEMS sensor. The Endotronix system uses a portable aerial that is placed over the sensor. The antenna is attached to a rechargeable high-power transmitter and receiver i.e. semi-portable. The monitor notifies patients that the aerial is in good-position and be able to take measures and afterwards transfer data to them [56].

#### 3.1.4 *The SAW device*

Acoustic wave amplifiers attain approx. 50-fold improvement of quality factor as compared to MEMS devices that contain capacitive resonators or inductive and can function effectively (higher frequencies and lower power). In theoretical work, these characteristics enhance the sensitivity to evaluate BP and probably the precision of the SAW system. The ideal location of the tool over the chest is examined by 3D visuals. The data collection involves patient activity, respiratory as well as hemodynamic information [57].

Table 4: Comparison of implantable devices for hemodynamic monitoring

| **Device Name** | **Implantation Area** | **Monitor** | **Communication Apparatus** | **Implementation** | **Technology** | **Current Status** |
|---|---|---|---|---|---|---|
| CardioMEMS Device [54] | Distal branch of the descending pulmonary artery | Pulmonary Arterial Pressure | Customized pillow | Endovascular Surgery | MEM | Approved by FDA, after the outcomes of CHAMPION experiment |
| Titan Device [55] | Left ventricle or atrium | Left Atrial Pressure | Reader device held by patient | Vascular Surgery | MEM | unknown |
| Endotronix Device [56] | In branch of pulmonary artery | Left Heart Pressure | Hand-held device | Endovascular Surgery | MEM | Tested widely in animals and is currently being experiencing on humans for first-time |
| SAW Device [57] | Main, distal right or left pulmonary artery | Pulmonary Arterial Pressure | External, body-worn reader | Endovascular Surgery | SAW | Experiencing broad preclinical trials in making of first in-human implant |

## 4. Challenges And Future Direction

There are still some technical issues that must be brought into consideration for extensive practice and implementation of wearable and implantable devices as part of the digital medical period.

### 4.1 Protection of Data

Protection of data is of great importance in wireless and wearable devices. Before introducing any device in the market, its security and privacy parameters should be checked carefully. The size of the wearable device is really small and they are able to save an enormous quantity of information, which is why there are chances about hacking or losing medical information. The Health

Insurance Portability and Accountability Act (HIPAA) is accountable for the security of medical data, and transferring electronic health information to another recording device needs encoded and protected networks. There is a need for more protected and encrypted wearable and implantable devices, possibly with GPS competences, which is preferred to diminish security and privacy threats.

### 4.2 Individually Adjustment

One issue of Wearable devices is personal calibration. All human beings are diverse, and several aspects influence their healthiness, such as nutrition, inheritances, and family medical history. Consequently, the indications for initial syndrome analysis might vary for each individual. Therefore, individually adjustment of devices and machine learning–based evaluation of information that is personalized for patients is essential for precise and appropriate observing of the health condition of the individual employing wearable and implantable devices.

### 4.3 Methodologies of Big Data

Data that is consumed by huge residents of various countries is influential, but it can create confusion for some people, which is why wearable devices must be conscious of “small data” generated by any person and correctly exploit and understand it. Or else, it will analytically generate disastrous situation for some patients.

### 4.4 Imperfect Alignment of Devices

Misalignment of wearable devices disturbs the evaluation value and correctness. Even if there is an incorrect position amid patient and device, a wearable device must have the capability of functioning and collecting correct information. This is particularly vital because of the differences in human functioning and the size/3D anatomy of various body parts on which wearable devices function.

### 4.5 Endurance of Devices

Endurance of wearable devices also necessitates additional development. Wearable and implantable devices should have the capability of functioning under various circumstances, such as in moist or rainy atmospheres and hot weather. It should have characteristics of monitoring crucial parameters of heart without delaying its operation throughout different actions like walking, running, swimming, and sunbathing.

### 4.6 Battery Life

One of the challenges is the durability of the battery. Such devices need much durability of the battery, which is particularly important in GPS tracking. GPS tracking is a vital feature of wearable devices but they utilize a significant quantity of battery power. For such devices, we need batteries with many life-times.

### 4.7 Size of Wearable Devices

The size of the upcoming wireless wearable will be reduced than the wearables we are using now. But one thing should be in consideration in reduction of size is that the sensor should be packed in such a way that they don’t compromise their effectiveness due to small size and still fulfill the heart monitoring requirements.

### 4.8 The Requirement of Approval

For health purposes, more than one hundred thousand Apps have been launched [58]. Among these Apps, mostly don’t have approval for health usage. Also, there are many sensors used in wearable devices that don’t have usage confirmation against mentioned devices in medical training. The latest research revealed the hazards associated to the usage of stress-free to approach, little price, and badly structured and invalidated devices: 159,000 individuals had downloaded, and perhaps utilized, an App primary to the miscalculation of blood pressure in 79 % of hypertension events [59]. Before making or validating any device, there should be clear discussion between doctors, companies, and specialists.

Now, we will discuss some solutions to these challenges. These suggestions can benefit the researchers in the future for the improvement in WBANs in healthcare.

Table 5: Challenges for wearable devices and their improvement suggestions

| Challenges | Enhancement Methods & their Results |
|---|---|
| Constant remote monitoring | To make sure the constant remote monitoring in WBANs, the model of numerous gateway should have a link port with the present wireless system in the medical area. |
| High Power consumption | By choosing a diverse optimal receiver location for particular sensors, transmission power can be decreased by 28 dB as recommended by the researcher in [60].<br>This can also be done by triggering the sleeping mode of the device, whenever the sensor is unused. This would result in improved time synchronization among communicated periods. |
| Sensor Optimization | Sensor optimization in WBANs can be done according to its features employing an adaptable sampling rate. To make the system power effective, there is a need for an adaptive communication protocol to provide slight variations in the system. |

| | |
|---|---|
| Receiver Complication | In [61], the researcher recommended the usage of the Dual Band scheme. For example, to use the IR-UWB device for the sense. For response at the receiver side, use a narrowband device.<br>Receiver complications can be overcome by implementing a cross-layer scheme. |
| Battery/sensor Life-time | The life-time of the battery/sensor can be prolonged by advancing the techniques of energy optimization through merging the performance of both link and physical layer. We can also use wireless charging for batteries. |
| Flexibility & Integration | Sensors used in WBANs for healthcare should not function as separate, rather these sensors should be flexible enough to work well with third-party systems. |
| Bandwidth Restrictions | Bandwidth restriction can be reduced by broadcasting several pulses/bit and by lowering data rates as being proposed by the researcher in [62]. |
| The Lesser distance among the sender and receiver aerial | For this purpose, the researcher in [63] recommended the execution of diverse aerial models employment for different body parts. |
| Proficiently Determine the Network Operation | WBANs for healthcare purposes should compose of hierarchical models so that they can perform modified services, flexibility, and energy effectiveness. For this purpose, the topology control algorithm is required to perform mathematical functions and to accurately measure the performance of the network. |

## 5. Conclusion

This article indicates that Wireless Body Area Networks (WBANs) can be extensively used in health applications. It has surveyed several systems for cardiovascular monitoring, essentially wearable and implantable devices. Wearable and implantable devices for heart ailments monitoring are presenting the excessive potential for the initial signs of serious disorders by durable constant monitoring throughout routine everyday lives of patients. Instantaneous sensing of small variations in physiological parameters of the patient can be easily tracked due to improvements in the design of electrode as well as constituents and structure of wearable and implantable devices. By avoiding hospitalization and adopting self-management and interference approaches, these devices indicate a noteworthy potential of decreasing healthcare expenses.

This article outlines the current developments in wearable as well as implantable technologies by reviewing some of the existing systems. It analyzes wireless wearable systems for ECG monitoring based on device specifications and signals acquisition module, and some FDA approved commercial wearable devices for ECG monitoring. Implantable devices for heart failure monitoring and therapy are also analyzed in this article. It also discusses the challenges and some suggestions for the improvement of those technical challenges related to WBANs. Operated by current developments in hardware as well as software, wireless body area networks are going to outcome in important innovations in healthcare practice and investigation

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