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Mobile ECG Devices Selection: A Comprehensive Review

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Abstract: Cardiovascular diseases are the main cause of death across the globe. Therefore, it is critical to detect them at an early stage, while an electrocardiogram (ECG) presents a widely used tool for making diagnosis. There is a large number of ECG devices on the market, with different features that suit a wide range of users, but simultaneously it poses a problem for the end user because they have a difficulty in selecting the appropriate device for their exact needs. Current trends in the usage of contemporary mobile ECG devices are identified and analyzed. In this study authors reviewed numerous mobile ECG devices with either FDA approval or CE mark that are currently available on the market. All listed devices are presented with all technical features that could be found. Furthermore, an interactive sunburst diagram for the selection of mobile ECG devices is created, and published, to help everyone easily make a selection.

Keywords: ECG device selection; Electrocardiography; sunburst diagram; wearable ECG

1 INTRODUCTION

Electrocardiography has undergone a transformation because of the evolution of portable health technology in terms of recording, storage, and use of electrocardiograms (ECGs) [1]. It has been demonstrated that ECG provides information that cannot be obtained from other tests, as well as having some advantages such as simplicity and convenience of use [2].

Detection of cardiovascular diseases (CVDs), disorders of the heart and blood vessels, as early as possible contributes greatly to medical treatment. The primary tool for identifying cardiac arrhythmias is ECG, commonly the standard 12-lead ECG that restrains patient mobility [3]. According to the need for remote monitoring and obtaining patients health data, the approval of a single-lead smartphone ECG occurred in 2013, when numerous companies presented their own smartphone ECGs [4]. In both inpatient and outpatient settings portable ECGs record the electrical activity of the heart, heart rhythm and other vitals. Nowadays, a plethora of ECG devices can be found: gadgets, smartwatches, and patches, portable medical and nonmedical ECG devices. Current trends imply that small portable medical ECG devices can fully replace big stationary ECGs in medical facilities since they have the same quality of acquired signals with superior connectivity and they can be utilized in a home environment.

The aim of this paper is to review contemporary mobile ECG devices that are currently available on the market. A large number of technical features is given for every device, so it is easier to make a proper choice when selecting one. Many researchers published ECG review papers, but it can be observed that few of them provide technical features. Usually, they describe a specific characteristic. In this work, authors aim to help other scientific researchers and medical professionals make the best device selection based on their personal needs. For example, researchers like the possibility of programming ECG devices in terms of changing features such as the sampling rate or resolution. On the other hand, for medical professionals it is important that the device has the possibility of interpreting ECG signals and to be able to easily print acquired signals. Another important aspect for medical professionals is the ease of usage, such as starting recording with fewer steps when operating the device. Therefore, different users have different needs and preferences. In order to make the choice of a particular ECG device based on technical features, an interactive sunburst diagram that can help in the process is created.

Firstly, a search for contemporary mobile ECG devices that are currently available on the market is performed in this review. Most of these devices are also presented in numerous research articles and reviews, which provided additional data besides the information from the manufacturer. The inclusion criteria were that the device has either CE mark or FDA approval. Only medical devices were taken into account, so ECG devices without CE mark or FDA approval have not been considered.

In general, handheld devices, patches and wearable gadgets possess the possibility to record and gather ECG data that is further transferred online to special accounts, applications or cloud-based portals that physicians can access for further evaluation. In order to maximize the device's clinical impact, healthcare providers should comprehend the sensitivity, specificity and characteristics of the device's algorithms when interpreting data from patient's devices [5].

The main contribution of this paper is that contemporary medical mobile ECG devices that are currently available on the market are reviewed with all the technical features that could be found. This study should be considered as the most comprehensive review of mobile ECG devices. A set of common device properties is created and used for comparison. In addition, developed interactive diagram for mobile ECG device selection is suitable tool for quick and proper choice of desired device. To the best of author's knowledge, there are no similar methods published in the literature.

The rest of the paper is organized as follows: Section 2 deals with the related published work, Section 3 contains an overview of current single-lead and multiple-lead ECG devices, and Section 4 describes an interactive sunburst diagram for mobile ECG device selection. Finally, Section 5 represents conclusions.

2 RELATED WORK

Previously published reviews of ECG devices are presented in this section. A large number of review papers were published in the past years, which is an indication how important topic are ECG devices all over the world.

Cosoli et al. [6] presented a work which provides details on wireless ECG and cardiac monitoring systems. The authors focused on wireless devices, since cables can often interfere with the user's free movement. As authors claim, when approaching the development of a wireless ECG system, some important aspects should be considered, such as: analog front-end, digital signal processing, electrodes, data acquisition system, wireless communication technology, and also power consumption. After describing these aspects, they described a number of commercially available devices with a table containing some of their features. However, they provided less features than it is the case with the presented study.

A comprehensive survey of wearable and wireless ECG monitoring systems for older adults is presented in [7]. The authors reviewed and classified ECG monitoring systems into: smart wearable, wireless and mobile ECG monitoring systems. Additionally, ECG signal processing software and algorithms were described. ECG systems were also discussed in terms of signal quality and system reliability, user acceptability and medical professional's feedback and finally security and privacy. This paper does not provide technical features for reviewed systems, so it is not easy to make a selection based on some technical characteristics, as opposed to the presented study.

A review of the use of wearable ECG devices in the clinical setting is presented in [8]. The authors investigated the use of wearable ECGs in the clinic and acute care setting, and their impact on patient care, particularly pertaining to the management of cardiac arrhythmias. They found that wearable ECGs demonstrated their non-inferiority in detecting arrhythmias when compared to the current standard of care. Reviewed devices were classified into two categories: FDA-approved and non-FDA-approved devices. In comparison to this study, they reviewed a small number of devices and with less technical features as it is the case with the previously mentioned paper.

A brief review on wearable ECG devices and processing techniques for fall risk assessment, prevention and detection is done in [9]. The paper takes a systematic approach on the analysis of wearable ECG devices. The authors state that studies show that patients with cardiovascular disorders are at a higher risk of falling. A small number of ECG devices were reviewed again with a smaller number of technical features than it is the case with this paper.

Another review of mobile ECG devices is presented in [10]. In this paper, the authors classified ECG devices similarly to the study presented as single-lead and multiple-lead devices, but there are no specific guides for device selection. Some of the devices are similar in both papers, again with less technical features. The authors search revealed a total of fifteen devices, from which only six were described in more details because they featured in published medical literature as identified from PubMed search.

Bayoumy et al. recently published a review regarding smart wearable devices in cardiovascular care [11]. A large number of wearable devices were reviewed in this paper. Some of them are identical as in study presented, but they are described in a different manner – they examined the role of these devices in remote screening and diagnosis of common cardiovascular diseases. All devices were classified in these categories: chest strap, medical ear buds, smartwatch or band, ECG patch smart ring and clothing sensors. The authors stated that challenges such as clinical validity, device accuracy, and the absence of standardized regulatory policies and care for patient privacy are still hindering the widespread adoption of smart wearable technologies in clinical practice. Therefore, they presented several recommendations to navigate these challenges and proposed a simple practical guide for clinicians. In comparison to the study presented, they did not make any recommendations for the selection of any devices.

In [12], a systematic review was made to investigate if wearable devices provide a reliable and precise measurement of heart rate variability parameters in rest as well as during exercise. A search strategy was implemented to retrieve relevant articles from MEDLINE and SCOPUS databases, as well as through internet search. Results gave 31 different devices capable of measuring heart rate variability. Once again, not many technical features are provided for these devices, like it is the case with the presented study. The authors concluded that portable devices can give different solution for measuring heart rate variability.

Another review regarding the assessment of heart rate with wearable devices was published by Nelson et al. [13]. In this paper, the authors focused on wrist-worn consumer portable devices that be publicly found and purchased. They also discussed study design, biobehavioral, technological and demographic factors that can influence the accuracy of heart rate measurements. These devices have not been considered in the study since they are more often used for heart rate measurements than for ECG.

Wearable ECG devices that are capable of very long-term ECG monitoring (for example 14 days) are reviewed in [14]. These devices are connected straight to the skin, so wires and electrodes are not necessary for device operation. They are not restraining user's movements, which is a great benefit. Some of them are also described in the study presented with more technical details.

A review of wearable smart textile shirts is presented in [15]. These shirts have a sensor inside a textile which can record ECG data in a more comfortable way. As authors claim, they are not accurate and reliable as traditional ECG devices. For that reason, this kind of device is not included in the study.

In [16] authors provided a scoping review of mobile self-monitoring ECG devices to diagnose diseases. Some of the ECG devices are the same as in study presented, but the difference is that they focused on the diagnosis rather than the features of ECG devices.

Faruk et al. published an extensive study on inexpensive ECG acquisition systems [17]. The authors described contemporary ECG devices for different applications. Some of the ECG devices are the same as in this research, but the focus was not only on low-cost ECG devices. Another difference is that they do not provide a decision tree which could help home users and medical professionals to choose a certain ECG device based on their personal preferences.

Finally, work in [18] provided a detailed analysis of ECG systems which is based on schemes, monitoring environments and technologies. Furthermore, authors gave other details that comprises of a generic model and how to design and validate ECG systems.

As it can be concluded from this section, ECG devices are an active and attractive field of research generating many research materials. However, none of these previously mentioned papers provide a method for ECG device selection. Therefore, the authors of this research try to fill this gap with an interactive sunburst diagram as a method to make the choice of an ECG device. This can be a great help both for home users and medical professionals.

3 CURRENT TECHNOLOGIES

In this section, according to inclusion criteria, mobile ECG devices with either FDA approval or CE mark are presented. During the research, besides the information found on the Internet and from the manufacturers, available medical literature from SCOPUS, PUBMED and Google Scholar is considered. A vast number of ECG devices were found, but most of them do not have CE mark or FDA approval, which means that they could be suitable for researchers, but not for medical professionals. After including only devices that have CE mark and/or FDA approval a list of 25 devices is created. Other devices were excluded from this review study. This approach is more suitable for a wider target group.

3.1 Single-lead ECG devices

3.1.1 AliveCor KardiaMobile

KardiaMobile represents a handheld single-lead electrocardiogram recorder (Fig. 1).

Figure 1 KardiaMobile device

Two electrodes are located on top of the KardiaMobile device, two fingers from the left hand are placed on one electrode while two fingers from the right hand are placed on the other electrode [19]. Users commonly place fingers on each electrode for 30 seconds and the results are shown on the phone that can be easily transferred by email to clinicians. Narasimha et al. compared KardiaMobile to an external loop recorder (ELR) for detecting arrhythmias, where results show that KardiaMobile is suitable for the identification of symptomatic arrhythmias because of its simplicity and portability [20].

3.1.2 EPI Mini

EPI Mini is a single-lead device with three sensors that possess a display screen where the steps for recording of 30 seconds can be easily followed. ECG data is stored on the EPI Mini and can be transferred to a smartphone via Bluetooth to visualize the ECG tracing. A medical professional's prescription is required for the device [4]. Michael et al. compared EPI Mini to clinically approved EPI Life, which had previously been validated with standard 12-lead [21]. Results of a comparison where participated 30 individuals aged 18 to 48 years have shown a high level of correlation between compared devices.

3.1.3 NUVANT Mobile

The NUVANT Mobile Cardiac Telemetry system, developed by Corventis, incorporates a wearable device PiiX in combination with a transmission device zLink that receives data from PiiX and has a role to wirelessly transfer data to Corventis [22]. PiiX should be positioned on the left side of the chest, the upper left quadrant and a single blinking green light within the circle symbol is shown when the PiiX is working properly. PiiX should be worn for up to 7.5 days. When individuals have cardiac symptoms, patients use the Patient Trigger Magnet to record ECG [23].

3.1.4 Omron HCG-801

Omron HCG-801 represents a single-lead handheld device with a display. The device's lower surface, which includes one electrode, is positioned to the chest for ECG recording, while it is held in place by the right index finger where the second electrode is positioned. After a 30-second recording, results are shown on display and it can be saved on an SD memory card or sent to a PC. Seven different types of cardiac rhythms are possible to be detected with this device [24]. Kaleschke et al. validated Omron HCG-801 as highly accurate to detect atrial fibrillation comparing to standard 12-lead ECG, and it is also stated that it could be used by patients without supervision by healthcare personnel [25]. Study including population above 65 and 75 years old resulted as cost-effective device in identifying new atrial fibrillation patients and decreasing the number of stroke occurrences [26].

3.1.5 BodyGuardian Heart

BodyGuardian Heart possesses two inner electrodes which record a single-lead ECG [27]. Physician has to prescribe the device and the length of time that users are supposed to wear it. A box is equipped with two heart monitors, chargers, strip electrodes and a smartphone [28]. Strip electrodes are supposed to be attached to the chest either horizontally or vertically and can be angled at 30 degrees to avoid muscle or fat. The smartphone that is provided is only used for monitoring, not for calls or any other phone activities. Castelletti et al. validated the accuracy of QTc measurements of this device by comparison with 12-lead Holter recordings in long QT syndrome (LQTS) patients [29]. Results showed that the QTc measured by BodyGuardian was indistinguishable to the manual measurement.

3.1.6 Easy ECG Monitor PC-80A

The Easy ECG Monitor PC-80A represents single-lead device with a display that consists of three embedded metal electrodes [24]. The user has four options for positioning the device either using both hands or only right hand and the chest, also it is possible to position using the right hand and the left leg, or to use lead wires for measurement [30]. Recording lasts 30 seconds and can be transferred to a PC with a proprietary data cable.

3.1.7 Easy Monitor MD100B

Easy Monitor MD100B possesses two embedded metal electrodes and displays ECG in 30 seconds. Palm and chest measurement is provided, either between the right hand and left hand or between the chest and right hand. Additionally, the cable measurement is possible where electrode slices are positioned on the specific area [31]. Recordings can be transferred with a USB cable to a PC [24].

3.1.8 QardioCore

QardioCore represents a single-channel chest strap with an electrode. Adjusting the length of the strap to adapt it for the chest size, switches on automatically the device and starts recording after a few seconds. It can be worn under clothes without being noticed [32]. Apart from recording ECG, it detects skin temperature, heart rate and respiratory rate [33]. ECG recording is transferred to the cloud-based portal. When QardioCore was compared to a 12-lead ECG, no significant differences were found, indicating that it is a clinically valid tool [34]. One of the limitations is that the patient was supervised by a study researcher while using QardioCore, whereas the patient would use it independently in real conditions.

3.1.9 Zenicor ECG

Zenicor consists of two electrodes on which the thumbs should be placed for 30 seconds to obtain the recording, which is sent to a central ECG database via the mobile network [35]. Web-based service for storage and evaluation of results is the second component of Zenicor system and it can be accessed using a web browser. Zenicor was compared to the 12-lead ECG by Doliwa et al. where the examined approach showed a high sensitivity (96%) and specificity (92%) in detecting and diagnosing sinus rhythm and atrial fibrillation [36]. It was also compared to 24-hour Holter ECG to detect atrial fibrillation and paroxysmal supraventricular tachycardia (PSVT), twice daily for four weeks and when symptoms were present, Zenicor had a higher level of effectiveness [37].

3.1.10 Reka E100

Reka E100 is a single-lead ECG device that records by placing both thumbs on the integrated electrodes or with adequate electrode placement. By connecting the device to a computer or a smartphone, the ECG data is transferred to the REKA Cloud online health record portal [38]. Reka E100 was compared to 24-hour Holter ECG monitoring, it resulted in greater consistency and efficacy for identifying and interpreting heart arrhythmias [39]. The majority of patients regard E100 as simple to operate, comfortable and secure.

3.1.11 Zio XT/AT Patch

Zio Patch represents ECG adhesive patch monitor that is positioned on the left anterior chest wall for up to 14 days, while continuously recording. Prescription by a healthcare provider is needed, Zio XT (Fig. 2) is intended for low-risk patients while Zio AT is intended for high-risk patients.

Figure 2 Zio XT patch

Findings by Turakhia et al. suggest that extended Zio Patch monitoring is feasible and can detect arrhythmias that would otherwise be undiagnosed by traditional 48-hour monitoring [40]. Barrett et al. compared a conventional 24-hour Holter monitor and a Zio adhesive patch monitor, where Zio patch resulted as less visible and more patient-friendly with 93.7% of patients finding it comfortable to wear and 81% of patients preferring it to the Holter monitor [41]. The patch can detect significanlty more arrhythmia occurrences in comparison to the Holter monitor. It was evaluated on individuals who were under the age of 18, in pediatric patients [42, 43] both compared with Holter with positive outcomes.

3.1.12 AfibAlert

AfibAlert records a single-channel ECG during a 45-second period. Thumbs on the electrodes are used to obtain recordings or by utilizing the patient cable with a wristband or sticky electrodes. AfibAlert is only purchasable with a physician's prescription. The emission of red or green light represents a high or low level of probability of atrial fibrillation. Additional lights are the following: blue light means that data is being analyzed, while a yellow light indicates that recording should be repeated due to incapability of reading results [44]. ECG data can be transmitted by a USB cable to PC and uploaded to AfibAlert web site.

3.1.13 Beurer ME90

Beurer ME90 represents a single-channel device with a display that obtains ECG recording in 30 seconds. There are three alternative ways to obtain an ECG [45]. The first approach involves placing the right index finger on the top electrodes and pressing the lower electrode towards the chest. The second way is similar to the first, but the left index finger is used instead of the right, while the third approach uses the right index finger on the top electrodes and a finger of the left hand on the lower electrode. The device can be connected to a PC via the USB port to transfer the data and display it in greater detail, or it can be connected to a smartphone via Bluetooth. Brito et al. compared Beurer ME90 with 12-lead ECGs for the presence of arrhythmia and their findings indicate that Beurer ME90 had a high level of sensitivity for detecting Atrial Fibrillation but a low level of specificity [46].

3.1.14 SnapECG

SnapECG is a single-lead ECG device with dual electrodes, on the top side of the device, which should be pressed with fingers to start the 30-second recording. ECG recording is transmitted to mobile phones via Bluetooth. According to Guan et al., the SnapECG can accurately detect AF in patients aged between 65 and 74 years with high sensitivity and specificity [47]. They additionally state that SnapECG is currently used only in clinical practice, without screening procedures among wide population.

3.1.15 ECG Check

ECG Check is a single-lead ECG recording device with two built-in electrodes pads where fingers should be placed for a 30-second measurement. A rhythm strip is displayed on a device screen, saved on a phone and sent to ECG Check Web Center via Bluetooth [48]. The ECGs are classified as normal or abnormal by the application's algorithm. According to Haverkamp et al., the ECG Check possesses acceptable sensitivities and specificities for detecting pathological rhythms [49].

3.1.16 MyDiagnostick

MyDiagnostick is shaped like a stick and has electrodes on both ends. The device instantly turns on when it is hold with both hands and emits one short beep and starts ECG recording. After one minute of recording, lights should indicate the result. Green light indicates the case of normal cardiac rhythm and absence of atrial fibrillation, while red light is shown in case of rhythm irregularity suspicion for atrial fibrillation [50]. The device must be connected to the PC via USB and MyDiagnostick Management Studio is the application program for managing MyDiagnostick recordings and data [51]. According to the study by Tieleman et al. MyDiagnostick has a 100% sensitivity and 95.9% specificity for detection of atrial fibrillation [52]. Another study that showed similar results, high sensitivity and specificity for atrial fibrillation was done by Vaes et al. [53].

3.1.17 CardiBeat

CardiBeat is a single-lead device that records ECG by pressing the metal sheet with the thumbs and index fingers on both hands. Connection to a smart device via Bluetooth is necessary to take 30-seconds recordings. Recordings can be uploaded to SMART Monitoring reading service for evaluation reviewed by an ECG technician or a doctor [54].

3.2 Multi-lead ECG devices

3.2.1 AliveCor Kardia Mobile 6L

KardiaMobile 6L is capable of recording both single-lead and six-lead ECG [55]. The device consists of three electrodes, two on the top side and one additional sensor on the bottom side. Electrodes on the top side are used for positioning thumbs, while the bottom electrode is used for positioning on the bare skin of the left leg, either on the left knee or the left ankle for 30 seconds. ECGs from the device are wirelessly transferred to a smartphone via Bluetooth, where recordings are displayed [56]. KardiaMobile 6L was compared to conventional 12-lead ECG in terms of QTc monitoring in COVID-19 Patients, stated that the time of recording was decreased with the use of KardiaMobile 6L and close contact was reduced which contributed to the prevention of virus dissemination [57]. No major differences in QTc measurements were found between devices. Frisch et al. state that the KardiaMobile 6L can be used to safely and effectively monitor patients at high risk for arrhythmia in both inpatient and outpatient settings [58].

3.2.2 Humeds

Humeds represent a device that records a three-lead ECG signal. Four dry electrodes are placed in the corners of a rectangle on the bottom side of the device [59]. Humeds gathers ECG signals on the body surface, where recording starts by placing four dry electrodes against the chest for 30 seconds [60]. ECG data is transferred from the device to the mobile device via Bluetooth.

3.2.3 IEM Beam

IEM Beam records three-channel ECG and sends the results to the medical practice that uses HMS CS Evaluation Software. Four fixed electrodes are embedded within the monitor, which is put on the chest during symptoms [61]. Event recording with four fixed electrodes is possible as well as loop recording with four, cable, single-use electrodes [62]. IEM Beam can be worn by the patient for up to two weeks using long-term monitoring electrodes, and recordings can be sent to the cloud database.

3.2.4 CardioSecur

CardioSecur application that can generate a 12-lead or 22-lead ECG from four electrodes requires connection to a smartphone by cable. Placing the four adhesive electrodes on the chest allows obtaining results after a 10-second reading. A baseline reading should be done when patient does not have any symptoms and it is necessary to be taken for comparison with the next recordings. CardioSecur technology is based upon the EASI standard and has the ability to eliminate electrode misplacement and make ECG recording more accessible in athlete training and competition situations [63]. Spaich et al. compared CardioSecur to conventional 12-lead ECG and defined the device as user-friendly and practical for ECG acquisition [64].

3.2.5 Schiller Miniscope MS-3

Schiller Miniscope MS-3 possesses a tripod electrode on the bottom side, which could be applied directly to the chest for a recording of 47 seconds [65]. Additionally, it has the option to connect the Miniscope to a 3 or 5 lead patient cable with the patient cable adapter [10]. The ECG signals are displayed on the wide monitor display. Therefore, an ECG and heart rate could be seen in a real-time.

3.2.6 D-Heart

The D-Heart is a six-electrode device that records eight or twelve leads ECG. Number of leads for the measurement can be selected in the application. For the usage of 12 leads the physician must utilize D-Heart device and properly position the electrodes. On the other hand, using 8 leads recording, the smartphone should be linked to D-Heart and used to help position the electrodes. The smartphone camera algorithm can show the patient's own chest with proper electrode placement. Using camera and image processing technologies to locate the theoretical electrode placement on the patient's own chest facilitates the patient to position electrodes adequately [66]. D-Heart was shown to be as effective and reliable as 12-lead ECG in stratifying ECG abnormalities [67]. Fumagalli C. et al. states that D-Heart is effective and accurate and that it is able to diagnose ECG abnormalities with the same accuracy as a typical 12-lead ECG [68].

3.2.7 Coala

In about a minute, the Coala records a 2-lead ECG and heart sounds. Coala Heart Monitor provides both thumb and chest ECG. The first recording is taken by placing the device on the chest followed by the thumb recording. To increase accuracy, a thumb ECG is always recorded after the chest measurement, where fingers are placed on the electrodes to perform the second recording [69]. The Coala device is wirelessly connected to a smartphone via Bluetooth. Olsson et al. compared Coala to a single lead thumb-based ECG, the 2-lead ECG and mobile application had substantially higher accuracy in detecting atrial fibrillation [70]. Coala's feasibility was demonstrated throughout a one-month period among patients who underwent chest and thumb ECG examination after a stroke [71].

3.2.8 Cardions E2

CardioNS E2 represents a 12-channel ECG device with 10 leads and it is shown in Fig. 3. The ECG leads with distinct positions are identified by different colors. By connecting the device to an Android phone or tablet via a USB cable, the mobile application can show the ECG signal in real time [72]. The device is suitable for both patients and medical staff because it has two separate modes, normal and expert [73]. Device can be used independently or with remote monitoring center.

Figure 3 CardioNS E2 device

4 ECG DEVICE SELECTION

For the purpose of this review, authors contacted with researchers, medical professionals and home users in order to find out which features are important to them when it comes to ECG device selection. For medical professionals following features were important: number of leads, CE mark, FDA approval, recording duration, thermal printer, sampling rate and resolution. On the other hand, home users valued these features: connectivity, positioning, disease detection, weight, display, application and battery. The next step was to find which of those can be publicly found. Combination of personal preferences and available information resulted with a list of 14 features. The list is given in Tab. 1. One of the considered features was the price of the device, but it was not included in the final list while it varies a lot between different regions, and values found in the websites are not confident.

All features can have up to three different values. Number of leads can be either single-lead or multi-lead. Most of the devices can be connected via USB or Bluetooth, but some devices use a different type of connection and they are classified as Other. CE mark and FDA approval have values Yes or No, but some devices have both. Recording duration is divided into 3 different values: less than or equal to 30 seconds, between 31 and 60 seconds, and longer than 60 seconds. All devices have one of two types of positioning: on chest or fingers, including some devices that can use both methods. Some of devices have the ability to automatically detect diseases and this feature has two possible values: Yes and No. Weight of devices is divided into three categories: less than or equal to 50 grams, between 51 and 100 grams, and more than 100 grams. Only a few devices have own display, but some of them do have, so the values are Yes and No. Regarding application that is used with a device, most of them work using both Android and/or iOS applications, but some of them are proprietary. The values for this feature are: Android, iOS and Other. The self-powered feature has a Yes value when the device is powered from the battery source, otherwise, when it is powered by the other device, like mobile phone, the value is No. Only one of the reviewed devices has the ability to print on a thermal printer and others do not have this feature. Since this is important to medical professionals, it is included in the list with values Yes and No. Sampling rate varies among devices and it is divided into three categories: less than or equal to 200 Hz, between 201 and 500 Hz, and more than 500 Hz. Similar case is with resolution, so it is divided as for: 10 bits, between 11 and 23 bits, and finally 24 bits.

All 25 mobile ECG devices that are previously described are listed in Tab. 2 and Tab. 3 with corresponding attributes from Tab. 1. In case where none of the options are available for the specific device, then attribute "Other" is assigned and shown with "O" in the table. For example, Schiller Miniscope MS-3 does not use an Android or iOS application because the device cannot be controlled with a smartphone, so its application is classified as "Other".

Table 1 Features with corresponding values

Feature	Feature value		
Number of leads	Single-lead (S)	Multi-lead (M)	
Connectivity	USB	Bluetooth (B)	Other (O)
CE mark	Yes	No	
FDA approval	Yes	No	
Recording duration	≤ 30s	31-60s	> 60s
Positioning	Fingers	Chest	
Disease detection	Yes	No	
Weight	≤ 50g	51-100g	> 100g
Display	Yes	No	
Application	Android	iOS	Other (O)
Self-powered	Yes	No	
Thermal printer	Yes	No	
Sampling rate	≤ 200Hz	201-500Hz	> 500Hz
Resolution	10 bits	11-23 bits	24 bits

For some devices it was not possible to find information about its sampling rate or resolution. For those devices attribute "n/a" is assigned meaning that the information for that feature is not available. These two features are listed in the last two columns of Tab. 3.

Table 2 ECG device features – part 1

ECG device	Number of leads	Connectivity	CE	FDA	Recording duration	Positioning	Disease detection
AliveCor KardiaMobile 6L	M	B	Yes	Yes	> 60 s	Fingers	Yes
AliveCor KardiaMobile	S	B	Yes	Yes	> 60 s	Fingers	Yes
Humeds	M	B	Yes	No	≤ 30 s	Chest	No
EPI Mini	S	B	Yes	Yes	≤ 30 s	Fingers	No
Nuvant Mobile	S	O	Yes	Yes	> 60 s	Chest	Yes
Omron HCG-801	S	O	Yes	No	≤ 30 s	Chest	Yes
BodyGuardian Heart	S	B	Yes	Yes	> 60 s	Chest	No
IEM Beam	M	B,O	Yes	No	> 60 s	Chest	Yes
Easy ECG Monitor PC-80A	S	USB	Yes	Yes	≤ 30 s	Fingers, Chest	No
ECG Monitor MD100B	S	USB	Yes	No	≤ 30 s	Fingers, Chest	No
CardioSecur	M	O	Yes	No	> 60 s	Chest	Yes
QardioCore	S	B	Yes	No	> 60 s	Chest	No
Zenicor	S	O	Yes	No	≤ 30 s	Fingers	No
Schiller Miniscope MS-3	M	O	Yes	No	31-60 s	Chest	No
Reka E100	S	USB	Yes	Yes	31-60 s	Fingers, Chest	No
Zio XT and AT patch	S	O	Yes	Yes	> 60 s	Chest	No
AfibAlert	S	USB	No	Yes	31-60 s	Fingers	Yes
Beurer ME 90	S	USB,B	Yes	No	≤ 30 s	Fingers, Chest	No
D-Heart	M	B	Yes	No	31-60 s	Chest	No
SnapECG	S	B	Yes	Yes	> 60 s	Fingers	No
ECG Check	S	B	Yes	Yes	≤ 30 s	Fingers	No
Coala	M	B	Yes	Yes	≤ 30 s	Fingers, Chest	Yes
MyDiagnostick	S	USB	Yes	No	31-60 s	Fingers	Yes
CardiBeat	S	B	No	Yes	> 60 s	Fingers	Yes
CardioNS E2	M	USB	Yes	No	> 60 s	Chest	Yes

In order to make a choice for one of selected 25 mobile ECG devices, an interactive sunburst diagram for easier selection is created. It is available online on the following URL [74].

A sunburst diagram displays ranking in a form of series of slices which are shown for every rank. Each slice correlates to ranking and the central slice represents the source. Slices are divided according to their correspondence with the parent slice. The angle of the slice can be divided equally under its parent node, or can be proportional to some specific value [75]. The initial idea was to create a standard decision tree diagram, but this was not a convenient method since the tree would have too many branches that cannot fit on one page and it would be cumbersome for a user to navigate through it. Therefore, an interactive sunburst diagram was a much more appropriate choice for displaying large amounts of data. Interactive means that the sunburst diagram responds to user input when a part of the diagram is clicked. When a particular sector is clicked, diagram changes in a manner that the selected sector becomes the root of the diagram and displays only slices that are connected with it. It is possible to zoom in and zoom out on the diagram. When a feature is selected on the diagram, all mobile ECG devices that fulfil the selected criteria are listed on the right side of the diagram. To the left of the diagram filters show which features are selected. A toolbar for navigation is also included on the left side containing two buttons for navigation through the diagram. The first button is for getting one step back in the process of selection, removing the last feature from selection. The second button acts as a home button which will take the user to the root of the diagram or simply just reset and start over the selection process. In this way it is easy to navigate through the diagram and see in every moment which devices are selected with which features. The first step is always to choose the number of leads, the second is to choose connectivity type, and so on, in the order as it is given in Tab. 1. This is given as a case study to show one path for ECG device selection. For future work it is planned to make the diagram fully dynamically interactive. That means the user will not have to follow only one feature order, but rather select features in the order they prefer. Full sunburst diagram based on data from Tab. 2 and Tab. 3 is shown in Fig. 4 and the initial diagram shows all ECG devices on the right side. The root of the diagram is labeled with "ECG" decision.

Table 3 ECG device features – part 2

ECG device	Weight	Display	Application	Selfpowered	Thermal printer	Sampling rate	Resolution
AliveCor KardiaMobile 6L	≤ 50g	No	Android, iOS	Yes	No	201-500Hz	11-23 bits
AliveCor KardiaMobile	≤ 50g	No	Android, iOS	Yes	No	201-500Hz	11-23 bits
Humeds	51-100g	No	Android, iOS	Yes	No	> 500Hz	11-23 bits
EPI Mini	51-100g	Yes	Android, iOS	Yes	No	n/a	n/a
Nuvant Mobile	≤ 50g	No	O	Yes	No	≤ 200Hz	10 bits
Omron HCG-801	> 100g	Yes	O	Yes	No	≤ 200Hz	n/a
BodyGuardian Heart	≤ 50g	No	O	Yes	No	201-500Hz	11-23 bits
IEM Beam	> 100g	No	O	Yes	No	≤ 200Hz	11-23 bits
Easy ECG Monitor PC-80A	51-100g	Yes	O	Yes	No	≤ 200Hz	n/a
ECG Monitor MD100B	> 100g	Yes	O	Yes	No	201-500Hz	10 bits
CardioSecur	≤ 50g	No	Android, iOS	No	No	201-500Hz	n/a
QardioCore	> 100g	No	Android, iOS	Yes	No	> 500Hz	11-23 bits
Zenicor	> 100g	Yes	O	Yes	No	n/a	n/a
Schiller Miniscope MS-3	> 100g	Yes	O	Yes	Yes	201-500Hz	10 bits
Reka E100	> 100g	No	O	Yes	No	201-500Hz	10 bits
Zio XT and AT patch	≤ 50g	No	Android, iOS	Yes	No	201-500Hz	10 bits
AfibAlert	> 100g	Yes	Other	Yes	No	> 500Hz	n/a
Beurer ME 90	≤ 50g	Yes	Android, iOS	Yes	No	201-500Hz	n/a
D-Heart	> 100g	No	Android, iOS	Yes	No	> 500Hz	24 bits
SnapECG	≤ 50g	No	Android, iOS	Yes	No	n/a	n/a
ECG Check	≤ 50g	No	Android, iOS	Yes	No	≤ 200Hz	n/a
Coala	≤ 50g	No	Android, iOS	Yes	No	201-500Hz	24 bits
MyDiagnostick	> 100g	No	Other	Yes	No	n/a	n/a
CardiBeat	≤ 50g	No	Android, iOS	Yes	No	≤ 200Hz	n/a
CardioNS E2	≤ 50g	No	Android	No	No	> 500Hz	24 bits

Fig. 5 shows two examples of the sunburst diagram. Fig. 5 (b) shows when features multiple-lead and USB connectivity are selected. Those features are displayed to the left of the diagram. To the right of the diagram is displayed CardioNS E2 as the only device that has multiple leads and USB type of connection. Fig. 5 (c) shows an example of a diagram when four features are selected: Single-lead, Bluetooth connectivity, CE mark and FDA approval (shown to the left of the diagram). In that case, four devices have these features: AliveCor KardiaMobile, EPI Mini, Snap ECG and ECG Check (shown to the right of the diagram).

As it was mentioned in the previous section, for some devices data regarding sampling rate and resolution could not be found. For that reason, these two features are put in the last two columns of the Tab. 3. ECG devices without this information are not shown in the diagram when sampling rate and/or resolution are selected. Putting these two features in the last two columns enables the user to select them based on all other features before these last two are selected.

None of these 25 devices can be chosen as the best among them. Personal preferences are different for each medical professional, as well as for each home user. Based on their individual needs and preferences, everyone can find the best device for themselves.

5 CONCLUSION

In this paper the authors made a review of contemporary medical mobile ECG devices including analyses of different features devices are equipped. It could be considered as the most comprehensive review of medical mobile ECG devices containing data acquired from manufacturers, Internet presentations and publicly available academic papers databases. In order to make a proper selection of specific

ECG device based on technical features, an interactive sunburst diagram that can support a selection process is created. This poses a new approach for selection of best suited device for different purposes for researchers, physicians and other medical staff.

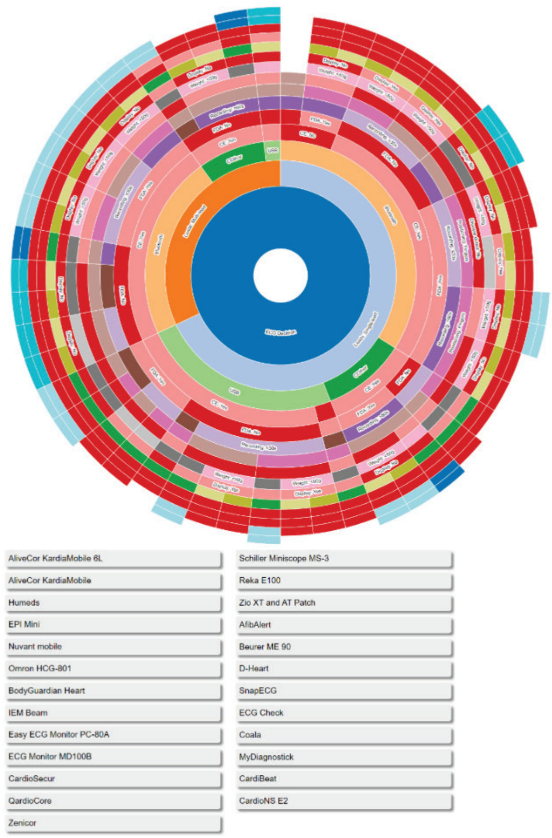

Figure 4 Full sunburst diagram with the list of all ECG devices

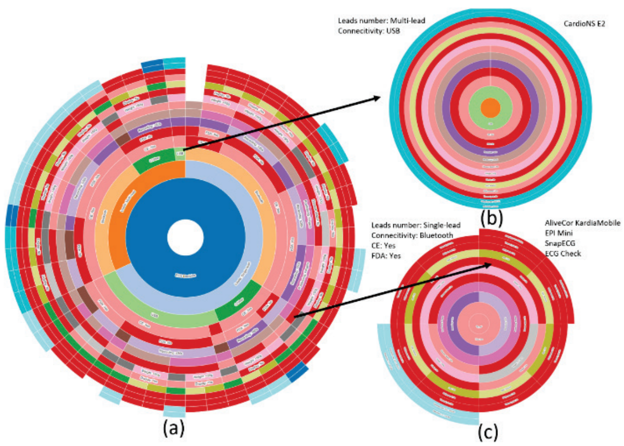

Figure 5 Full sunburst diagram (a) with an example when two features are selected (b) and with an example when four different features are selected (c).

Motivation for and the aim of the research along with contributions is highlighted in the introduction section. Related work is given to show the current trends in the literature. The results imply that this is an active area of research. Section three lists all mobile ECG devices that were found based on the inclusion criteria. The interactive sunburst diagram which is created for mobile ECG devices selection followed by several examples is presented and explained. All covered devices are included in the interactive diagram which is publicly available online as a free mobile ECG selection tool.

The main contribution of this paper is that currently available contemporary mobile ECG devices are reviewed with as much as possible technical features including the development of an interactive diagram for mobile ECG device selection. Proposed method for ECG device selection and comparison based on provided set of features is also a contribution. Another contribution of the paper is the addition of value on a practical side for choosing a particular mobile ECG device based on personal doctor, home user or researcher preferences.

Regarding future work and according to presented study results, there is a plan to extend the list of mobile ECG devices, their related features, and to develop a smart survey which will help stakeholders to choose an appropriate device. Finally, these steps lead to the creation of a complete decision support system for selection of mobile ECG devices.

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