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Review Article

A comprehensive survey on low-cost ECG acquisition systems: Advances on design specifications, challenges and future direction



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ARTICLE INFO

Article history:

Received 26 October 2020

Received in revised form

19 February 2021

Accepted 21 February 2021

Available online 19 March 2021

Keywords:

ECG

Cardiovascular Disease

ECG acquisition Systems

CVD

Low-cost ECG devices

ABSTRACT

Availability of low-cost, reliable, and portable Electrocardiography (ECG) devices is still very important in the medical world today. Despite the tremendous technological advancement, Cardiovascular Diseases (CVDs) remain a serious health burden claiming millions of lives on an annual basis globally. This is more prevalent in Low and Middle-Income Countries (LMICs) where there are huge financial instability and lack of critical infrastructure and support services for the health care system. Efforts aimed at reducing the prevalence of CVDs are confounded by late diagnosis, frequently, caused by lack of access to or non-availability of basic diagnostic modalities such as the ECG. Hence effective mitigation of the effect of CVDs in LMICs depend on the development of such devices at low-cost with reliability, accuracy and energy efficiency. This paper therefore, was developed to understand the state of the art of low-cost ECG acquisition systems with respect to design features and system capabilities for different use cases. In addition, different design options and taxonomies of available low-cost ECG devices, case studies reports of efficacy tests have been provided. The paper proposes a generalised ECG framework and provides imple-

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<https://doi.org/10.1016/j.bbe.2021.02.007>

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mentation challenges and open research directions that should be considered when developing such devices for proper management of CVDs.

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1. Introduction

Cardiovascular Diseases (CVDs) is a class of diseases that affect the heart and/or blood vessels. CVD includes heart failure, stroke, hypertensive heart disease, cardiomyopathy, congenital heart disease, valvular heart disease, to mention just a few [1]. It has been established that it is responsible for about half of the global death from Non-Communicable Diseases (NCD), with over 17 million deaths per annum globally, and this is expected to increase to about 23 million by 2030 [2]. Out of the 17 million premature deaths (under the age of 70) due to NCD in 2015, 82% are in LMIC, and 37% are caused by CVDs [2]. In 2015, 17.7 million people died from CVDs, repre-

senting 31% of all global deaths. Of these deaths, an estimated 7.4 million were due to coronary artery diseases and 6.7 million were due to stroke [3]. Fig. 1 shows the global leading causes of death in 2016, among which 32.3% are as a result of CVD [4].

In Nigeria, the number of annual deaths as a result of heart-related problems is in excess of 150, 000 and this is expected to exceed a million by 2030 [5]. In furtherance to this, [6] determined the most common CVD in Northwestern Nigeria, between 2001 and 2005, the study reported Hypertension as the most prevalent CVD, while, congenital heart

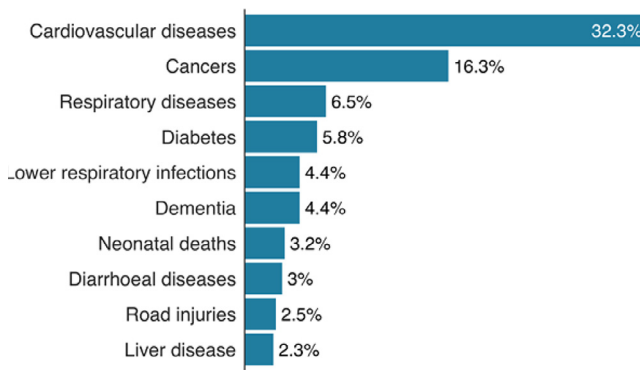


Fig. 1 – Leading causes of death globally [4].

disease, was the lowest. A steady increase in the incidence of CVD was however observed during the period under review. Coronary artery disease and hypertension are not the only causal factors for heart failure, as Type 2 diabetes mellitus (DM2) have been found to have increased the risk for heart failure in patients, even in the absence of coronary artery disease and hypertension [7]. This called diabetic cardiomyopathy which is typically characterized by left ventricular (LV) diastolic dysfunction [8] and has very high prevalence up to 50% [9]. Zimmermann-Schlegel et al. [7] explored the impact of depression on heart rate (HR) and Heart Rate Variability (HRV) as a marker of Autonomic Nervous System (ANS) impairment in depressed and non-depressed patients with advanced type 2 diabetes mellitus (T2DM) and was found that depression was not directly associated with cardiac autonomic control. However, the mindfulness-based group intervention training may have influence on the HR and HRV. Liraglutide has however been found to reduced early left ventricular diastolic filling and left ventricular filling pressure in patients with diabetes mellitus type 2 (DM2) [10].

Electrocardiography (ECG) is considered as the most basic and most widely used investigation for evaluating the heart. It records the activities of the heart in a dynamic real-time fashion. The first ECG recording was done in 1887 [11]. The most common modality used nowadays is the 12-lead ECG system that was developed in 1942. It has been established that this type of test is capable of providing information that is not available from other tests. Also, it has some unique characteristics such as simplicity, simple to undertake, and uniqueness. In addition to the recording of electrical activities, ECG is also used in large clinical trials to determine the suitability and effects of new drugs. ECG abnormalities are classified based on Minnesota coding whereby, an internationally agreed set of rules is used to describe the ECG pattern [12]. This technique is used for large-scale analysis by Epidemiologists. The entire procedure of carrying out an ECG recording is risk-free [13]. Contemporary applications of ECG now included ECG units that are PC (Personal Computer) based gadgets and can be associated with the PC system to enable concurrent monitoring of several patients [14].

The Holter ECG monitoring has been introduced in the 1960s and since then, it has been largely used as a convention for the investigation of cardiac arrhythmias mostly for outpatients. The monitor offers up to 72 h continuous ECG record-

ings with the benefits of obtaining complete records of all beats within the 24–48-h. This, consequently, permits the identification of baseline rhythm and other conduction anomalies such as pre-excitation syndromes and bundle branch blocks. However, the relative size of the Holter device, inconvenience, and its inability to support long term monitoring resulted in low diagnostic yield.

In today's clinical cardiology, it is desirable to extend the period of the ECG monitoring thereby improving the diagnostic yield and compatibility with typical real-world applications such as in homes and workplaces. Thus, this necessitated the development of portable devices that are lightweight, such as Event Recorders (RE) and Implantable Loop Recorders (ILR), that would provide long term recording periods of cardiac activity. However, cost-effectiveness and device capability of connecting to smartphones and remote monitoring centres that would meet the desired needs of remote areas, particularly in low and middle-income countries are issues of concern [15,16]. Even though, extending the monitoring duration has proven to give higher diagnostic yield, yet, the optimum duration for monitoring is case-specific [17]. Most of the new ECG devices developed, come with different designs interfaces and features that ultimately affect their accuracy, size, sensitivity, specificity, reliability and power consumption. These, have significant implications for device development, cost and device selection, from clinical and research point of views. Despite considerable efforts geared towards the development of cheap and portable ECG devices, the diagnostic accuracy, reproducibility, features and utility components are still major issues that can not be sacrificed.

This paper therefore, has proposed a critical review of low-cost ECG acquisition systems with special emphasis on design elements, signal acquisition, transmission links, application interfaces and prediction accuracy. Furthermore, different designs and implementations based on cost-minimizations have been reported. In addition, different design options and taxonomies of available low-cost ECG devices, case studies reports of efficacy tests have been provided. The paper provides implementation challenges and open research directions that should be considered when developing such devices for proper management of CVDs particularly, in the low and middle-income countries.

The remaining part of this paper is organised as follows: In Section 2 we presented the list of abbreviations and acronyms used in the paper. The previous reviews on ECG monitoring systems are presented in Section 3. Section 4 presents the experts' taxonomy of ECG monitoring Systems. In Section 5 we provided a simple generalised ECG framework. Section 6 highlights the ECG monitoring systems designs and various implementations. Section 7 presents trials, performance studies evaluations and case studies report from different authors. Section 8 discusses the challenges and open research areas, and finally, Section 9 concludes the paper.

2. Definition of abbreviations and acronyms

Table 1 provides a list of Abbreviations and Acronyms used in the paper.

Table 1 – Abbreviations and acronyms.

AC	Alternating Current
AAA	Abdominal Aortic Aneurysm
ADC	Analog To Digital Converter
AI	Artificial Intelligence
AF	Atrial Fibrillation
BP	Blood Pressure
BLE	Bluetooth Low Energy
BAN	Body Area Network
CVD	Cardio Vascular Disease
CMPCYBHIDC	CardiomyopathiesThe Check Your Biosignals Here initiativeDirect Current
DSS	Decision Support System
DDA	Differential Diagnoses Algorithm
ECG	Electrocardiogram
EDA	Electrodermal Activity
EEG	Electroencephalogram
EGG	Electrogastrogram
EMG	Electromyogram
ES	Expert System
FAA	Federal Aviation Administration
GUI	Graphical User Interface
HPF	High-Pass Filter
HHD	Hypertensive Heart Disease
ICM	Insertable Cardiac Monitor
IA	Instrument Amplifier
ICU	Intensive Care Unit
IPI	Interactive Progressive Based Interpretation
IoTILR	Internet of ThingsImplantable Loop Recorders
LCD	Liquid Crystal Display
LMIC	Low and Middle-Income Countries
LPF	Low-Pass Filter
NCD	Non-Communicable Diseases
NF	Notch Filter
PAD	Peripheral Arterial Disease
PDA	Personal Digital Assistant
RFID	Radio Frequency Identification
RHD	Rheumatic Heart Disease
SCAF	Sub-Cutaneous Electrocardiographic Monitors To Monitor Subclinical Atrial Fibrillation
UART	Universal Asynchronous Receiver/Transmitter
USB	Universal Serial Bus
WMEMS	Wearable Mobile Electrocardiogram Monitoring System
WBAN	Wireless Body Area Network
WHIMS	Wireless Health Monitoring System
WHO	World Health Organization

3. Previous ECG monitoring systems reviews

This section presents previous reviews of ECG monitoring systems from 2011 to 2020. We focused on the recent developments as evident in the review articles while at the same time trace the advancement in this field. Each review was conducted for a particular purpose and taxonomy. Víctor et al. [18] presented a review that provided details on ‘LOBIN’ which was an E-Textile and remote sensor-based platform for healthcare monitoring in future emergency clinic conditions and environment. Various architectures and communication

technologies for Wireless Health Monitoring System (WHMS) were highlighted. Parameters such as frequency band, data rate, range, transmission power, network topology and stack size for different monitoring technologies were compared. In [19], a review was conducted on application of wearable sensors in restoration and rehabilitation. The review explores various sensing technologies and assessed the treatment efficacy of these rehabilitation systems. An extensive review of various ECG signal processing software and algorithms from the perspective of Smart wearable ECG monitoring systems for older adults was conducted by [20]. It was discovered that most exploration in wearable ECG monitoring systems is centred around older adults. Also, some limiting factors such as forced impediments on patients, short battery life, absence of client’s acceptability and security, and privacy were identified. Ref. [21] reported a brief review of the appropriate components with which a portable ECG machine can be constructed, citing some companies who have had success in designing their own remote ECG monitoring system. A 5 module system for heart monitoring systems was proposed by [22], these include; body sensors, signal conditioners, Analog-to-Digital Converter (ADC) and pressure, remote transmission and analysis, and arrangement modules. The work stressed the need for the utilization of mobile phones for monitoring purposes as it wipes out extra hardware ownership, hence, expands client comfort. Nicole et al., [23] presented a qualitative review of the implementation of Atrial fibrillation screening in pharmacies using an iPhone ECG. The paper investigated the experience of executing an atrial fibrillation screening administration from the drug specialist’s or pharmacist’s point of view and it was found that people can develop the fear of being screened for heart diseases.

One of the benefits of a continuous real-time monitoring system is its capability of generating a large amount of ECG signal data for storage and processing. Moreover, the restrictions on movement imposed on some patients justify the need to access the ECG data remotely. However, the need to filter signal noise and artefacts, and compress the size of the sample data is necessary. This influences the choice of ECG compression technique [24,25]. These problems have further been highlighted in many works [25,18,26]. Some non-versatile signal processing strategies applied for fetal electrocardiogram were presented by [27]. Furthermore, [28], presented surveys of various filtering and detection methods of ECG signals in the context of reliability and energy efficiency. The review paper classified embedded devices used for ECG monitoring into two folds: (i) a pure acquisition system that stores and transmits continuous data to health centres for monitoring and (ii) a system that acquires and detects events or cardiovascular diseases.

In more recent times, with the aid of ECG data repository, automated or computer analysed methods were developed for recording, classifying and interpreting of the ECGs. There are several ECG databases available around the world such as the American Heart Association Database for Evaluation of Ventricular Arrhythmia (AHA DB), Massachusetts Institute of Technology-Beth Israel Hospital Arrhythmia Database (MIT DB), European Society of Cardiology ST-T Database (ESC DB), Noise Stress Test Database (NST DB) and Creighton University Sustained Ventricular Arrhythmia Database (CU

DB). Reviews on ECG database are scanty, however, [29] presented a review of the ECG databases, with a focus on CYBHI (The Check Your Biosignals Here initiative) and UofDB databases. The work highlighted the need for standardization and open access rights for wider accessibility. These would, in turn, minimize the time lag in ECG reports, providing quick services and avoid high susceptibility to observers' bias when applying subjective assessment of ECG signals, which are relatively tedious and time-consuming.

In [30], the coherent taxonomy on the application of triage and sensors on remote health monitoring systems was established. The first category included studies and reviews on triage and priority-based sensor innovation in telemedicine. The subsequent category examined articles on the three-layered engineering of telemedicine; users, network, and healthcare providers' tier. The work provided recommendations in handling and controlling real-time remote health systems to designers, analysts, doctors, and patients in different fields of telemedicine.

In [31], a review of the ongoing advancements in the area of ambulatory and remote monitoring solutions to cardiovascular diagnostics was presented. The review highlighted various diseases monitored with ECG in the light of wearable devices, cell phones and other ambulatory sensors. The restrictions of current advances, their adequacy and their adoption in the general population were identified. An extensive review on the use of implantable cardiac defibrillator (ICD) for sudden cardiac death prevention was presented by [32]. The work focuses on the underlying issues affecting the selection of ICD and its role on patients with non-ischaemic cardiomyopathy. The review concluded that patients' clinical characteristics and the advantages or otherwise of each ICD device should be taken into account. Architectures of ECG systems were examined and classified into various monitoring contexts; home, ambulatory, hospital and remote monitoring [33]. The review analyzed the ECG monitoring value chain which assisted in comprehending the worth and contribution of every processor module as characterized in [22]. An expert scientific classification of ECG monitoring frameworks was likewise conducted to help researchers analyze and classify these systems. This led to the creation of a model called "Cluster" which alludes to a class of examination works sharing basic attributes. The different bunches proposed are context-aware ECG monitoring frameworks, innovative ECG monitoring frameworks, ECG monitoring systems that are dependent on plans and frequency, ECG observing frameworks, targets and purposes, and Futuristic ECG observing systems.

In Table 2, we provided a summary of the previous reviews conducted on the ECG monitoring systems. Objectives of the work and common findings were all presented. It is worthy to acknowledge the efforts invested in ECG monitoring framework reviews that have been carried out in the past decade due to the rapid development of cutting edge monitoring strategies and techniques. However, past works concentrate mainly on taxonomies and did not provide a component synthesis for the ECG monitoring systems. More so, the efficacy and case studies reports have not been addressed by past reviews.

4. Experts' taxonomy of ECG monitoring systems

In Fig. 2, the experts' taxonomy of the ECG monitoring systems is presented. The development of the monitoring system is divided into five main clusters based on, context-aware, technologies, scheme and frequency adopted, target and purpose, and the futuristic monitoring systems [33].

4.1. Applications domain-specific (context-aware) low-cost ECG devices

Considering the experts' taxonomy of the ECG monitoring system in Fig. 2, the specific design components of the ECG monitoring system would depend on the domain where the device would be applied. The context-aware generally rely on the purpose and application deployment areas of the system. There have been four categories of designs of low-cost ECG monitoring systems [33] and each design was developed for specific purpose and functionality. Thus, the designs were classified as Home-based, Hospital-based Remote-based and ambulatory-based designs. These are described further hereunder:

(i) Home-Based Design Specific Systems

This ECG monitoring is designed for home use and could be categorized into (i) telemonitoring, (ii) wearable continuous monitoring, and (iii) system for monitoring elderly ones in the society. Generally, the systems are designed and developed to reduce the burden to hospitals having patients that require continuous health monitoring at homes. In the same way, it is suitable for people with life-long, chronic diseases and elderly people that need continuous surveillance and monitoring.

(ii) Hospital-based design specific systems

This monitoring system is designed and developed for hospital applications. Depending on the design; it can be suitable for the Intensive Care Unit (ICU) clinical setting wherein the device can be used to detect and predict the mortality rate among patients. Another design is a non-ICU clinical setting which can be used for remote monitoring of outpatient. Also, it can be used to improve the diagnostic accuracy of cardiac arrhythmia. Besides, this specific design can still be used to obtain information from patients. The third option is the Holter setting/model that could be connected to a patient's body through the use of electrodes.

(iii) Ambulatory-based design specific systems

Presently, this technology supports ECG data collection, transmission and analysis for an emergency in ambulances. Globally, there are many efforts in this area cutting across design and development. The monitoring can be categorized into textile-based and countless-based ECG monitoring technologies. In any of the categories, the system was used for

Table 2 – Summary of Previous ECG Monitoring Systems Reviews.

Authors	Year	Title	Objectives	Comments/Findings
[19]	2012	A survey of wearable sensors and frameworks and their application in rehabilitation.	To provide advancements in the field of wearable sensors and to give a short portrayal of key empowering advances (e.g sensor innovation, technology advancements in communication, and techniques in data analysis)	The first decades of examination in the field of wearable technology was centred around the designing work needed to create wearable sensors and frameworks, ongoing investigations have been centred around the use of such innovation toward real-time health monitoring.
[18]	2012	A Review on Architectures and Communications Technologies for Wearable systems on health monitoring.	To survey and give more subtleties on the work introduced in “LOBIN: E-Textile a Wireless-Sensor-Network-Based Platform for Healthcare Monitoring in Future Hospital Environments”.	Points of interest and weaknesses of utilizing various models and communication advances to create wearable frameworks for applications on pervasive healthcare were provided.
[20]	2013	A comprehensive survey of wearable and wireless ECG monitoring systems for older adults	To explore wearable ECG monitoring systems	The survey recommends that most exploration in wearable ECG monitoring systems centre around older adults. The principal downsides of conveyed ECG observing frameworks including forced impediments on patients, short battery life, absence of client's acceptability and security, and privacy of essential were identified. Detailed explanation of ECG waveforms and various parts of an ECG system were provided
[21]	2013	A Review on Design of Portable ECG System	To present a review on the considerations for the design of a portable ECG machine, which mainly deals with the circuitry of ECG machines, such as electrodes, analog front end unit, processing, and display units	
[22]	2014	Heart monitoring systems - a review	To give an explicit review of ongoing headways of heart monitoring systems.	ECG systems have restrictions in long term heart-monitoring because of the prerequisite of skin contact of electrodes and the utilization of gel. The utilization of mobile phones for monitoring purposes wipes out extra hardware ownership and thus expands client comfort
[26]	2014	Wavelet-based electrocardiogram signal compression methods and their performances: A prospective review	To introduce a forthcoming review of wavelet-based ECG compression techniques and their exhibitions.	Wavelet-based compression technique shows an improvement in compression effectiveness that isn't seen in the other change based compression strategies
[23]	2015	Atrial fibrillation screening in pharmacies using an iPhone ECG: a qualitative review of the implementation	To investigate the experience of executing an atrial fibrillation screening administration from the drug specialist's or pharmacist's point of view	People can develop the Fear of being screened for heart diseases.
[24]	2015	A Review of ECG Data Compression Techniques	To give an examination of the significant strategies (boundary extraction, direct, transform, and 2D approaches) of ECG information compression.	The need to filter signal noise and artefacts, and compress the size of the sample data influences the choice of ECG compression technique.

Table 2 – Continued.

Authors	Year	Title	Objectives	Comments/Findings
[34]	2016	A review of ECG-Based diagnosis support systems for obstructive sleep apnea	To review papers that aim to automate Obstructive Sleep Apnea detection.	OSA detection is difficult because ECG signals are complex, complex detection tasks are best handled with computer algorithms.
[25]	2016	Design, a review of wireless ECG monitoring systems	To summarize the latest advancements in the field of wireless heart monitoring.	GPS is very useful for determining the location of the patient in an emergency. It aids the efficiency of remote monitoring.
[35]	2016	Review of ECG Compression Techniques and Implementations	To review the diverse ECG compression strategies and ECG compression usage accessible in the literature.	ECG compression requests fluctuate from one application to another. The choice of ECG compression technique for genuine ECG information compression will consistently be the exchange off between memory prerequisite, computational intensiveness, and simplicity of usage.
[29]	2016	ECG databases for biometric systems: A systematic review	To provide a quantitative analysis, assess and compare the acquisition equipment and the procurement protocols of ECG databases accessible in the literature and fit to create Computer-based biometric systems (CBBSSs)	ECG signals can be used for biometric systems due to its stability over a period of time
[28]	2016	Review of Energy-Efficient factors for ECG Devices	To survey different methods used or proposed for noise removal of ECG signals and different methods for detection of Ventricular fibrillation.	For the long term, ECG monitoring, Wavelet-based transforms perform better based on reported performance in removing the different noises, although requiring more computational power and hence more energy.
[27]	2018	Non-Adaptive Methods for Fetal ECG Signal Processing: A Review and Appraisal	To introduce a broad literature overview of various non-versatile signal processing strategies applied for fetal electrocardiogram extraction and improvement	Various types of non-versatile signal processing strategies were highlighted. These methods can be used to monitor fetal ECG
[30]	2018	Systematic Review of Real-time Remote Health Monitoring System in Triage and Priority-Based Sensor Technology: Taxonomy, Open Challenges, Motivation and Recommendations,	To present a comprehensive survey and classification of works related to real-time monitoring frameworks in Triage and Priority-based sensor innovations	Provided recommendations in handling and controlling real-time remote health systems to designers, analysts, doctors, and patients in different fields of telemedicine.
[32]	2019	Current device therapies for sudden cardiac death prevention—the ICD, subcutaneous icd and wearable ICD	To provide extensive review on the use of implantable cardiac defibrillator (ICD) for sudden cardiac death prevention	Patients' clinical characteristics and the advantages or otherwise of each ICD device should be taken into account
[31]	2020	Wearable Devices for ambulatory Cardiac Monitoring	To provide the state of the art advancements in the area of mobile and remote monitoring solutions for cardiovascular diagnostics.	Remote and ambulatory monitoring shows a noteworthy capability of diminishing social insurance costs by forestalling pointless hospitalizations.
[33]	2020	ECG Monitoring Systems: Review, Architecture, Processes, and Key Challenges	To propose a far-reaching, expert-verified scientific categorization of ECG monitoring frameworks and lead a broad, orderly survey of the literature.	The current advancements in ECG monitoring frameworks utilized innovations, for example, deep learning, AI, Big Data, and IoT to give effective, cost-productive, completely connected, and incredible monitoring frameworks.

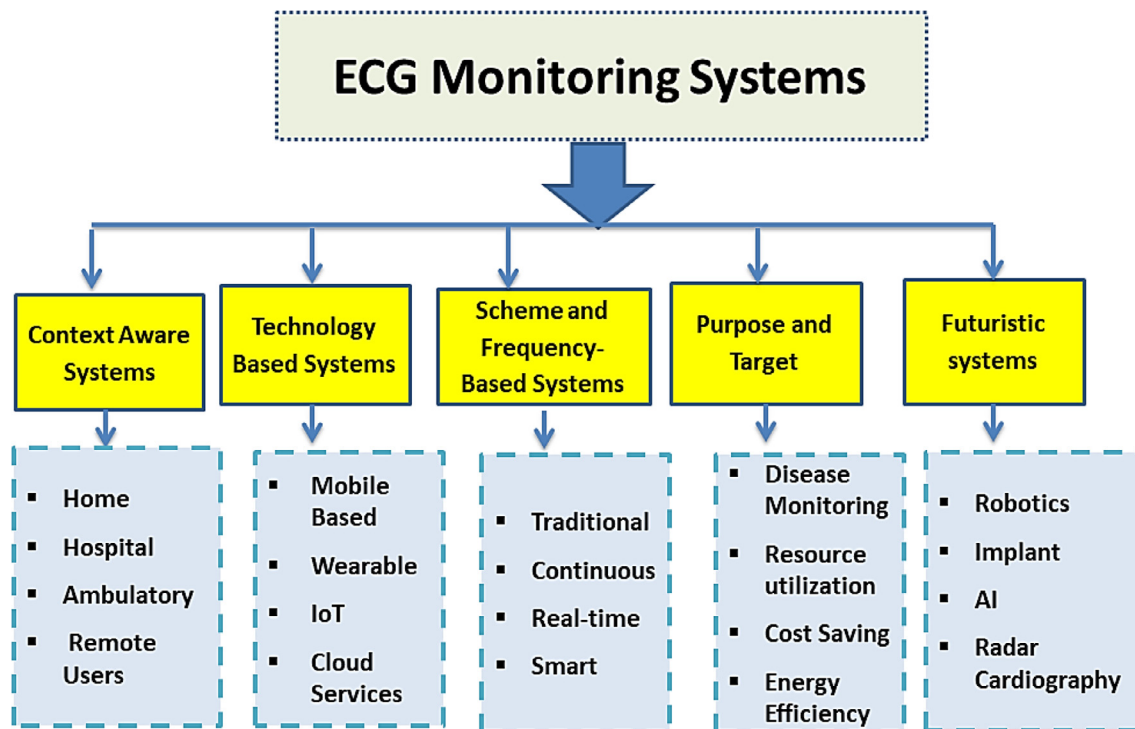


Fig. 2 – Experts' taxonomy of ECG monitoring systems [33].

monitoring and detection of arrhythmias in both ambulance and home situations.

(iv) Remote-based design-specific

Remote-based technology designs are specific for distant patients that undergo frequent movement. Therefore, the systems are designed to detect different cardiac disorders. It can also detect a sudden change in cardiac parameters. Therefore, it is suitable for real-time monitoring of the patient and remote diagnostic issues.

4.2. The technology-aware ECG monitoring systems

Technology-aware ECG monitoring systems emphasized the type of enabling technologies that would be used to support the ECG monitoring. This may involve the Internet of Things (IoT), Cloud Infrastructure and Storage, and Fog computing for high-end processing, low latency, and energy efficiency, and cost of data transmission over the cloud [36,37]. This is of particular interest in the case of emergencies where real-time ECG data are needed. Quite a number of research initiatives that implemented enabling and emerging technologies for efficient, accurate and real-time ECG data transfer for the internet. Such implementations include; Edge Computing Devices [37,38]; Cloud-based Services [39–41]; IoT-based Solutions [42–44] and Wearable Devices [45–47].

4.3. The scheme and frequency-based ECG monitoring system

The scheme and frequency-based system focus on the computational aspects of the ECG monitoring system. The

scheme for ECG data collection depends on the system set up in which the patients' ECG signal is measured and analyzed using the Traditional monitoring setup [33] by direct connection between the patient and the ECG devices. Measurements are conducted on one-time (ad hoc) or the real-time ECG monitoring where patients data are monitored continuously such as the 24-hour Holter monitoring [46]. These designs have been widely used in hospitals [48] or remote [49] settings for monitoring HRV. The methodology for data collection, monitoring duration, activity of the subject and indeed the study population are paramount when monitoring the HRV as [50] found that time-domain variables are sufficiently enough in describing the HRV from long-term ECG monitoring. However, further cautions are required for the selection and use of frequency-domain variables. In furtherance to the effect of activity of the measurements outcomes, resistance exercise have been found to have great impact on the HRV measurements [51], where, the validity of Heart Rate Variability (HRV) measurements from photoplethysmography (PPG) via a smartphone application was examined using pre- and post-resistance exercise (RE) on Thirty-one adults. The measurements were conducted simultaneously using the ultrashort-term ECG and PPG, and it was found that the measurements for HRV for the smartphone PPG and that of the ECG were comparable, particularly, when the subjects are at rest, but errors were observed after resistance exercise. One of the benefits of a continuous real-time monitoring system is its capability of generating a large amount of ECG signal data for storage and processing. However, the need to filter signal noise and artefacts are necessary. These problems have been highlighted in many works [52], hence requiring advanced noise filtering and smart features selection algorithms.

4.4. The targets and purposes of ECG monitoring systems

The targets and purposes of ECG monitoring systems are designed for specific targets, thus requiring specific functionalities. These are broadly categorized into service-based or performance-based ECG monitoring systems [33]. The service-based ECG monitoring systems could be medical applications (detection of CVDs) or non-medical applications (such as sports and elderly activities). However, performance-based monitoring systems intend to concentrate on performance improvements of the system itself in terms of cost, energy efficiency, battery life, and reliability among others.

4.5. The futuristic ECG monitoring systems

Modern technologies such as the IoT, Artificial Intelligence (AI) and robotics systems will play a vital role in revolutionising the health care system. These may include the integration of radar cardiography, implants, robotics, steganography, and other AI technologies into the mainstream of the ECG data collection and processing. The futuristic system is seen as domain-specific due to the fact that the design and enabling technology deployments would be influenced by the application domain where the ECG will be collected and processed. Real-time and continuous heart rate monitoring could be challenging in contemporary healthcare systems. Radar cardiography is identified as enabling technology that provides touchless, contactless, and continuous monitoring of heart rate through clothes, blankets, or other isolators [33]. The relative small size of implanted sensor technologies such as the Insertable Cardiac Monitors (ICMs) makes it a good candidate for long-term continuous monitoring up to three years and this type of technology are suitable for continuous ambulatory ECG monitoring settings. Advancements have been made recently where robotics are introduced into the healthcare system particularly, where there is limited medical manpower. Already, such practical applications have evolved where robotic-assisted heart surgeries have been achieved [53]. Therefore, this affords new opportunities for deploying robots in cardiac monitoring, medical feedback, diagnosis, and notifications [54].

Artificial Intelligence (AI) technologies have also advanced opportunities in ECG recording, automation, classification and interpretation. Development of medical Decision Support System (DSS) and Expert System (ES) for effective detection and diagnosis of CVDs is of great importance. Building accurate and fast techniques for automated ECG, heartbeat signal classification and monitoring is vital for clinical diagnosis of different CVDs. Researchers have proposed different models for automatic ECG heartbeat classification [55]. One major challenge for automatic ECG analysis is the significant variability in waveforms and characteristics of ECG signals among different patients and patient groups. However, it is worthy noting the work by [56] where an Automatic Subject-Adaptable Heartbeat Classifier was developed based on Multiview learning to address significant inter person variations in ECG signals. In the design, two models were used, the general model that was trained using similar subjects out of a population dataset and a pattern matching

based algorithm was developed to select the subjects that are “similar” and specific classification model that was trained using a small amount of high-confidence personal dataset. The models were found promising. Recently, other novel automatic ECG Classification methods are presented in [57] using Continuous Wavelet Transform and Convolutional Neural Network; in [58] using Pre Trained Neural Networks and in [59] using hybrid signal processing and neural networks.

A decision support system called Interactive Progressive Based Interpretation (IPI) to complement the human interpretation of ECG tracing is proposed by [60]. The work integrates decision support algorithm, Differential Diagnoses Algorithm (DDA) to suggest potential diagnoses based on the interpreter’s annotations of the 12-lead ECG. A deep neural network with pretraining using input from raw ECG signals was proposed by [61]. The experiment involved 1390 patients at Hospital Clinic in Barcelona between 2011 and 2012. Each patient was exposed to a 12-lead ECG and diagnosis was conducted by the cardiology service at the same hospital. Automated tools, web-based solutions assist medical specialists in the diagnosis and early detection of numerous diseases. The detection of asymptomatic Atrial fibrillation requires a long-term monitoring, this monitoring is found to be more efficient when the heart rate (HR) features are estimated based on the irregularity of the beat-to-beat intervals. An automated classifier based on Lagrangian Support Vector Machine was developed by [62] consisting of sixteen features. The classifier was validated with the MIT-BIH AF Database and was found to have achieved a sensitivity of 98.94%, positive predictive value of 98.39%, and classification accuracy of 98.86%. Cardiac abnormality is another major cause of the Congestive Heart Failure (CHF). The oxygenated blood supply from the heart to the body tissues is disrupted as the results of this abnormality, hence, resulting in abnormal functioning of the body, which eventually, weakens the ventricles and ejection fraction of blood that results in heart failure [63]. Recently, support vector machine classifiers are developed to diagnosis of CHF patients. In [63], eigenvalue decomposition of Hankel matrix (EVDHM) method was employed to analyze heart rate variability (HRV) signals for the diagnosis of CHF. The least-squares support vector machine (LS-SVM) classifier coupled with the radial basis function (RBF) were used. In the study, three normal datasets and two CHF datasets were employed. Findings from the work show greater improvements with accuracy of 93.33%, sensitivity of 91.41%, and specificity of 94.90%. The automated toolkit can aid cardiac physicians in the accurate diagnosis of CHF patients hence, providing timely treatment for CHF patients and subsequently, saving life. Alfaras et al., [64] developed classifier that is fast, automatic and used a simple brain inspired machine learning approached called Eco State networks. In addition, the classifier has low demand capability since both training and validation used inter-patient technique. Due to the nature of signal generated as a result of heart activities and non-stationary nature of the ECG signal there is difficulty in the analyses of arrhythmias. [65] developed a better method of the analyses based on Genetic Bat optimization algorithm for training support vector machine.

The developed method outperformed KNN, Neural network (NN), Fuzzy Subtractive Clustering and Support Vector Neural Network (SVNN) considering accuracy, sensitivity and specifications. In similar manner, another identification algorithm called nonconfidential ECG identifier algorithm has been demonstrated in [66]. The proposed algorithm is statistical base. In addition, the feature extraction approached used were direct and band based. The proposed method achieved accuracy of 99.61%. A method that does not require ECG wave delineation to achieved the required compression of the ECG signal has been developed in [67]. Also, the method is flexible such that any training method could be adopted by simple alterations in the training template. It was shown that the proposed method could identify and extract feature with about 98% biometrically. The authors in [68] investigated another technique for the extraction of silent information from ECG signal. The study was based on the use of discrete

wavelet transform (DWT) technique. The authors were able to study the effects of de-noising orders, type of mother wavelets and threshold levels on the final authentication of the model. The feasibility of the proposed system was shown in real life and has achieved Genuine Acceptance Rate (GAR) of 92.5%, False Acceptance Rate (FAR) of 5% and Equal Error Rate (EER) of 6.9499%. A novel method called short for Peak-to-peak entropy, R-R interval entropy, Correlation coefficient and Heart rate (PRCH) was proposed by [69] for maternal ECG QRS detection. The proposed method used four features for identification. These includes correlation coefficient, amplitude, instantaneous heart rate, morphology and average heart rate for decision making. The decision due to its complexity was carried out using machine learning. Other advanced methodologies proposed to improve the automatic detection and classification of the ECG signals to ease the work of doctors are discussed extensively in [70].

Table 3 – Applications domain-specific low-cost ECG devices, causal factors and enabling technologies and services.

Application Domain	Application Context	Causal Factors	Enabling Technologies and Services for the ECG Device
Home	■ Elderly Patients Monitoring	■ Burden to hospital	■ Integrated smart system
	■ Wearable continuous monitoring	■ Comfort	■ Data transmission mode
	■ Telemonitoring	■ Lifelong and Chronic disease ■ Elderly	■ IoT ■ Real-time ■ Cost-Effective
Hospital	■ ICU continuous Monitoring	■ General Outpatients	■ High performance-system
	■ Non ICU continuous Monitoring	■ ICU patients	■ Storage capability
Ambulatory	■ Holter monitoring		■ Traditional monitoring
	■ Ambulatory cardiac monitoring	■ Chronic disease	■ Data transmission mode
	■ Telemonitoring	■ Emergencies	■ IoT ■ Storage capability ■ Cloud-Based Storage ■ Real-time ■ Continuous monitoring ■ Energy Efficient
Remote	■ Real-time monitoring	■ Burden to hospital	■ Integrated smart system
	■ Patient self and remote diagnosis issues.	■ Comfort ■ Lifelong and Chronic disease ■ Elderly	■ Data transmission mode ■ IoT ■ Cloud-Based Storage

In Table 3, we provided a summary of the ECG monitoring systems based on their application areas, causal factors and basic requirements and services for the device.

5. Generalised ECG framework

In LMIC countries, there is a poorly developed health infrastructure, particularly in the rural areas where over 60% of the population resides. Further complicating the anomaly is the overall marginal expenditure on health culminating in poor access to efficient and effective health care system. Remote monitoring of health indices such as heart rate and rhythm real-time would allow for early detection and evaluating of the risk associated with it. In Fig. 3, a typical generalised ECG framework is hereby proposed. The framework consists of low cost and energy-efficient ECG acquisition unit that captures electrical activity of the heart, transmits the signal to an ECG device that processes the signal and then the processed ECG data will be transmitted to a smartphone via Bluetooth. The ECG device can also have WiFi capability to ensure the transmission of the ECG data to the Cloud. Aggregated ECGs from different smartphones could be transmitted to a centralized cloud-based server from where the ECG core laboratories pull the ECG tracings. The Cardiologist can access patients' ECGs directly from the patients' mobile phone or cloud server for interpretation. Alternatively, the ECG reports could be obtained from the ECG core laboratory, copies of

which could also be transmitted electronically to the patient's mobile phone.

6. ECG monitoring systems designs and implementations

Depending on the application domain and purpose, the ECG acquisition systems come in two forms, i.e. single lead and multiple leads ECG monitoring system. Each of these is discussed thus:

6.1. Lead configuration for ECG monitoring system

6.1.1. Single lead ECGs

Single Lead is used for basic heart monitoring. It can also be useful in checking various arrhythmias and in some cases for simple educational and research activities. Other includes establishing the effects of exercises on the ECG. Furthermore, a single lead recorder could be used to achieve the 12 lead recordings sequentially. Due to simplicity, and for personal, home and sports use, there are many handheld ECG recorders available in the market. Once medical personnel or trained emergency personnel is available, they can be used for emergencies otherwise they can be used for public use to establish baseline information of patients. In some cases, it can be used for routine monitoring and uncommon situations. Some of the existing single lead devices can be seen in Fig. 4. Table 4

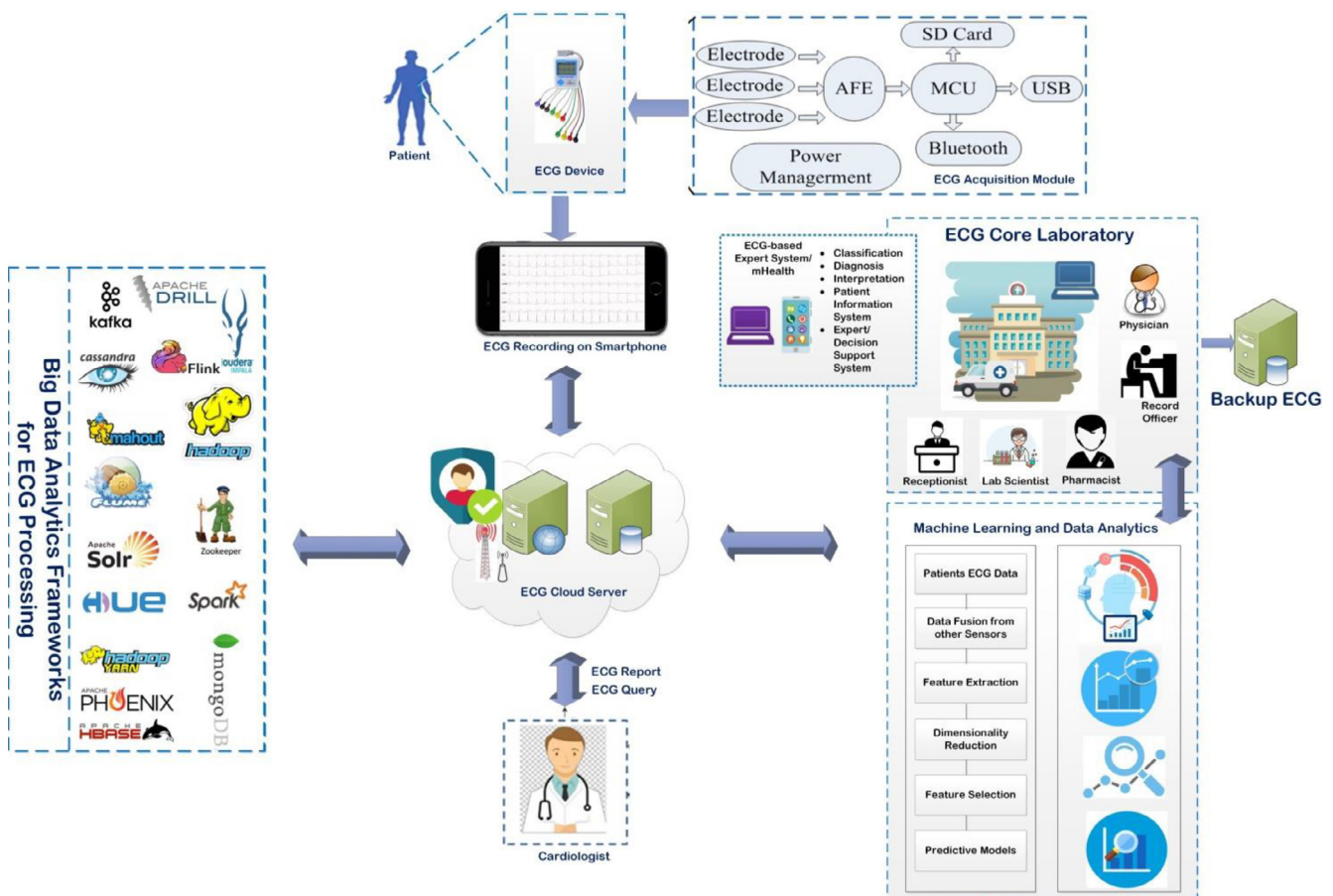


Fig. 3 – Generalised ECG framework.



Fig. 4 – Some available single ECG device [71].

provides some commercially available single lead devices and their features.

6.1.2. Multiple lead ECGs

Different ECG devices can distinguish irregular rhythms and ischemic anomalies localization. It uses chest patch /electrodes. An example of such devices can be seen in Table 5. In some cases, they can be categorized as second-generation ECG devices. They are available in both wearable and non-wearable forms. Unfortunately, the literature on wearable ECG devices is scanty due to many constraints such as regulations, environmental, and domain of development.

In Table 6, we provided the taxonomy of Utility components of some available commercial ECG Devices. Both in Single and Multiple leads ECGs were considered. The Table provides the utility component such as display capability, built-in battery, transmission capability, cloud-based service support, smartphone interface, inbuilt GPS among others are all provided.

6.2. Design elements of ECG acquisition system

As the heart experiences the process of depolarization and repolarization, electrical charges spread all through the body that goes about as an electric volume conduit [72]. Besides the heart, electrical activities have other sources in the body. Hence, the different signals that can be observed via the skin surfaces due to the electrical activities in the body have been

listed in Table 7. Note that the scope or range of Electromyogram (EMG), Electroencephalogram (EEG), and Electrogastragram (EGG) frequency spectra and amplitudes of the signal overlap with the ECG signal [72]. Thus, the signal intended to be observed guides the designs of the acquisition system – in this case, the ECG. Typical ECG signals usually have a signal amplitude range of about 0.5–4 mV with a frequency range of 0.01–250 Hz [73]. The electric potential differences that are seen between electrodes configuration connected to body surfaces represents their time course and are consequently used for obtaining ECG leads [74]. An ECG signal processing system design chain usually consists of the sensors, Instrumentation Amplifiers (IA), filtering circuits (low-pass filters (LFP), high-pass filters (HP), and notch filters (NF) if necessary) before it is passed on for further processing as shown in Fig. 5. Any ECG signal processing chain would consist of all or most of these components with other additional components such as operational and isolation amplifiers.

Usually, the first stage of the IA (front-end) is used to amplify any incoming signal to the desired amplitude level for easy acquisition. Various instrumentation amplification stages have been designed using components such as ADS129X series, INA121, digital CMOS front-end circuits, 3-Stage Op-amp instrumentation amplifiers, AD620, and many others [75–79] just to mention a few.

Noise is the most widely recognized impairment in ECG signals, this is mostly generated by sensor–skin interface half-cell potential variations that affects the electrode

Table 4 – Some commercially available single lead devices.

S/No.	Device/Product	Remarks
1	AlivecorKardia	It is a smartphone device embedded in a phone case. The device is approved for use in over 25 countries
2	OmronHeartScan	This type is compact, portable and it has a very high-resolution screen that displays the ECG waveforms. Unfortunately, there is no reachable battery attached
3	Heal Force	The gadget has 3 electrodes, High-Resolution LCD, it is battery controlled, measures a solitary lead of ECG signal, and it's fit for recording 30 s of ECG.
4	Instant Check	InstantCheck is a portable handheld ECG device with a wide LCD screen to display ECG real-time. It is easy to use which allow users to record their ECG signals anywhere and anytime.
5	Heart Check Cardi Beat	It is a small handheld ECG monitor that is capable of capturing a wide range of arrhythmias such as tachycardia, bradycardia and atrial fibrillation. It connects to a mobile phone via Bluetooth to take ECG recording.
6	Nuvant mobilecardiac telemetry	The ECG device is used for the detection of non-lethal arrhythmias. This is a three-lead device that is based on a remote fix and naturally distinguishes and transmits ECG to an external research facility. However, it suffers the need for prolonging applications to obtain a true reading of individuals.
7	AFibAlert	It is a portable heart monitor designed specifically for atrial fibrillation patients. Patients can use AfibAlert® to take readings and transmit them to their physician or a specialized receiving centre for interpretation.
8	ECG Check	It is a small ECG device that records ECG signals for 30 s and sends to a mobile phone (iPhone or Android). It processes the signal and shows a result indicating abnormality or normality. It takes record by holding the monitor in both banks.
9	Dimetek	It is a portable device with the ability to record ECG waveforms which can be reviewed on the device. It has a real-time visual of ECG signals and audio alarming is supported. It comes with inbuilt storage for more than 980 recordings.
10	ZioPatch	This ECG device does not require battery charging and no electrode is necessary. It uses a cloud database for diagnosis. Unfortunately, it must be applied continuously before a true reading is obtained.
11	Zenikor ECG	This device is small and therefore portable. It has an inbuilt rechargeable battery and a cloud-based server. Unfortunately, it does not display ECG tracing
12	Reka e100	The device is a pocket ECG device that has a chest contact sensor and it has the option for 3 to 5 ECG leads.
13	Read My Heart	This is a handheld ECG recorder designed to be simple to use. It makes use of the patient's thumb via a dry conduction electrode to take a continuous recording of up to 25 s. It can be connected to a PC via USB,
14	Medtronic Reveal	It is an insertable ECG monitor which captures ECG signal and transmit it to a large LCD monitor that works with it. It has an inbuilt battery that is meant to last for at least, 3 years.
15	Apnea MedAssist	Continuous rest apnea monitor utilizing a single lead ECG using a cell phone.
16	MEDIC	This a medical embedded device that can be used for individualized consideration. It was created dependent on an inventive programming design for predicting diseases and empowering effective sensor control utilizing the common personal digital assistant (PDA) or mobile phone.
17	Heartsaver	This is a versatile medical device, which was created for real-time ECG monitoring and programmed detection of numerous heart pathologies.

Table 5 – Some commercial multiple ECG lead devices.

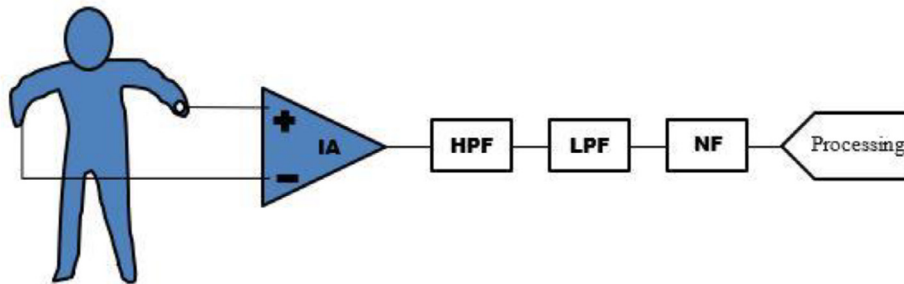
S/No.	Device	Remark
1	SanketLife	It is a 12 lead ECG device with a high degree of correlation sensitivity (98.15%) and specificity (100%)
2	UN-MEDICAL UN8003	This is a portable digital hospital that has 12 leads touch screen that performs the physiological functions of diagnosis and monitoring of patients.
3	CONTEC ECG300g	This is also a portable digital 3 channels, 12 leads ECG monitor machine. It can store up to 1000 cases due to its large storage capacity.
4	Wincom ECG-Rb300	This is a medical digital 3 channel, 12 lead ECG that is used for biological diagnostics.
5	Miniscope M3	It is a handheld ECG Monitor, it has a display time of 45 s with inbuilt memory up to 30 min of ECG recording. It has the ability to printout through an ECG unit.
6	Welch Allyn CP 300 CardioLaptop	It is an FAA class ECG gadget, with a full-shading display and noninterpretive, 12-lead estimation abilities, 40 GB of information storage, recurrence domain of 0.05 to 150 Hz, and contains a printer for the ECG data.
7	FUDE FD-E26	This is a device used for the acquisition of 12 lead, full-screen display of 12 channel ECG waveforms. It has very high storage capacity and portability with a durable rechargeable battery. However, it is very expensive.
8	Avante True 12 t	It allows report preview for ECG printout, with a large 8.4' colour touch-screen. It has an inbuilt memory for 200 ECG recordings.
9	Avante Velocity Pro	It is a multi-lead portable device that has the ability to detect arrhythmias. It can be integrated into a PC ECG software.
10	Dre Sage 12c	It is a lightweight ECG monitor that uses one AAA battery. It is designed to be waterproof, with USD and SD card slot for data analysis.
11	CardioLeaf	It has three lead, wearable electrode, visual display, audio support also data recorded can be sent to the cloud.
12	Smart vest	This is a wearable physiological monitoring framework, fused in a vest that utilizes an assortment of sensors coordinated into the piece of clothing's texture to simultaneously gather certain bio-signals in a non-intrusive and unpretentious way.
13	VITAL - ECG	It is a wearable and low-cost device used to get the fundamental parameters that include skin temperature, pulse and ECG, periphery oxygen level saturation, and moistness humidity. Additionally, it monitors the degree of physical movement.

Table 6 – Taxonomy of utility components for some available commercial ECG devices.

S/N	ECG Devices/utilities	Single Lead	Multiple Lead	Display Capability	Storage Facility	Built-in Battery	Transmission Capability	Cloud-Based Services	Smart Phone Interface	GPS Interface	FDA Approved	Cost
1	KARDIA MOBILE	✓	x	✓	x	✓	✓	x	✓	x	✓	\$89.00
2	OMRON HS	✓	x	✓	✓	x	✓	x	x	x	x	\$387.76
3	HEAL FORCE	✓	x	✓	✓	✓	✓	✓	x	x	✓	\$170.00
4	INSTANT CHECK	✓	x	✓	✓	✓	x	x	x	x	✓	\$422.61
5	HEART CHECK CARDI BEAT	✓	x	x	✓	✓	✓	✓	✓	x	✓	\$129.00
6	NUVANT MOBILE	✓	x	x	✓	✓	✓	✓	✓	x	✓	\$754.00
7	AFiBALERT	✓	x	✓	x	x	x	x	x	x	✓	\$449.00
8	ECG CHECK	✓	x	✓	✓	✓	✓	✓	✓	x	✓	\$79.99
9	DIMETEK	✓	x	✓	✓	✓	x	x	x	x	x	NA
10	ZIOPATCH	✓	x	x	✓	✓	✓	✓	✓	x	✓	NA
11	ZENICORE	✓	x	x	✓	✓	✓	✓	x	x	x	NA
12	REKA E100	✓	x	x	✓	✓	✓	✓	✓	x	x	NA
13	READ MY HEART	✓	x	✓	✓	✓	✓	x	x	x	✓	NA
14	MEDTRONIC REVEAL	✓	x	x	✓	✓	✓	✓	x	x	x	NA
15	SANKETLIFE	x	✓	x	✓	✓	✓	x	✓	x	x	\$33.35
16	UN-MEDICAL UN8003	x	✓	✓	✓	✓	x	x	x	x	x	\$300.00
17	CONTEC ECG300g	x	✓	✓	✓	✓	x	x	x	x	x	\$359.00
18	WINCOM ECG-RB300	x	✓	✓	✓	✓	x	x	x	x	x	\$330.00
19	MINISCOPE M3	x	✓	✓	✓	✓	✓	x	✓	x	x	\$1,395.00
20	WELCH ALLYN CP 300	x	✓	✓	✓	✓	x	x	x	x	x	NA
21	FUDE FD-E26	x	✓	✓	✓	✓	x	x	x	x	x	NA
22	AVANTE TRUE 12 T	x	✓	✓	✓	✓	x	x	x	x	x	NA
23	AVANTE VELOCITY PRO	x	✓	✓	x	x	✓	x	x	x	x	NA
24	DRE SAGE 12C	x	✓	✓	✓	✓	x	x	x	x	x	NA
25	CARDIOLEAF	x	✓	x	✓	✓	✓	✓	✓	x	x	NA
26	SMART VEST	x	✓	x	x	✓	✓	✓	✓	x	x	NA

Table 7 – Sources of electric signals observable on the body surface [73].

Source	Signal amplitude range	Signal Frequency range (Hz)
Heart, electrocardiogram, ECG	0.5–4 mV	0.01–250
Brain, electroencephalogram, EEG	10–5000 μ V	0–150
Gastrointestinal tract, Electrogastrogram, EGG	10–1000 μ V	0–1
Nerve potentials, electroneurogram, ENG	0.01–3 mV	0–10,000
Skeletal muscles, electromyogram, EMG	0.1–5 mV	0–10,000


Fig. 5 – Basic ECG signal acquisition and processing chain.

impedance [72]. They are usually generated by motion artifacts, temperature changes, changes in skin dampness (sweat) and spilling gel or glue [80–82]. In any event, during the resting state, the progressions or changes at the sensors may offer ascent to potential vacillations in the ECG that are bigger than the ECG itself. Under these conditions, the progressions have a low-frequency range, much lower than that of the ECG. However, high pass filters are commonly used to minimise these effects and the cut-off frequency that would be implemented in the design configuration of the filter is application specific. Furthermore, an low pass filters are used to circumvent an observed high frequency signals that lie above the ECG frequency spectrum. This signal is generated by skeletal muscles electric movements and charges [72]. Another utilization of the lowpass filter is that of diminishing the impact of the aliasing [72]. Similarly, [83] employed two filters, i.e. Wiener and Kalman Filters to remove noise from ECG signal. It was found that Wiener filter is an outstanding filter for denoising the ECG signal. Interference of the external environment may also cause a large amount of noises in the dynamic ECG signal; this affects the automated analysis of ECG. A novel ECG signal denoising algorithm based on the deep factor analysis was proposed by [84]. In the work, a layer-by-layer denoising deep neural network was developed and a top-down strategy was used to reconstruct the signal. The proposed approach was found to achieve good performance, by removing the Gaussian-distribution noise at each layer. This model was verified on the MIT-BIH database.

In any ECG acquisition system design, the choices of components in implementing each stage of the acquisition system must be carefully chosen. The common-mode rejection ratio must be prioritized in the choice of IAs as this greatly affects the quality of the acquired ECG signals. Also, right leg drive circuits. In addition, most present-day front-end configurations uses dynamic elimination of the common-

mode impedance or interference [81,85–87] by applying these same common-mode signals to the right leg drive circuits of devices in opposite phase [88]. The inner organs and muscles interference signals mix up with the ECG and can't be handily filtered through without influencing the data transfer capacity of the ECG. Great skin readiness and the unwinding of subjects ordinarily brings about baseline shifts and reduced muscle tremor.

6.2.1. Signal acquisition modules

Here we discuss the sensing platforms as used by many inventors. It should be emphasized that the process of data acquisition is the first stage/process in the lifecycle of ECG monitoring systems and encompasses the selection of the following: (1) the types of sensors (e.g., wireless, or wired), (2) the placement location of sensors, (3) the number of sensors, and (4) the hardware required for data acquisition, storage, and transmission [89]. This process of acquisition offers various sensing platforms and devices, such as ECG electrodes, IoT sensors, Wireless Body Area Network (WBAN) sensors, mobile sensors, and wearable sensors. Sensors vary from embedded sensors mounted on biological tissues, easy-to-handle smartwatches and smart vests [33]. In Table 8, we provided summary of acquisition modules, their benefits and shortcomings.

A novel dry foam electrode was designed in [93]. This type of electrode has widespread applications in past ECG monitoring systems and was incorporated in the wearable ECG devices. The electrode could give great conductivity to procure ECG viably without conduction gels. Furthermore, the motion artefacts and skin-electrode impedance during movement exercises can likewise be decreased. [77,82] uses wet Ag-AgCl electrodes for their sensors to reduce skin impedance. Similarly, in [97] a dry flexible ECG electrode was developed using the graphene films on polyethylene terephthalate (PET) substrates. A graphene textile was synthesized for the

Table 8 – Signal acquisition module sensors benefits and shortcomings.

Authors	Sensor Types	Benefits	Shortcomings
[90]	IoT sensors	Improved safety, IoT cloud server provides more functionalities such as web monitoring and mobile applications, e.t.c	Less comprehensive diagnosis, a limited number of leads, proneness to cyberattacks, e.t.c
[91]	WBAN sensors	Portability, high linearity, and jitter, scalable battery life, reduced power consumption, e.t.c	Increased signal delays and Inaccurate removal of motion artefacts.
[92–94]	Wearable sensors	Minimized power consumption, increased and stabilized input impedance of input signals, e.t.c	Increased proneness to motion artefacts and inconvenience to users.
[95,96]	Mobile sensors	Low-Cost, real-time bio-parameter tracking, increased portability e.t.c	Less comprehensive diagnosis and records a single lead at a time.

fabrication. The graphene electrode was able to acquire the characteristics and features of the ECG signals with a high signal-to-noise (SNR) ratio, when measured at different states of motion. Furthermore, no ECG signal quality degradation observed for a week-long continuous measurements. Hence, suitable for a portable wearable wireless ECG systems for a typical long-term dynamic cardiac monitoring. Ref. [98] presented a graphene oxide (rGO) electrodes for the measurements of EMG, EOG and EEG signals. The electrode have been found suitable for applications in the healthcare system as it measures signals with high fidelity. A variety of application-specific wearable sensors, physiological and activity monitoring systems have been proposed in various literatures for various wearable commercial products such as a polydopamine and silk fibroin (SF) adhesive, and washable on-skin electrodes [99]; Adhesive biocomposite electrodes on sweaty skin [100] and Textile ECG Dry Skin Electrodes [101].

Wearable gadgets can screen and record real-time data about one's physiological condition and locomotive exercises. Portable, wearable and WBANs sensor-based health monitoring frameworks usually consist of various kinds of adaptable sensors that can be incorporated into a material fibre, garments, or straightforwardly appended to the human body. The sensors are fit for estimating physiological signs (e.g. heart and breathing rates, ECGs, EEGs, EMGs, blood vessel oxygen immersion, internal heat level, etc. [33,92,102,103]. Ref. [91] made use of electrodermal activity (EDA) sensor and two channels electrocardiogram (ECG) sensor. These EDA sensors work in tandem with the ECG sensors, such that it acquires data and transmit via Wi-Fi communication interface.

6.2.2. Transmission links

Bluetooth, Wi-Fi, RFID (Radio Frequency Identification) and Zigbee have been implemented in various wireless communication systems. In typical ECG applications, some implementations also made use of USB (Universal Serial Bus) for communication between the ECG device and the sink, which is usually a smartphone or a personal computer. In [104], a GSM module was implemented to send ECG signals to a remote Cardiologist. Ref. [105] used a 3.5 mm headphone cable to transfer ECG signals from the ECG device to a PC for analysis. This bypass the use of modules such as ADCs, DSPs, and transmitters, etc., which can greatly reduce the size and power consumption of ECG acquisition circuits. [106] developed an ECG device that used a mobile phone applica-

tion as the monitoring device, Wi-Fi was implemented as communication channel. The work incorporated cloud services for the storage and analysis of the acquired ECG data. In [79], a proprietary RF network protocol; SimpliciTI was used as the transmission link between the acquisition device and the PC. The simplicity protocol is based on low data communication rate and optimized to be battery operated. Nilanjan et al. [107] presented a low-power/low-cost ECG system that utilizes Zigbee as its communication link. Zigbee is a typical open technology that works within a short-range for applications that requires a relatively low data rate. [93,108–112], made use of a Bluetooth module as the transmission link between the acquisition device and the application interface device. Sung-Nien and Jen-Chieh [113] developed a wireless monitoring system based on Bluetooth and Wi-Fi. The Bluetooth was to further transmit the wearer's physiological signals to a server, and a web page for monitoring was communicated through Wi-Fi.

Table 9 presents a comparison between the various transmission technologies used for the Body Area Networks. The metrics used for the comparison includes: Standard, Frequency Band, Standard Range, Data Transfer Rate, Transmit Power, Maximum number of support Nodes and Scalability. Bluetooth was however found to be the most widely and adopted means of data transmission and this was due to its power efficiency, data reliability and scalability.

6.2.3. Application interfaces and display units

ECG signals acquired needs a form of visual display for the user or doctor. The visualization combines all the functionalities that will enable users to interact with the acquired signals and inspect them in real-time, offline, or from a remote location. GUI (Graphical User Interface) is commonly implemented in a PDA (Personal Digital Assistant), PC, or Smartphone. The GUI presents a better representation of ECG and sometimes built to identify abnormalities in ECG signals. The implementation of GUI applications varies in terms of development; some are implemented as a web service through a browser, some are desktop mobile applications and others are desktop applications.

An ECG monitoring system was developed in [105] that collects ECG signals through a 3.5 mm headphone cable using a microphone. A PC was used as the smart device to facilitate ECG signal inspection. The application interface was implemented in Matlab on the PC. A PC was chosen because in general, sound cards in PCs support sampling rates of 8000,11,025, 22,050, 44,100, 4800, or 96,000 Hz, with a

Table 9 – Comparison of various transmission links utilized in Body Area Network.

	Bluetooth	WiFi	Zigbee	USB
IEEE Specification	802.15.1	802.11a/b/g	802.15.4	1394a/b
Frequency Band	2.4 GHz	2.4 GHz, 5 MHz	868/915 MHz, 2.4 GHz	–
Standard Range	100 m	100 m	100 m	4.5 m
Data Transfer Rate	3 Mbit/s	54 Mbit/s	250 Kbit/s	3200 Mbit/s
Transmit Power	10 mW	100mW	Adjustable	–
Max No. of Nodes	8	2007	Greater than 65,000	1
Scalability	High	High	High	Low

sampling accuracy of 16 or 24 bit which can output a fixed frequency signal that will be similar to playing an audio signal. [79] designed an ECG system with a test application GUI implemented on a PC using LabWindows/CVI version 2013. Refs. [114] and [108] reported an ECG monitoring system using NI LabVIEW software as the interface application on a PC. An ECG monitoring system was developed by [93] with Bluetooth as the transmission link between the acquisition device and a mobile phone as the application interface device. In [104], an ECG system was presented, details about the ECG values such as heart rate were displayed on an LCD on the acquisition device, it was also equipped with a GSM module that sends SMS via UART commands when an abnormal heart is detected. The acquisition device could also connect to LabVIEW for more details and analysis of the ECG signals on a PC.

Chao, Xiangpei and Lili [110] used an Android smartphone for the application interface due to the popularity of smartphones and because the Android platform is open source. The application was developed using Java and it could communicate with the acquisition device using Bluetooth. Similarly, [112] developed a smartphone enabled ECG monitoring system. The developed system was able to realized and display fetal ECG signals in real time. In order to send the real data collected; the ECG data is sent via Bluetooth to smartphone. The work further showed that fast fixed pint algorithm for independent component analysis (FastICA) algorithm clearly extracted a clear fetal ECG.

Ee-May and Wan-Young [111] also implemented the used of mobile monitoring terminal to observe and analyze the ECG signals in real-time. In [115] mobile applications for patients and doctors was designed. The patient application could receive real-time signals and process them, check the heart rate every 5 s, and then save the data on a database that will be synchronized with a server. In [116], a generic ECG system that is accessible from any computer, smartphone, or tablet connected to the internet was provided. An IoT server was implemented where health data can be combined with other data, merged, processed by users and authorized health workers.

It has been seen that PC was used for many implementations at the testing phase because there is an open-source application for an easy test such as LabVIEW and most commercial implementations used either a smartphone or a web-based server for their application interface and in some cases combined with USB for analysis on a PC.

6.3. Taxonomy of design elements for low-cost ECG devices

The employment of portable ECG devices for numerous heart monitoring applications has been developed with significant and impressive results. One of the major drawbacks, however, has been the cost of these devices as the cost of procurement dissuades readily available users [117]. Although the cost has to be considered, the accuracy of the device and its reliability must not be compromised. In this section, we would critically examine the current developments of Low-Cost ECG devices while highlighting their usability and implementation. Table 10 reveals the taxonomy of design elements for some Low-Cost ECG acquisition devices.

In [119], the design of a compact wireless monitoring gadget utilizing MSP430FG439 and ZigBee remote transmission module is introduced. Wet Ag/AgCl electrodes were used to increase signal integrity. Tomáš and Novotný [14] made a convenient, battery-controlled device for three-lead ECG acquisition including its firmware and user PC software. Although, the ECG bends from this device were not as precise as the expert devices, demonstrated that such an affordable device could be built.

For client comfort, in [118], two active dry electrodes were utilized as contact sensors. A cradle circuit was applied to evacuate the over-affectability impact of the electrodes. Test results demonstrated that ECG quality when utilizing dynamic dry electrodes is proportionate to that of wet Ag/AgCl electrodes application

The low-cost device in [77] made use of a single board plan which utilizes economical and promptly accessible discrete segments and was used to non-obtrusively acquire ECG/EMG signals which were sent to the utilized MCU's ADC for postprocessing and examination. The sensor multipurpose capability and cost-effectiveness make it utilized in several applications.

The monitoring devices in [120,121] could quantify, transmit, and get the pulse information of the patients progressively while expending low power and data transfer capacity. The devices could be used in rural hospitals and for physical and psychological infection surveillance in a smart home framework.

A wireless electrocardiogram (ECG) device developed in [122] integrates Bluetooth Low Energy (BLE) technology. This BLE-based system is comprised of a single-chip ECG signal acquisition module, and can acquire ECG signals through a 2-lead electrocardiogram (ECG) sensor, transmit the ECG information employing the Bluetooth remote connection, process and show the ECG waveform on a cellphone. The usage of Bluetooth Low Energy (BLE) innovation showed in the outcomes that not only can the monitoring system dispose of the physical limitations forced by hard-wired connections yet could likewise profoundly decrease the power utilization of the long-term monitoring systems.

Jayita et al. [78] presented a design methodology of a cost-effective and portable ECG acquisition circuit using the AD620 instrumentation amplifier. The ECG signal in [104] which was processed by an AT89S52 microcontroller was able to count the heartbeat for one minute while the Heart Rate was displayed on an LCD. The system could be configured such that, if an abnormality was detected in the ECG signal, an alert SMS was sent by the framework to the specialist through GSM modem to empower him to take proper protective measures. In [130] a non-intrusive ECG based stress detector was developed to identify stress level for both gender and different classification of age. In the work, work data acquisition was divided into two normal and stress states, after extraction and final classification of the signals using RR intervals (RRI), findings show that ECG signals can be used as an alternative mechanism to recognize stress more efficiently. It was also found out that women could be more affected by the stress compared to men.

The advancement of wearable ECG gadgets has developed so marvellously during the most recent decade that it has

Table 10 – Taxonomy of Design Elements for Low-Cost ECG Acquisition Devices.

S/N	Ref	Purpose	MCU	Mode of Transfer	GUI	No. of Leads	PSU (AC/DC)	Module	Implementation
1	[14]	ECG	STM32L0	WiFi	C++	3	Dual	PC	Trial
2	[118]	ECG	MSP430	USB OTG	Mobile Application	1	Dual	Smartphone	Home/ Real-Time
3	[119]	EKG	MSP430FG439	ZigBee	PC	3	Dual	PC	Real-Time
4	[77]	EMG & ECG	N/A	USB	N/A	1	DC	Oscilloscope	Real-Time
5	[106]	ECG	BMD101	WiFi	Mobile Application	1	DC	PC	Trial
6	[120]	ECG	Arduino	WiFi	MQTT	1	DC	Raspberry Pi	Hospital/Trial
7	[121]	ECG	TMS320F2812	ZigBee	Visual C++	–	DC	PC	Home / Trial
8	[122]	ECG	RS232	Bluetooth	Mobile Application	2	DC	Smartphone	Trial
9	[114]	ECG	RS323	USB	LabVIEW	1	DC	PC	Real-Time
10	[78]	ECG	AD620	USB	DSO	3	–	DSO	Real-Time
11	[104]	ECG	AT89S52	SMS	LabVIEW	3	DC	GSM Module	Real-Time
12	[93]	ECG	–	Bluetooth	J2SE & JDIC	3	DC	Smartphone	Real-Time/Hospital
13	[123]	Heart Rate	Arduino	USB	Processing 2.0	1	DC	PC	Trial
14	[124]	ECG	Sensor	Bluetooth/ WiFi	MedAssist	1	Dual	Smartphone/ PC	Real-Time/Hospital
15	[82]	ECG	MSP430	Bluetooth	N/A	1	Dual	PC	Hospital
16	[79]	ECG	ADS1298/ MSP430F2274	eZ430-RF2500	LabWindows CVI Version	3	DC	PC	Trial
17	[125]	ECG	–	Bluetooth	PDA	1	Dual	Smartphone	Real-Time
18	[126]	ECG	BIOPAC MP160	USB	AcqKnowledge 5.0	3	N/A	PC	Trial/ Hospital
19	[127]	EEG	ADS1298/ ATmega	Bluetooth/Wi-Fi	OpenBCI	N/A	DC	PC	Trial/Hospital
20	[128]	EEG	ADS1298	Bluetooth/Wi-Fi	N/A	N/A	DC	PC	Trial/Hospital
21	[129]	ECG	INA333/CC2640R2F	Bluetooth	Mobile Application	3	Dual	Smartphone	Real-Time

gotten a new name, Wearable Technology [77]. Other than its design quotient, it has genuine social insurance applications, especially for old age individuals and health monstrosities. The sensors utilized in such gadgets have a few requirements over structure and advancement of their parameters which incorporate wearability, movability, size, weight, life span, ergonomics, and power consumption [131]. Simply in the wake of meeting these design parameters, such sensors can be effectively utilized for constant real-time health monitoring in everyday life [132]. Still considering Low-Cost devices, a wearable mobile electrocardiogram monitoring system (WMEMS) proposed in [93], comprising of a wearable ECG acquisition gadget, a cell phone stage, and a health service server was used for monitoring ECG. A novel dry foam electrode was also embedded in the designed acquisition device. Interestingly, WMEMS could monitor the user's ECG state continuously and anywhere in the globe due to its usage of the mobile phone as the system's platform. Federica and Eros [82] revealed that a wearable ECG device could be developed to be reliable ECG diagnosis without cables, heavy instruments, uncomfortable procedures, and most importantly, reduced costs.

Similarly, in [106] Building up using IoT innovation, a wearable ECG data acquisition device which enables monitoring utilizing a cell phone was planned. The wearable ECG gadget is intended to be smaller than typical human palm. The ECG signals acquired by the wearable device and captured by the cell phone demonstrates the effective estimation of ECG signals in their outcomes. This gadget is expected to be utilized with a cell phone application for checking purposes along with the combination of cloud administrations for information examination and storage.

7. Trials, performance studies evaluations and case studies reports

The need to test the efficacy of low-cost ECG devices is paramount for wider applicability, diagnostic accuracy and reproducibility. Some research works attempted to compare the accuracy of a few of these low-cost ECG devices with the standard ECG machines. For example, [133] conducted PubMed and Internet searches for available and commercial “hand-held” or “wearable” or “patch” electrocardiography devices. 15 ECG devices consisting of single and multiple leads were identified. Pros and Cons of each of the devices were provided. The work also indicated that most of the devices were single lead and best suited for short-term rhythm analysis. [134] found out that no significant difference was observed in the QRS, frequency, and QT intervals between single-lead ECG from smartphones and standard ECG machines. In the experiment, a commercially available smartphone ECG device was utilized to record a 30-sec single lead ECG in 144 subjects, 20 of whom rehashed the test after some energetic exercises. The cell phone ECG accounts isolated pathologic rhythms (Atrial Fibrillation (AF)/ripple, atrioventricular block, customary supraventricular rhythm, and pacing) from sinus rhythms with an sensitivity of 0.75 and a accuracy of 0.97. The particular conclusion of AF showed up in 11 patients and was identified with an accuracy of 1 and sensitivity of 0.94. The cell

phone ECG precisely gauges most standard spans and has worthy sensitivity and specificity for pathological rhythms, particularly for AF. It was reasoned that it would be appropriate as a screening gadget for pathological rhythms.

Similarly, [135] evaluated the precision of 4 single-lead versatile ECG gadgets contrasted with a regular 3-lead medical clinic cardiovascular screen. A 30-second cardiac rhythm recording from 25 patients was interpreted and it was concluded that the single lead might be a sensible alternative for long-term surveillance of rhythm. Ref. [136] also evaluated the accuracy of a single lead smartphone-based ECG device in 28 horses. Twenty-five pairs of 30 s ECG recordings were acquired simultaneously with the smartphone ECG device and the standard ECG machine, and it was found that the smartphone ECG device can accurately identify cardiac rhythm and heart rate when compared to a standard machine. For both readings, the intra-observer agreement for rhythm assessment was very high. Also, the polarity of the QRS complex was similar to both ECGs acquired. However, these findings may be attributed to the short time pulse recording as [137] conducted 14 days continuous ECG recordings on 212 patients and observed that the Holter ECG monitoring was better in separating untimely atrial from ventricular beats and was increasingly exact to survey PVC morphology when contrasted with the single lead, despite the fact that, a fantastic correlation was seen between the two devices for detecting atrial fibrillation with 99% agreement.

In [138] the diagnostic accuracy of SanketLife, wireless, pocket-sized ECG biosensor, in the detection of cardiovascular diseases was assessed. Standard (GE-2000) 12 lead ECG was used to gauge the performance of the device. A total of 100 patients were used for the study and it was found that there was a high degree of agreement and accuracy of the device with sensitivity (98.15%) and specificity (100%) in diagnosing major cardiovascular diseases. In [139], a randomized controlled trial of AF screening using a WiFi-enabled iPod AliveCor Kardia monitor was conducted. The study was conducted for 12 months for 1001 patients. The device was found to be effective. In [140], 57 patients were monitored for AF for 4 weeks utilizing a single-lead ECG device that can record consistent ECG. In the assessment, the electrodes were supplanted every 3–4 days. The primary outcome was proportion, out of every eight patients, AF was detected in one.

In [141], 146 patients were evaluated for cardiac arrhythmia the ECG was recorded for the period of 14-days using an adhesive patch monitor and the findings were compared with a conventional 24-hour Holter monitor. The findings of their study showed that more arrhythmia (ninety-six events) were detected by the adhesive patch monitor compared with the sixty-one events detected by the Holter monitor. The adhesive patch monitor is found to be more comfortable compared with the Holter monitor. In any case, the loss of value, automated rhythm examination, and failure to recognize myocardial ischemia keeps on remaining one of the significant issues that should be tended to before the usage of these new gadgets [142]. In [143], an implanted sub-cutaneous electrocardiographic monitors to monitor Subclinical Atrial Fibrillation (SCAF) in older patients within the ages of 65 and

80 years was presented. In the study, 256 patients who are attending cardiovascular or neurology outpatient clinics were used. The investigation lasted for 20 months. Findings from the work show that the SCAF is detected by continuous monitoring of the electrocardiographic in patients, even without a prior history of AF. However, its clinical significance was unclear. Kane et al., [144], conducted an extensive systematic review to identify studies that report the diagnostic accuracy of automated blood pressure (BP) monitors used for the detection of AF in patients. From the work, seven papers that evaluated six BP devices were reviewed and it found out that the BP devices with embedded algorithms for detecting arrhythmias can effectively be used as a screening tool for AF as all studies reported specificity greater than 85% and 6 reported sensitivity greater than 90%.

In [145], an iPhone based single-lead electrocardiogram (iECG) was employed to investigate unknown AF in 1000 pharmacy customers aged ≥ 65 years. 30 s (sec) pulse was measured while 30–60 sec was used to record the iECG. In the study, an automated AF algorithm was applied to collected iECGs. The automated iECG algorithm showed sensitivity and specificity of 98.5% and 91.4% respectively for AF detection. In [146], 2-leads android App-based WebCardio using WiPatch with a standard Holter for the arrhythmia detection were compared. The objective of the study was to investigate the efficacy of the device in detecting any of the 6 arrhythmias (i.e. the atrial fibrillation, atrioventricular block, sinus pause of ≥ 3 s, supraventricular tachycardia, premature ventricular complex and ventricular fibrillation. In the study, 141 patients were used and the recording was undertaken for 72 h using the WebCardio while 24 h for the Holter. Interestingly, the WebCardio was able to pick up at least one of the 6 arrhythmias in 98 cases when compared to 88 in the Holter. In Table 11, we provided a summary of some case studies reports where the efficacies of some of the low-cost ECG devices were evaluated.

8. Challenges and open research areas

This section presents implementation challenges and open research areas identified from the extensive review. These include the cost of device development, data transmission modes/interfaces, device power modes, end-user power availability and energy consumption of devices, storage and monitoring duration, choice of sensors and number of leads, smart cloud-based systems for device remote monitoring and location features, and device accuracy.

8.1. Low-cost ECG device development

There are many efforts in the development of low-cost ECG devices ranging from developed to developing nations. Traditional ECG machines cost between \$2000 and \$10,000. However, this is not affordable for most clinics and health centers in developing economies, especially health facilities based in rural areas. The relatively need to develop an ECG device that has the required utility features outlined in Table 6 is extremely important. However this usually come with a cost. Therefore, to achieve this, the ECG device should be

designed in modular form and each module should be carefully chosen, and designed with Low-Cost and reliable electronics components that would meet the emerging needs. Some of the strategies include different types of electrodes, the use of discrete components, monitoring devices, and front-end devices. Other options development of low-cost sensors considering many constraints during design and development. To achieve the optimum system utilization at least cost; the emphasis ought to be on ergonomics, compactness, size, life span, and power consumption.

8.2. Data transmission modes/interfaces

To achieve the global dream of a robust ECG system, there is a need to implement all the available options of data transmission. Some of the available technology (i.e. Bluetooth, Wifi and USB) have already been implemented. These technologies are commonly implemented to bridge the communication between the ECG device and the sink, which are usually a smartphone or a personal computer and/or uploading the ECG data to the cloud. Some implementation included embedded GSM module [104], headphone cable [105], Wifi [106], Zigbee [107] and hybrid modes, such as the Bluetooth and Wifi [113]. Triple mode of data transmission (Bluetooth/Zigbee, Wifi and USB) is currently not available in the market. However, many others communications have not been tested for better system efficiency and accuracy of the transmission link. Therefore, any technology to be used in the new design should consider specifications, range, transfer rate, power handling capabilities, number of nodes, and scalability.

8.3. Device power modes

A recent trend in biomedical research has shown that devices suitable for biomedical applications should be supplied with a power supply unit that is of good quality and stable. However, future biomedical systems should be designed carefully with power supply units having reliable and available power supply unit. Unfortunately, developing countries are suffering from acute shortages, unreliable power supply [153,154,16]. Other ECG devices that depend on battery for power supply contribute to environmental contamination due to the hazardous element available in the battery at the end of its useful life. Another study expected in this area is the relationship between the quality of the power supply and the quality of the signal to be observed from the ECG machine. In addition, the effects of components reliability on the quality of the out of the device. Furthermore, to enhance the reliability and availability of the power for the ECG machines; it is recommended to design a hybrid power supply module for the ECG machines.

8.4. End-user power availability and energy consumption of devices

To solve the problem of power consumption; it is very critical the new ECG design is based on a low power consumption device. In order to achieve these requirements, each building block should be on a low power consumption device. An

Table 11 – Trials, Performance, and Evaluations Case Studies Reports.

References	Device Name	No. of Leads	Case Study	Duration of Monitoring	Sample Size	Outcome
[138]	SanketLife	12	Monitor rhythm	30 sec	100	A high degree of correlationsensitivity (98.15%) and specificity (100%)
[134]	–	1	pathologic rhythms	30 sec	114	No significant differences observed in the QRS, frequency and QT intervalsThe sensitivity of 1 and a specificity of 0.94 for AF
[135]	PC-80AMD-100B Alive Cor,HCG-801	1	monitor rhythm	30 sec	20	Over 40% of the portable ECGrhythm strips were classified as uninterpretable
[137]	Cardiostat	1	Atrial Fibrillation	14 days	73	Excellent correlation
[147]	Zio Patch	2	Atrial Fibrillation	14 days	74	24hr Holter MonitorHigher rates of AFDetection
[143]	St. JudeConfirm ICM	1	Atrial Fibrillation	20 months	256	patients without prior history of AF were detected
[139]	AliveCor Kardia	1	Atrial Fibrillation	1 year	501	The device outperformed routine care method
[145]	AliveCor Heart Monitor	1	Atrial Fibrillation	30-60sec	1000	cardiologist reviewSens. 98.5%, Spec.91.4%
[148]	Medtronic Reveal		Atrial Fibrillation	–	247	Sens. 96.1%, Spec. 85.4%,
[144]	BP monitor		Rhythm	–	3621	sens. greater than 85% and spec greater than 90%
[136]	Smart Phone ECG	1	Rhythm and Heart Rate	30 s	28	Accurately identified cardiac rhythm and heart rate
[149]	Alivecorkardia	1	Rhythm	30 s	1013	Prevalence of AF-2.76%Sensitivity-71.4% (51%-87%)Specificity-99.4% (99%-100%)PPV-76.9% (56%–91%)NPV-99.2% (98%–100%)
[150]	OmronHeartScan		Monitor rhythm	30 s	1000	Prevalence of AF-7.9%Atrial cycle length<200 ms on ECG.Sensitivity-98.7 (93.2 to 100)Specificity-76.2 (73.3 to 78.9)
[151]	OmronHeartScan		Monitor rhythm	–	503	Prevalence of AF-9.34%Sensitivity-100%
[152]		2	Monitor rhythm	10.9 days	1171	Specificity-92%Accuracy-95% Atrial fibrillation was defined as RR irregularity for more than 30 s

example is the monitoring group which comprised of enabling technology group comprising of IoT, Fog, and cloud, and the second group called the monitoring group. This group comprised of sensors, wearable, and mobile devices. Each of them can be designed with low power electronics circuitry.

8.5. Storage and monitoring duration

To achieve real-time monitoring, modern efficient and communication technologies are recommended. This could assist in achieving long-term monitoring of patients. One of the available options is to use a sampling algorithm for energy conservation. Others include the use of Bluetooth as a low communications protocol. Furthermore, data size could be reduced with the help of dimensionality technique; this process eliminates the pre-processing which eventually assists in monitoring duration.

8.6. Choice of sensors and number of leads

There many efforts in the area of increase in the number of leads for ECG machines globally. However; challenges related to different electrode design, type of conductor, and the number of leads remained an issue in the development of ECG machines across the globe. This is further confirmed by many researchers. In-depth of these challenges is the design of wearable devices, therefore to move forward and solve this problem; a more realistic design needs to be proposed.

8.7. Smart cloud-based systems for device remote monitoring with location features

The Home and Remote ECG monitoring systems are designed for telemonitoring and continuous surveillance and monitoring of life-long, chronic and elderly people that distant patients and may experience frequent movement. The requirement of these use cases, the systems are expected to be designed to be able to detect different cardiac disorders and may involve the Internet of Things (IoT), Cloud Infrastructure and Storage, and Fog computing for high-end processing, low latency, and energy efficiency, and cost of data transmission over the cloud [36,37,155]. This is particular of interest in the case of emergencies where real-time ECG data are needed. Some recent implementations thus: Edge Computing Devices [37,38]; IoT-based Solutions [42–44]. Yet, a considerable number of the existing commercial devices in Table 5, did not have Cloud-based supports either with smartphone interface or display capability. Interestingly, all the available commercial low-cost ECGs reviewed do not have support for GPS that could be used to provide remote location features for the patients. The location enabled and cloud-based ECG devices would be of particular interest in the real-time monitoring of ECGs patients in ambulatory settings for continuous surveillance and monitoring. Some advance algorithms for automated system capable of helping cardiologist crosschecking their diagnosis and also an ECG device capable of extracting informative and discriminative features from raw ECG data are presented in [145,146].

8.8. Device accuracy and reliability studies

Even though the development of low-cost ECG devices has experienced wide acceptance, due to global spike of CVDs cases, little efforts have been invested in conducting wide efficacy studies of the available devices. Few works conducted as highlighted in Table 10 have shown promising results with a very high correlation between the low-cost ECG devices and the standard ECG machines. However, most of the efficacy tests are skewed to pathologic rhythms with much emphasis on Atrial Fibrillation (AF). It is quite understandable that the AF is the most common sustained cardiac arrhythmias and the prevalence is increasing due to increased ageing of the population. However, long-time continuous ECG monitoring with large subjects conducted in [137] suggests that the Holter ECG monitoring was better in separating untimely atrial from ventricular beats and was increasingly exact to survey PVC morphology when contrasted with the single lead, despite the fact that, a fantastic connection was seen between the two devices for detecting atrial fibrillation. Also, other classes of diseases aside the AF, such as the Hypertensive heart disease (HHD), Cardiomyopathies (CMP), Rheumatic heart disease (RHD), Abdominal aortic aneurysm (AAA), Peripheral Arterial Disease (PAD) and Endocarditis that majorly contributed to CVDs are not widely investigated as some of these low-cost ECG devices failed to recognize myocardial ischemia and remains one of the significant issues [141].

8.9. Prevention for interpretation error

Errors in ECG measurements, recordings and interpretation are issues of great concern as many systems will be used without the physiological background. The methodology for ECG recording, monitoring duration, activity and the study population could cause errors in extracting the measurement results particularly when observing HRV. Smartphone PPG was found to be prone to larger errors when measuring HRV during exercise [51]. Hence, physiological background should be considered when developing such devices with minimal error to cater for different conditions such as during resting and after exercise. Many innovative methodologies have been proposed and deployed for detecting major arrhythmias and also measuring HRV, each come with its merits and demerits. The procedure for identification of effective benign ECG signals recording, integration onto the ECG acquisition and diagnostic systems is another possible source of error. In addition, the interpretation error can also be avoided by correct placement of the ECG electrodes attached to the patient's body. This is because wrong placement will lead to erroneous recording from the ECG acquisition system. Correct placement of ECG electrodes will play significant roles in getting accurate and correct ECG traces.

9. Conclusions and further works

This paper has studied the literature of ECG monitoring systems comprehensively. Unfortunately, the complexity of these devices makes it difficult for researchers and medical practitioners in developing countries to have access to it.

Another issue of concern is the cost of the device makes it almost impossible for hospitals in rural areas to afford it. In conclusion, it could be deduced that most of the devices reviewed were not able to implement a dual ECG data transfer mechanism, proceed to real-time commercialization, and had a limited scope of diagnosis. Also, the number of leads for the ECG acquisition devices was not more than 3 and the power consumption and power usage were not made flexible i.e. the use of dual power supply sources (i.e. an AC and DC). In addition, smart cloud-based systems for device remote monitoring with location features were not available.

Furthermore, a comprehensive and extensive review of literature relating to present ECG monitoring system with an emphasis on different technologies such as new cost-effective designs, integration of IoT, AI, deep learning to mentioned just a few. In addition, the paper has provided a thorough taxonomy on the ECG devices according to the number of leads. Details were reported on different single lead and multiple leads ECG systems available in the market. Furthermore, expert systems for ECG development have been investigated. Different designs of ECG devices have been reviewed with a critical look into different modules that make up the system. After careful consideration; it has been established that single lead ECG machines are available and the number of trials has shown the success rate of such different designs. Some of the factors used in comparisons are sensitivity, correlation, and accuracy. Finally, research challenges and future directions were highlighted in the manuscript.

CRedit authorship contribution statement

Nasir Faruk: Conceptualization, Funding acquisition, Methodology, Validation, Visualization, Writing - review & editing. **Abubakar Abdulkarim:** Conceptualization, Validation, Visualization, Funding acquisition. **Ifada Emmanuel:** Data curation. **Yusuf Y. Folawiyi:** Data curation. **Kayode S. Adewole:** Formal analysis. **Hammed A. Mojeed:** Formal analysis. **Abdukareem A. Oloyede:** Investigation. **Lukman A. Olawoyin:** Investigation. **Ismael A. Sikiru:** Investigation. **Musa Nehemiah:** Investigation. **Abubakar Abdulkarim:** Methodology, Writing - review & editing. **Abdulsalam Ya'u Gital:** Methodology. **Haruna Chiroma:** Methodology, Writing - review & editing. **Ibraheem A. Katibi:** Project administration, Resources, Supervision, Validation. **James A. Ogunmodede:** Writing - original draft. **Mubarak Almutairi:** Writing - original draft.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work is fully sponsored by the Federal Government of Nigeria, tertiary Education Trust Fund TETFund Reference no, TETFund/DR&D/CE/NRF/CC/09/Vol 1, 2019.

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