Wrist-worn and chest-strap wearable devices: Systematic review on accuracy and metrological characteristics

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Wireless ECG and cardiac monitoring systems: state of the art, available commercial devices and useful electronic components

Gloria Cosoli[1], Susanna Spinsante[2], Francesco Scardulla[3], Leonardo D'Acquisto[3], and Lorenzo Scalise[1]

[1] Department of Industrial Engineering and Mathematical Sciences, Università Politecnica delle Marche, Ancona, Italy
[2] Department of Information Engineering, Università Politecnica delle Marche, Ancona, Italy
[3] Department of Engineering, University of Palermo, Palermo, Italy

E-mail: g.cosoli@staff.univpm.it

Abstract

Wireless ElectroCardioGram (ECG) systems are employed in manifold application fields: tele-monitoring, sport applications, support to ageing people at home, fetal ECG, wearable devices, ambulatory monitoring. The presence of cables often hinders user's free movements, alongside clinicians' routine operations. Therefore, wireless ECG systems are desirable. This paper aims at reviewing the solutions described in the literature, besides commercially available devices and electronic components useful to setup laboratory prototypes realization. Several systems have been developed, different in terms of the adopted technology; when approaching the development of a wireless ECG system, some important aspects should be considered: electrodes (disposable, wet/dry, without contact, insulated), analog front-end, data acquisition systems (including amplifiers, multiplexer), wireless transmission technology (e.g. WiFi, Bluetooth) and power consumption (battery lifetime, miniaturization purposes). Technological advancements and continuous research have already brought to miniaturized and comfortable devices, but there is still room for improvement on multiple sides.

Keywords: Biomedical engineering, ECG, electrocardiography, wireless ECG, electrodes, wireless communication

Highlights:

- Wireless electrocardiogram systems are increasingly common in many use fields
- Available devices and useful electronic components are being reviewed
- Electrodes, electronics, wireless technology and power consumption are treated
- Miniaturised and comfortable devices development is the current research trend

1. Introduction

Healthcare systems are currently facing new challenges, linked to multiple aspects.

On one side, an unprecedented change in population age is currently ongoing; according to the United Nations, by 2050 one out of six people in the world will be over 65 years old (16%); moreover, in Europe and North America one out of four people could be aged 65 or over [1]. This represents an ageing trend quicker than ever before, with almost a doubling of the population over 60 years between 2015 and 2050 (from 12% to 22%) [2].

On the other side, people are now driven by the desire for health awareness, hence willing to self-monitor their basic health conditions and wearable devices are spreading with this purpose, not only in health but also in sport applications [3]. Even in clinical applications there is a urgent need of practical instrumentation, allowing routine actions while minimizing the hindrance of cables or bulky apparatuses. Furthermore, extended studies and field tests have shown how remote monitoring represents a valuable option for all those patients who do not need a direct medical assistance, but would manage their own health better with the support of this type of technology: diabetic, overweight, elderly subjects, people with cardiovascular diseases (CVDs) [4] or Chronic obstructive pulmonary disease (COPDs) [5], and hypertensive people [6].

The increase in life expectancy and the related health costs are pushing biomedical research focus on the development of cost-effective and easily available solutions for healthcare services, aimed at promoting both the ease of use and the comfort of the users (also reducing the necessary travels for outpatient visits, which is extremely important in case of fragile people, how the recent Covid-19 pandemic has clearly underlined [7,8]). Lightweight, compactness, low-power consumption, and interoperability are desirable features for portable devices, also easing their miniaturization in real wearable devices. Mobile telemedicine has recently known a rapid development thanks to new mobile technologies, communication bandwidth, and miniaturization capabilities easing the systems portability [9,10], consequently increasing the flexibility of healthcare services delivery [11]. Furthermore, the advances in microelectronics and communication fields allow cost effectiveness and better performance of these devices, thus fostering their market penetration [12].

In this context, the trends in electrocardiographic (ECG) activity monitoring are heading towards wearable [13] and/or wireless systems [14], which can even be combined (also with advanced computing technologies and artificial intelligence – AI – tools) to enable better healthcare services. They both represent interesting fields of research, because of two main reasons: 1) the fact that cardiovascular diseases are very spread all around the world (17.9 million deaths from CVDs in 2016, i.e. 31% of all global deaths [15]) and consequently monitoring cardiac functionality is paramount, and 2) the application in a wide range of fields:

- home telecare and Ambient Assisted Living (AAL) for the monitoring of ageing people living at home [16]. Even applications of continuous ECG recording in the bathtub [17], in the toilet [18] or embedded in armchairs [19,20] have been studied recently, exploiting capacitive electrodes and conductive fabrics. These solutions for remote monitoring (employing sensing electrodes distributed on the living environment furniture) attempt to reduce the healthcare costs [21], with a pivotal role played by wireless communication systems [22,23] enabling data transfer to the hospital/the healthcare server [24] or, more generally, to a specific base station [25] or to a smartphone application [26];
- sport applications [27], where ECG monitors report better performances than wearable devices using photoplethysmographic (PPG) signals [28], which on the other hand are prone to motion artifacts [29] and determine a quite high power consumption, contributing to the relatively short battery lifetime of wearable devices [30]);
- fetal ECG (f-ECG) [31];
- ambulatory monitoring [32];
- continuous monitoring of patients with diabetes, hypertension, CVDs or COPDs;
- surgical interventions.

Wireless ECG systems are desirable to promote the users' (common healthy people and patients, but also medical personnel) free movements and normal lifestyle and routine actions, without being hindered by the presence of wires, thanks to the fact that the person under monitoring has not to be tethered to a bulky instrumentation. Plus, the development of algorithms for automatic ECG classification [33,34] has the potential to reduce the misdiagnosis problems and the need for the live presence of the doctors. Consequently, the whole healthcare quality is strengthened [35], also thanks to the fact that remote monitoring can be performed in normal life conditions, allowing routine daily activities. However, it is worthy to underline that the presence of cables cannot be completely eliminated, since electrodes need to be connected each other to measure electric potential differences, besides being connected to a main unit. In any case, these connections can be optimized and also miniaturized in a compact and portable system, avoiding wires for the connection to the main (bulky) ECG system. Both the cables length and the amount of wires influence the quality of the measurement, impacting on the signal-to-noise ratio (SNR) and on the comfort of the user, whose movements could cause artifacts (the so-called "leads-off", due to a momentaneous loss of connection between electrodes and skin, as well as false signal peaks due to motion [36]).

Furthermore, electronics can also be embedded in textile materials, enhancing the naturalness and the comfort perception [37–41], without requiring skin preparation and avoiding skin irritation due to adhesive materials [42]. Indeed, an important aspect to consider consists of sensing electrodes; for long-term monitoring, it is discouraged to employ wet disposable electrodes (often made of Ag/AgCl), because they could easily cause skin irritation, inflammation, and allergic reactions [43–45], as well as feature a progressive degradation of signal quality because of the gel dehydration; therefore, many other types of electrodes have been explored in the literature, even if they are not widely adopted in clinical applications and commercial systems yet.

To complete this overview, even if the focus of this study is on medical applications (to support the healthcare system), it is worthy to note that research is rapidly growing also on non-clinical applications, bringing to the development of advanced commercial systems for everyday life. Indeed, the recent spread of wearable wrist-worn technologies has offered the unique chance to detect the Heart Rate (HR)-related parameters across long periods during daily-life activities. The latest development toward this direction is the use of single-lead ECG in smartwatches [46] to detect atrial fibrillation [46, 47], even though this functionality is not suitable for continuous monitoring, as users have to stay still for 30 seconds during the acquisition, while closing the circuit by putting a finger of the other hand onto the watch. Thus, the aim of these devices is not to provide a full ECG path, but rather to process the data through an alghoritm able to identify specific episodes suggesting heart disorders such as atrial fibrillation.

Currently, different commercial products, such as the KardiaBand (AliveCor) and Apple watch Series 4-6 have gained FDA (Food and Drug Administration) 510 (k) class II clearance for ECG feature and the ability to detect arrhythmias [49], as well as the FDA-Cleared Electrocardiogram Monitor App from Samsung, which is available on the Galaxy Watch3 and Galaxy Watch Active2, and it is able to record and classify an ECG as either sinus rhythm, or atrial fibrillation. Similarly, the ScanWatch (Withings) [50] has received CE medical certification in Europe, and other similar devices from different wearable companies are expected to be soon FDA cleared and regulated to be able to measure beats per minute, to detect normal sinus rhythms and atrial fibrillation. Despite the limited applicability of these devices to clinical practice, as they are only one lead, several studies evaluated their potential in obtaining 3-lead electrocardiogram recordings based on Einthoven's triangle, showing a strong correlation when compared to standard ECG [51,52], and therefore new potential opportunities for cardiac disorders diagnosis.

Finally, it is worth to mention that nocturnal polysomnographic monitoring devices, such as the Compumedics Somnté and Grael, also provide the ECG through surface electrodes [53] and are commonly used to determine different sleep disorders such as sleep apnea [54].

The goal of this article is to provide an extensive technical and product review, examining not only the available commercial systems for wireless ECG monitoring, but also discussing the main components for the laboratory development of devices with research purposes. This is intended to give advices to the developers and provide them an up-to-date overview on the different components characteristics and also producers, to try reducing the design effort, with no claim to be exaustive, given the rapidly and quite unpredictable market and research growth in this field. Furthermore, the authors want to discuss the state of the art (SotA) on laboratory developed systems and filed patents. Finally, the authors aim to specify the differences between daily monitoring applications and clinical purposes, undoubtedly requiring different metrological characteristics of the sensing devices. With respect to the SotA, this review is aimed at merging both research and commercial systems, as well as electronic components, while elaborating on different application fields, since, to the best of the authors' knowledge, this kind of manuscript is not present in the literature; there are in fact specific studies on different topics but no review papers including all these aspects. For example, Ghasemzadeh et al. reviewed signal processing and classification techniques for application in wearable devices, focusing on ECG and inertial sensors [55], as well as Elgendi et al, who revisited QRS detection algorithms for wireless ECG systems [56]. Custodio et al. focused on architectures and communication technologies [57]; similarly, Wang et al. reviewed low-power technologies for wearable systems [58], while Al-Zaiti et al. reported technical solutions for wireless transmission of ECG signals [59]. Patel et al. concentrated their study on wearable sensors for rehabilitation purposes, both at home and in community settings, with a short description of key technologies [60]; also Ramasamy and Balan considered wearable sensors for ECG measurement, making a comparison among the different solutions (e.g. wet electrodes, dry sensors, textile-based sensors, knitted integrated sensors and planar fashionable circuit boards) [61]. Mansoor Baig et al. reviewed wearable patient monitoring systems with the aim of underlining challenges and opportunities for their clinical use [62]; however, they did not make a distinction between research and commercial devices, neither focused on electronic components. Alfarhan et al. made a review on wireless ECG systems focusing on the main components, without extensively discussing commercial and research devices [63]. There is only a quite short review of both research and commercial wireless medical devices dated back to 2013 [64], but since that time the research on the field and the technological development have undoubtedly made great strides, bringing new solutions to the market and contributing to the SotA. This paper is organised as follows: Section 2 discusses the literature on wireless ECG systems, Section 3 presents the patents available in this field, Section 4 reports commercially available devices, Section 5 considers some electronic components useful for the realization of wireless ECG laboratory prototypes, and finally Section 6 reports the authors' conclusions.

2. The state of the art

When designing a wireless ECG system, multiple components should be taken into consideration [63], as schematically summarized in Figure 1.

Figure 1 Wireless ECG systems: components to consider in the design process.

Electrodes. As mentioned above, conventional Ag/AgCl gel electrodes are surely the most common ones, but they reveal to be inappropriate for ambulatory and long-term monitoring. To compensate for the dehydration effects, some studies tested miniature water reservoirs [65] or superabsorbent polymers [66], however reliability and motion tolerance issues could be raised. Dry electrodes are preferable; they do not use any gel or moisturizer, hence suffer from high electrode-tissue impedance, due to the poor contact with the skin. To minimize noise and motion artifact effects (transversal motion causes instantaneous changes in the contact impedance, whereas lateral motion induces triboelectric charge on the electrode surface [67]), flexible substrates (e.g. elastomeric polymer materials [68–70], where sometimes conductive materials, such as silver nanowire [71], carbon nanotubes [72], carbon black, carbon nanoparticles [42], and graphene [73] are embedded) can enhance the conformability to the skin [74,75], which is particularly useful when wide movements are foreseen, making the sensor capable to stretch and flex without being damaged, thanks to its ability to adapt to the skin topography and maintain the contact effectively [24]. Moreover, also conductive rubber can be used [76], in which stretchability can be further enhanced by specific geometrical configurations, such as serpentine, mesh, sponge, net-shaped, or spring-like structures [73,77]. These electrodes (e.g. Plessey^{TM} electrodes [78]) are capacitively coupled to the skin through a layer of insulating material [79] (e.g. textile, like cotton), making them suitable to be integrated in smart clothing. A third electrode, larger than the others, is commonly used (maybe integrated on the main board [80]) to improve the robustness against noise and artifacts. Concentric ring electrodes have also been proposed to acquire a more localized electrical activity than conventional disc electrodes [81]. There are also insulated electrodes, with a buffer amplifier [67] and an active shielding against noise [82], and non-contact electrodes (e.g. for automotive applications [82]). The latter are realized with smart fabrics, such as highly conductive polymers on a cotton substrate, integrating antennas for wireless transmission of data towards external devices [83,84]. Textile-based electrodes are more and more widespread, since they provide high comfort levels to the user and exploit both conventional fabric manufacturing techniques (e.g. weaving, knitting, embroidery and stitching) and advanced ones (e.g. ink-jet printing, coating, lithography and chemical vapour deposition); metallic yarns (e.g. stainless-steel) can be manipulated as textile materials and washed without loosing their properties. Also, nylon spandex [85] and chemical fibres [86] are widely employed. However, they show a high sensitivity to motion artifacts, suffering also from poor electrode-skin contact. For these reasons, it is preferable to use a 3-electrode configuration than a 2-electrode one; in addition, the signal quality is better when electrodes are wet. Finally, also silicone microneedle electrode arrays (on a polydimethylsiloxane substrate) have been proposed in the literature, resulting flexible and conductive, but at the same time semi-invasive, complex, and quite expensive [87]. Electrode arrays were realized also with Ni/Cu polyester conductive fabric tape from 3M, modelled on a thin foam pad and connected to wires [88]; three optimal electrodes for a differential 3-lead ECG measurement can be selected, then the signal is transmitted wirelessly.

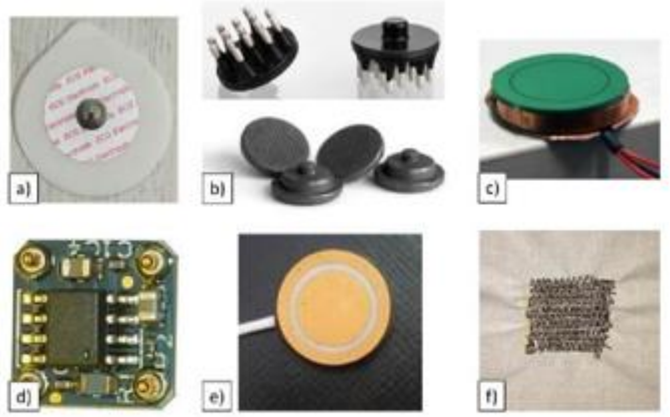

Figure 2 Electrodes examples: a) disposable wet-electrodes, b) dry electrodes, c) non-contact electrodes, d) Plessey^{TM} electrodes, e) capacitive electrodes and f) textile electrodes.

Coincident sensing and transmitting electrodes were developed as well, hence simplifying the system structure [89]. Finally, conductive inks can be used to realise electrodes, such as gold nanoparticle ink [90] or medical grade Ag/AgCl ink [91], presenting a better performance than silver, both in terms of long-term drift and contact noise [92].

Analog front-end. The analog front-end (AFE) filters (outside the band of interest) and amplifies the signal; it should have the following characteristics:

- high input impedance, which can be improved with resistors [93] or antiparallel diodes [94];
- high common mode rejection ratio (CMRR), in order to reduce motionnoise artifacts noise associated to electrodes impedance imbalance;
- large DC electrode offset;
- low noise floor, to obtain better signal quality.

Low-power and low-cost sensors are desirable for wearable and wireless applications [95]. In fact, a low-power design for AFEs is essential to extend the battery lifetime of the device. In [96], a fully integrated, low-power, high-resolution AFE is proposed, which includes a 14-bit low-power inverter-based Sigma-Delta modulator, and a differential amplifier with a subthreshold transistor to obtain a good trade-off between power consumption and noise. The proposed AFE is specifically targeted to ECG/EEG signal recording and features a noise efficient factor (NEF) of only 3.658, better than previous works analysed by the authors. Pavani et al. [97] designed a compact, wireless and low-cost 12 lead ECG AFE system, choosing the TI ADS 1198 Delta-Sigma ADC, to avoid expensive ASIC or custom ICs which are typically used in ECG systems. The same board is also capable of running some signal processing algorithms that allow to use the device as a stand-alone system, for additional easiness of use and portability. Lukas et al. [98] present a wireless sensing heterogeneous system-in-package (SiP) containing an ultra-low power (ULP) SoC, a non-volatile boot memory (NVM), and a 2.4 GHz frequency shift key (FSK) radio, all integrated with custom ULP interfaces. An energy harvesting platform power management is also included to feed the SiP and the sensors. The design of the system is fully targeted at maximally reducing the power consumption: in fact, the proposed SoC consumes 1.02 µW during continuous ECG monitoring and post-processing. A prototype wearable device to be used on the upper arm for continuous ECG monitoring, based on commercial off-the-shelf (COTS) components, has been recently proposed by Richards et al. [99]. Again, the prototype exploits full powering from harvested energy, thanks to the use of a BLE data transmission link, and to an optimised design of an ULP AFE, handling ECG signal amplification and filtering. The prototype achieves continuous ECG recording and wireless transmission of digitized ECG data at a throughput of 816 bits/s, in a low-cost and compact form factor. In a recent work [100], an AD8232 chip is used for the AFE of a low-cost, low-power, and wireless ECG Lead II monitoring system, equipped with cloud-enabled deep learning-based automatic arrhythmia detection, and powered by two 450 mi-Ah Li-ion batteries. The device exploits a flexible fabric-based design that helps its easy adoption out of clinical settings, especially in low-resources contexts. Saleem et al. [101] present the design of an AFE circuit for an ECG monitoring system, in which the instrumentation amplifier INA128 is used to amplify the signals acquired through electrodes, followed by high- and low-pass filtering to remove artefacts. Tests performed on a digital storage oscilloscope confirm the AFE provides a standard ECG trace, however, aiming to use AC power, isolation between the patient and the device is still needed, for safety purposes.

Data AcQuisition (DAQ) system. A DAQ system consists of integrated circuits, including amplifiers, multiplexers, analog-to digital converters (ADCs), and communication modules. While the design of highly efficient microcontrollers and transmission devices has been the main focus of research from industry and academia in the last years, aiming for energy efficient modern wearable systems, sensor data acquisition performed by medical devices is still mostly based on the standard paradigm of regular signal sampling at the Nyquist rate. Some innovative proposals are emerging, for example to create event-based heart-rate analysis devices, such as in the work by Zanoli et al. [102], where the proposed approach is compared to the standard one, on the same ULP platform, providing a reduction of the energy consumption in runtime up to 15.6 times, while keeping almost the same detection performance. The traditional acquisition approach based on sampling at the Nyquist rate leads to data overload and an extra use of resources in the full processing pipeline, when applied to sparse and highly non-stationary signals, like those typically handled by medical devices. The adoption of the compressed sampling (or sensing) approach to optimize the ECG signal acquisition has been proved effective by several works in the literature [99,103–105].

Digital signal processing (DSP) unit. The acquired and AD-converted signals need to be processed by a DSP unit to derive valuable information on the health status of the monitored person; in this context, it is appropriate to distinguish between real-time processing (through an onboard microcontroller or a Field Programmable Gate Array – FPGA, i.e. on-chip signal processing) and post-processing (through a PC or a Personal Digital Assistant – PDA) operations. The former requires fast algorithms executed onboard, essentially for noise reduction and to infer fundamental evidence on the ECG signal (e.g. detection of QRS complex and calculation of HR [106,107], or short-term Heart Rate Variability, HRV), whereas the latter allow to perform a deeper analysis even in more relaxed times, for example to identify all the ECG signal components [56,108] and related figures. Computing devices can also improve the SNR by filtering [109] and decomposition [110–112] techniques. Recently, AI technologies are increasingly employed to reduce noise and estimate the health status of the monitored person [113,114].

Wireless communication technology. Different solutions can be adopted to facilitate wireless data transmission in real-time:

- IR, which is suitable for short distances and low data rate [115];
- Bluetooth at 2.4 GHz (i.e. an ISM – Industrial, Scientific and Medical – band), which can reach 100 m [63], at different data rates; Bluetooth Low Energy (LE) is advantageous in terms of power consumption [90];
- WiFi, for the realization of local area networks [116], with up to 100 m distance coverage and data transferrable at several tens of Mbit/s;
- RF (Radio-Frequency – e.g. RFID – Radio-Frequency IDentification – or ZigBee), which, however, can suffer from instability and packet loss during transmission [117], thus being best used for short-range transmissions in Personal Area Networks (PANs);
- ANT [79];
- GPRS (General Packet Radio Service) [118] for long-range and limited data rate communications, currently supported as a legacy technology in machine-to-machine (M2M) communications;
- Wireless mobile technologies (4G, Long Term Evolution (LTE) , Narrow Band – IoT (Nb-IoT), and the upcoming 5G, and Wide Area Networks (WAN) technologies) [62,119,120].

Back in 2008, the IEEE issued a guidance document [121] to address the use of RF wireless technology for the transport of medical data, both to and from point-of-care (PoC) medical devices, in home- or mobile-based healthcare scenarios, up to hospital ambulatory and stationary situations. Despite dating quite back in time, the document identifies the main critical issues to consider, which are still valid irrespective of the specific wireless technology adopted, such as: i) reliability, latency, priority, and bandwidth, that define the Quality-of-Service (QoS) requirements prescribed by the data being transported and the application or service that will use it; ii) the performance expected from the wireless technology to use, in terms of capability to establish and maintain the link, power consumption, link range, and throughput; iii) specific requirements defined by the end users, according to the application context. The guidance document established the foundations for adopting off-the-shelf RF wireless technologies for medical data transport, and it is still a reference guideline despite the impressive evolution of the available wireless communication technologies in the recent times.

In a modern and Internet of Things (IoT)-oriented perspective [122], connected devices can have some kind of local, on-board elaboration functions (so-called edge or fog computing approach [123,124]) to pre-process raw measurement data, or act as relays of raw data towards cloud-based computing platforms [125–127], where complex and resource-consuming processing algorithms (such as those used in AI) are executed, to share and access health-related data of different patients, and also to perform personalised diagnostics [128]. Years ago, Alesanco et al. [129] performed a complete study of wide-area wireless ECG transmission for real-time cardiac tele-monitoring. They considered both technical and clinical practice-related aspects, to elaborate recommendations for real-time monitoring: not only the transmission channel quality parameters but also the tolerance of cardiologists to the effects of interruptions introduced during transmission were included in the study. The results of the assessment showed that the maximum percentage of time for which the monitoring process could be stopped without discomfort for the cardiologists was around 15%, with a maximum monitoring delay of 3 or 4 s, depending on the scenario under consideration.

Power consumption. Power consumption should be limited as much as possible with a dual purpose: to extend the life time of the battery (thus enabling long-term monitoring) and to ease the miniaturization of the sensor (given that the battery is the most cumbersome component). A proper compromise should be found between power consumption and hardware efficiency, to optimize the system performance [112]. An example of an efficient solution consists in coin batteries (e.g. CR2032) or rechargeable LiPo batteries, representing a viable compromise between lifetime and size [36]. Harvesting techniques [107] are being developed and more commonly applied, as well as low-power electronic components [12] or dynamic power adjustment methods (considering strength indicators – depending both on the user's motion and the surrounding environment – to automatically regulate the transmission power [130]). In fact, it is worthy to consider that the transceiver and data transmission generally consume most of the power of the system, depending on the proximity between transceiver and receiver and the channel access protocol implemented at the MAC (Medium Access Control) and data link layers. The transmission power affects the signal quality, obviously influenced by propagation conditions and eventual interfering sources; it can be reduced, for example, by employing modulation techniques robust against interference, adaptive or compressed sampling methods [131], or adopting different operating modes (e.g. transmission on demand, triggered by specific events, or linked to pre-determined thresholds, rather than continuous transfer). At present, there is a large room for improvement towards the so-called IoT devices.

Table 1 Wireless ECG system components: overview

Component	Characteristics
Electrodes	Good contact with the skin, low electrode-tissue impedance, biocompatibility. Available types: Ag/AgCl, dry, insulated, textile-based, and microneedle array.
AFE	High input impedance, high CMRR, large DC offset, low noise floor.
DAQ	Pre-processing components: amplifiers, multiplexers, ADCs, communication modules.
DSP	Microcontroller or FPGA for real-time processing.
Wireless technology	IR, Bluetooth, WiFi, RF, ANT, last generations of cellular technologies (4G, LTE, 5G) and WAN.
Power consumption	Reduced thanks to low-power components and firmware, dynamic power adjustment methods, and energy harvesting techniques.

SotA systems. Compact wireless ECG systems have been developed in different application fields; Lin et al. [132] realized a wireless (Bluetooth) wearable ECG system for telecardiology applications, with the dimensions of a business card (90 x 35 x 15 mm). Yong et al. [133] implemented a wireless sensor network based on the MSP430 microcontroller for the acquisition (at 250 Hz sampling frequency), and a central ARM-based system (AT91SAM7S64 embedded microprocessor) for the monitoring; also Deshpande and Kulkarni [134] used a wireless sensor network, with a system-on-chip (SoC) processor featuring ultra-low power consumption and transmission coverage up to 100 m. Wu, Tang and Yang [135] proposed a sport physiological parameters monitoring system, based on a wireless sensor network and a software for PC platform. The data processing platform based on medical IoT has a built-in signal processing algorithm, which can process physiological data in real time and carry out a preliminary auxiliary diagnosis, remotely transmitted by a ZigBee module. Another compact system (hand-held device) is the Blue Box, which measures cardiac parameters, photoplethysmographic signal (PPG), and bioimpedance and transmits data through Bluetooth [62,136]. Aboalseoud et al. [137] developed another on-body wireless sensor network, with a variable number of electrodes (2-20); three main modules were considered: the sensing module, measuring the ECG signal and removing eventual DC shifts before amplification and filtering operations; the DSP module, converting the signal into digital form, saving it into memory, and reducing motion artifacts; and the RF unit, transmitting data to a base station according to Time Division Multiplexing (TDM) protocol. The whole sensor node measured 7 x 5 cm. Another sensor network was developed by Spanò et al. [12], who realized sensor and actuator nodes (including not only ECG, but also other ambient sensors) to collect data and communicate with an IoT server, making information homogeneous and sharing it with the final applications and users. Finally, Wang et al. [130] developed a small wireless ECG sensor node (5.5 x 2.5 cm, including an AFE, a microcontroller, a transceiver, and a recharging circuit – powered by a 600 mAh battery) together with a ZigBee coordinator (to be operated at a maximum distance of 30 m from the sensor node), and a Graphical User Interface to display and analyse data on a PC, forming a compact wearable system suitable for long-term home care monitoring applications. The system achieves an optimised transmission power thanks to the employment of a dynamic adjustment rule based on the received signal strength indicator (RSSI) and power levels; this way, power consumption was reduced by 20% and 30% during normal activities and resting, respectively.

Modular systems enable an easy redesign, hence they are adaptable to different situations; Borromeo et al. [138] designed a compact modular system (size of a business card) mainly composed by three layers, namely for communication (Bluetooth module: WRAP THR 2022-1-B2B chip from BlueGiga), processing (PIC16F876 microcontroller and Xilinx Spartan3E-100 FPGA), and sensing (bioamplifier and bandpass filter, besides a general purpose end-user application developed for mobile phones or PDAs).

Fully integrated wireless ECG measurement systems have been developed, obtaining valuable reductions in terms of power requirements, dimensions, and costs. A so-called SoC includes an AFE, an ADC, a power management unit, a DSP unit, and a wireless communication module. The power requirements of AFE architectures are in the range from hundreds of nW to tens of μW [106,107,139]. Attention should be paid to the fact that the input impedance is relatively low, therefore it should be compensated with electrodes showing low electrode-tissue impedance (ETI) (e.g. Ag/AgCl wet electrodes [140]). Tsai et al. [141] realized a portable ECG detection device with a low-power AFE, a quadrature CMOS voltage-controlled oscillator and an RF 2.4 GHz transmitter, which could all be integrated into a single chip, thus achieving a low-power system for wearable applications. Flexible hybrid electronics technology was also used to realize a wireless ECG monitor relying on a flexible substrate with printed electrodes and traces connecting the electronic components [90].

Compact and low-cost wireless ECG systems were realized also with the ATmega328 microcontroller (for signals acquisition and ADC), using capacitive electrodes (working also through clothes) integrated in the AFE [142]; data can be stored in memory in .csv format [143]. Different wireless protocols were tested, but WiFi seems to be more reliable than others [117]. Proper amplifiers and filters, as well as a high CMRR, are needed to deal with low-voltage signals.

Even attachable ECG sensor bandages (38 x 75 mm) were designed, deploying dry electrodes printed on fabric and a sensor chip (2.4 x 2.0 mm) wired on it, with ultra-low power consumption (12 μW) [144]; Planar-Fashionable Circuit Board (P-FCB) technology was employed. Also systems with double-adhesive tape were developed in a patch configuration, relying on a flexible substrate that can be discreetly worn under the clothes [36].

Portable, low-power, smart wireless ECG monitoring systems were developed also with the possibility of connecting multiple terminals to a unique central controller for the real-time acquisition and data transmission [145]; Yang and Chai [146] used an MSP430 microcontroller for ADC, digital filtering, QRS identification, and HR computation. A ZigBee network (providing low complexity, low power consumption, low data-rate, and low-cost) was used to send data from the terminals to the central controller through wireless chips (MG2455, suitable for short distance communication).

The field of smart clothing is experiencing a rapid development both in clinical and sport applications. Coosemans et al. [147] realised a system embedded in a body suit for the ECG monitoring of children with an increased risk of Sudden Infant Death Syndrome (SIDS). Stainless steel electrodes were knitted and woven on an elastic belt; the circuit was powered inductively (132 kHz) through two coils (used also for data transmission): the external one, large to cope with misalignments associated to movements, and the receiving one, realized on a flexible printed circuit (connected to electrodes through press-studs) that includes all the electronics for sensor interface (sampling frequency: 300 Hz), data processing, and wireless transmission (16.5 kbit/s, up to 18 cm distance from the external coil). Le et al. [148] used coils as well for inductively powering a wireless ECG monitoring system.

Hsu et al. [149] designed a 12-lead ECG monitoring system able to measure biopotentials across the clothes. An elastic chest vest provides the suitable pressure for maintaining the wireless module on site and acquiring a good quality signal; ECG signals are transmitted via Bluetooth to a back-end host system. The effect of sweating can improve the signal quality; on the contrary, the clothes thickness can attenuate the signal amplitude. An ultra-wearable wireless ECG monitoring system has been proposed by Park et al. [150]; they employed capacitive electrodes (QUASAR [151,152]) together with an ultra-compact, ultra-low power wireless sensor node (Eco [153], including also a triaxial accelerometer and the ability to measure temperature), resulting in a power consumption lower than 30 mW, which is fundamental to obtain a small form factor (26 x 15 x 7 mm). ECG signals (sampled at 1 kHz) were transmitted wirelessly to a base station. Majumder et al. [14] realized a wearable wireless ECG monitoring system using capacitive electrodes and Biometrics DataLog for data acquisition and transmission (based on Bluetooth). Diaz-Suarex et al. [154] used three textile active electrodes with embedded electronic boards: one with the energy components, the second with the analog components for amplification, filtering and security ground, and the third with the DSP and wireless transmission modules. Steinberg et al. [155] realized sensors for the measurement of 1-lead ECG integrated in garments (i.e. t-shirt, bra, etc.), using an acquisition module for storage and processing (both for real-time monitoring and off-line analysis), attachable to sensors by means of stainless-steel snaps. ECG signals were transferred to a web-based cloud and the acquisition was controlled wirelessly through Bluetooth (via a smartphone).

Sport applications are quite common for wireless ECG systems as well; Valchinov et al. [156] manufactured dry electrodes on a standard printed circuit board (PCB, acting as a physical substrate) that can operate also through clothing and can be embedded in fabric. The AFE, sensing and amplifying ECG signals, was built on the PCB top layer. Signals (sampled at 500 Hz) were sent via ultra-low power ANT+, but also Bluetooth was supported by the 2.4 GHz transceiver; a distance up to 65 m could be covered, whereas the system developed by Sigit et al. [157], consisting in a mini-sized hardware, supported Bluetooth transmission up to 20 m.

Capacitive electrodes were also embedded on the back of a chair, with a third electrode (ground, in the form of a conductive textile) on the seat [66]; a hygroscopic polymer was employed, with a super-absorbent layer, and moisture (ambient humidity or body sweat) was maintained with cotton layers at the electrodes extremities. This allowed to decrease the stabilization period needed before obtaining a clear and stable ECG signal, due to electrostatic charge build-up and the lack of discharge paths. Signals were transmitted via IEEE 802.15.4 (ZigBee protocol).

Prats-Boluda et al. [158] developed a high-spatial resolution ECG monitoring system based on a flexible tripolar concentric electrode (printed on a polyester substrate) and a PCB (43 x 36 x 10 mm). The electrode was connected to a module for the analog conditioning of the signal (including amplification and filtering, to minimise noise and interference that could compromise the signal of interest, which is in the order of μV), which routed the signal to the microcontroller ADC and then to the communication stage (nBlue Br-le-4.0-S2A transceiver module, including a low-energy transceiver and an antenna, operating at 2.4 GHz). The system consumption was of 9 mA in inquiry mode, 23.8 mA during transmission. Also Mathias et al. [159] developed a flexible electrode consisting in circular copper plates separated by a thin insulator; noise shielding capabilities were provided by the external plate, which additionally prevented from coupling to ground or external electronics.

3. Patents

Different patents regarding wireless ECG systems can be found. An implantable medical device was designed, comprehensive of a programmable sensing circuit to obtain a signal (approximating a surface ECG) measured through implanted electrodes embedded in the device [160]. Different pairs of electrodes can be selected to set differential inputs; acquisition commands are captured by a command receiver included in the processor. Also concentric electrodes are usable for this purpose; the almost real-time data transmission can be obtained through an antenna electrode, including a portion of a telemetry antenna. Istvan et al. developed a lightweight and portable wireless ECG system, assessing ECG signals and transmitting them to a base station via telemetry [161,162]; then, the signal can be reconverted into analog form and read by a conventional ECG monitor. The system includes three parts: a chest assembly (enabling to record up to 7 ECG leads, i.e. standard and augmented ones), which is a flexible circuit linking electrode connectors with conductive traces for electrical signals (sufficiently spaced apart or isolated to avoid arcing across each other), including an adhesive layer, an insulating layer, and a base layer (furthermore, a precordial assembly can be added to measure up to 12 leads, including the precordial ones); a body electronics unit, transmitting the signals wirelessly (via Bluetooth) to the base station, equipped with a user interface and a battery; a base station (portable transceiver), eventually wired to a standard ECG monitor. The positioning of the assembly on the patient's body is flexible, thanks to expandable arms, realized with a serpentine pattern; this is useful both to adapt to patients of different body sizes and to manage movements during the acquisition. A key token pairs the body electronics unit and the base station; a body electronics unit can communicate simultaneously with multiple base stations. A proper shielding layer in the chest assembly (made of dielectric or electrically/magnetically conductive materials) can prevent from external interfaces and noise. Data transmission can be Bluetooth or IEEE 802.11b. Balda [163] developed a retractable multi-use cardiac monitor, collecting different physiological signals, storing them in memory (e.g. RAM, EEPROM – Electrically Erasable Programmable Read-Only Memory, FLASH), before sending data wirelessly (e.g. via 900 MHz radio, Bluetooth, IEEE 802.11, WLAN, Personal Area Network, TransferJet, Ultra-Wide-Band, IrDA – Infrared Data Association, RFID, Wireless USB, Near Field Communication, and ZigBee) to a destination (e.g. smartphone). A retractable wire allows to adjust the inter-electrode distance, whose optimal value can be found automatically thanks to the cardiac monitor assistance.

4. Commercial devices

Also commercial devices for wireless ECG monitoring are available, as reported in Table 2. There are also relatively cheap devices, like HeartCheck^{TM} Palm or Easy ECG Check, able to record ECG signals and transmit data wirelessly. The former is FDA cleared and can measure both Lead I and II (with a sampling frequency of 250 Hz and an error of 1%), hence transmit the signals via Bluetooth Protocols (v4.0, Classic, and Low Energy); data can be stored together with diary information for an eventual review by a physician, also in remote monitoring applications, thus contributing to telemedicine market. Other hand-held devices are available, such as AliveCor© Heart Monitor, HeartCheck CardiBeat, BodiMetrics^{TM} Performance Monitor, AfibAlert® Heart Rhythm Monitor, Color Portable ECG Recorder Dicare, and Easy ECG Monitor. The signals are substantially captured by electrodes kept in contact with hands/fingertips and, thanks to the wireless transmission of data, alert signals can be sent to relatives or healthcare providers, thus enabling the monitoring at home, especially in case of ageing people with particular fragilities (e.g. those undergoing a cancer treatment or affected by dementia). These devices are not suitable for continuous monitoring, as they are not wearable but need to be kept in hands. On the other hand, there are the so-called "chest-strap" devices, like Physiological Status Monitor and QardioCore; the latter provides not only ECG signal, but also HR and HRV parameters, respiration rate, body temperature, and activity tracking, sending data to a caregiver for remote monitoring, which is particularly useful in case of people at risk because of hereditary predisposition, heart attacks, diabetes, hypertension, or overweight. Moreover, there are instruments connected to classical ECG patient cables, like BTL CardioPoint FLEXI, touchECG System, and H3+^{TM} Digital Holter Recorder, which measure ECG signals and transmit them wirelessly to a central platform. Adhesive-backed (or "patch") devices are available as well, like the Medtronic SEEQ^{TM} Mobile Cardiac Telemetry (MCT) System; it can be worn up to 30 days for the diagnosis of irregular heartbeats causes. Data are sent via Bluetooth for being stored on a web portal, enabling the physician to monitor the patient. Another cardiac monitoring solution of this type is Zio® by iRhythm; it has 14 days of battery lifetime and the monitored data are analysed by a dedicated service, so that the physician can receive an accurate and exploitable report about the patient. Also Philips Biosensor BX100 can be worn on the chest to measure vital parameters (e.g. heart and respiratory rates), posture and activity; eventual worsening of the patient's conditions is immediately detected, so as to act promptly. Data are automatically recorded and the use is possible up to 5 days. Savvy ECG [164] allows a long-term (up to 24 months) continuous monitoring; it also provides a mark event function, generating an ECG report for the physician. Finally, the BioRadio apparatus is a wearable device able to acquire different physiological signals (ECG, EMG, EEG, respiration, and motion) and stream them to a PC via Bluetooth or storing them in memory for mobile monitoring. In Table 2, a summary of the technologies employed in the different commercially available devices is presented, specifying the wireless technology adopted, the number/type of ECG leads, the sampling rate, the accuracy, the battery type and duration, the used software and data accessibility/location, the certifications of the device (in particular, for what regards both United States and European markets) and the target applications.

5. Electronic components

When planning to design a new wireless ECG system prototype, a research on the available electronics components should be performed. In Table 3 some useful commercial components, including electrodes, AFEs, operational amplifiers, microcontrollers, and wireless modules, are reported.

Analog Devices produces different AFEs (AD8233, ADAS1000), besides suitable amplifiers (AD8617, AD8605); moreover, they are developing a low-power and low-cost wireless ECG Holter monitor, just fitting on the back side of an electrode [165]. Similarly, Medlab developed an ECG board with multiple channels (EGxxxxx series), providing fundamental, augmented and precordial leads; also respiration measurements are possible over the ECG electrodes. Maxim realizes AFEs for ECG systems (MAX30001, MAX30003 series), also including a built-in Sigma-Delta high resolution (18 bit) ADC and a robust R-R detector. Texas Instruments provides the ADS129x series, which is a multi-electrode AFE with integrated sigma-delta 24-bit ADC, with different number of channels (from 1 to 8). Dry electrodes suitable for long-term monitoring are manufactured by Wearable sensing and Quasar, which also produces wireless DAQ systems, just like Biometrics Ltd. Finally, STMicroelectronics and Telit provide wireless transceivers and communication interfaces. Nordic Semiconductor produces NRF52xxx SoCs, which are ultra-low power 2.4 GHz wireless SoCs integrating 2.4 GHz transceiver and a CPU with flash memory, hence constituting an intelligent Bluetooth LE device, which is not only a miniaturized beacon but also an essential integrated circuit for Bluetooth LE-enabled smartwatches that include continuous ECG monitoring. There are obviously other vendors producing useful components, here the authors limit to report the most common products found in literature concerning wireless ECG systems.

Table 2 Wireless ECG commercial systems (information checked in February 2021)

Product	**Manufacturer**	**Price**	**Website**
HeartCheck Palm	HeartCheck	99.00 $	https://www.theheartcheck.com/preorders.html

Easy ECG Check	ECG Check	79.99 $	https://www.cardiacdesigns.com/purchase
AliveCor© Heart Monitor, Kardia Mobile (6L)	AliveCor©	210.00 €	https://www.alivecor.it/
HeartCheck CardiBeat	HeartCheck	129.00 $	https://www.theheartcheck.com/cardibeat/index.html
BodiMetricsTM Performance Monitor	HeartCheck	299.00 $	https://theheartcheck.myshopify.com/products/bodimetrics-performance-monitor
AfibAlert® Heart Rhythm Monitor	AfibAlert®	179 $ (starter kit)	https://www.lohmantech.com/product/afibalert-device-1-yr-wnty-1-yr-web-access/
Color Portable ECG Recorder Dicare m1CC	Dimetek	NA	http://www.dimetekus.com/Color-Portable-ECG-Recorder-Dicare-m1CC_p234.html
Easy ECG Monitor -- PC-80A (Bluetooth 4.0)	Heal Force	NA	http://www.healforce.com/en/html/products/portableecgmonitors/healthcare-equipment-portable-ECG-monitors-PC-80A.html
Physiological Status Monitor	Quasar	NA	http://www.quasarusa.com/

QardioCore	Qardio	499.00 €	https://www.getqardio.com/it/qardiocore-wearable-ecg-ekg-monitor-iphone/
BTL CardioPoint FLEXI 	BTL corporate	NA	https://www.btlnet.com/products-cardiology-wireless-ecg-flexi
touchECG System	Cardioline	NA	https://www.cardioline.it/en/product-details-touchecg-system/
H3+TM Digital Holter Recorder	Hillrom	NA	https://www.welchallyn.com/en/products/categories/cardiopulmonary/holter-monitoring-systems/h3.html
SEEQ^{TM} Mobile Cardiac Telemetry (MCT) System	Medtronic	NA	https://www.yet2.com/active-projects/medtronic-offering-seeq-mct-mobile-cardiac-telemetry-patch-and-wireless-continuous-monitoring/
Zio	iRhythm	NA	https://www.irhythmtech.com/
Philips Biosensor BX100	Philips	NA	https://www.usa.philips.com/healthcare/product/HC989803203011/biosensor-bx100-wearable-biosensor
Savvy ECG	Savvy	NA	http://savvy.si/en/
BioRadio	Great Lakes NeuroTechnologies	8000$ (complete kit)	https://glneurotech.com/bioradio/

Table 3 Overview of technologies characterising the wireless ECG commercial systems

Product	Wireless technology	Monitored leads	Sampling rate	Accuracy	Battery type and duration	Software and data accessibility	Certifications	
HeartCheck Palm	Bluetooth (v4.0, Classic and LE)	I and II	250 Hz	±1 bpm or 1%	Rechargeable lithium battery	SMART monitoring ECG service, smart device with GEMS™ Mobile App	FDA cleared, CE mark	Cardiac
Easy ECG Check	Bluetooth LE	Single lead	200 Hz	NA	Lithium ion r rechargeable battery, up to 8 hours duration	ECG Check App, cloud server	FDA cleared, CE marked	Monitor
AliveCor© Heart Monitor, Kardia Mobile (6L)	Ultra-high frequency to transmit data to the smartphone microphone	6 leads	300 Hz	NA	Coin cell battery, up to 200 hours operational time	AliveECG app	FDA cleared	Detectio bradyca heart rh
HeartCheck CardiBeat	Bluetooth LE	Single lead	200 Hz	NA	Lithium ion battery, up to 8 hours duration	GEMS™ Mobile App on smartphones/tablet	NA	Monitor rhythms
BodiMetrics TM Performance Monitor	Bluetooth	Single lead	NA	±2 bpm or 2%	Rechargeable lithium-polymer battery, up to 1000 checks duration	BodiMetrics Mobile App	NA	Well-be
AfibAlert® Heart Rhythm Monitor	Data transmitted through a standard telephone (or via USB)	Single lead	NA	±1 bpm	Alkaline batteries, up to 27 days duration (if used once a day)	AfibAlert® application on PC, AfibAlert® website	NA	Control
Color Portable ECG Recorder Dicare m1CC	Bluetooth	Lead I, II, III and Chest (V1, V3 and V5)	100/200/400 Hz (adjustable)	NA	AAA batteries, up to 32 hours duration	SD card	FDA cleared, CE marked	ECG m patients
Easy ECG Monitor -- PC-80A (Bluetooth 4.0)	Bluetooth 4.0	Up to 3 leads with the patient cable	NA	NA	AAA batteries, up to 10 hours duration	Built-in memory	FDA cleared, CE marked	Monitor CVDs
Physiological Status Monitor	Ultralow-power wireless link	Single lead	240 Hz	NA	AAA lithium ion battery, up to several days duration	Micro-SD memory card	NA	Non-inv physiolo
QardioCore	Bluetooth 4.0	Single lead	600 Hz	NA	Lithium-ion polymer battery, up to 24 hours duration	Qardio App	FDA cleared, CE marked	Monitor
BTL CardioPoint FLEXI	Wi-Fi	12 leads	NA	NA	Internal rechargeable Li-Ion battery, up to 6 hours duration	Computers in the BTL NETwork; BTL CardioPoint® software	NA	Assessm cardiac-
H3+TM Digital Holter Recorder	NA	Modified I, II and III, aVR, aVL, aVF and V	180 Hz	NA	AAA alkaline battery, up to 2 days duration	Internal, non-volatile memory, HScribeTM 5 Holter analysis system, Web Upload solution	CE marking	Use in c medical patients monitor
SEEQ™ Mobile Cardiac	Bluetooth/cellular	Single lead	200 Hz	NA	Long-life battery, up to	zLink smart cellular device, to accesss a cloud portal	FDA cleared, CE marked	Arrhyth monitor

Telemetry (MCT) System					7.5 days duration			
Zio	Bluetooth LE	Single lead	200 Hz	NA	NA	myZio App, www.myZio.com	FDA cleared, CE marked	Detectio
Philips Biosensor BX100	Bluetooth LE, Wi-Fi	NA	250 Hz	±5 bpm or 10%	CR2032 battery	IntelliVue GuardianSoftware	FDA cleared, CE marked	Monitor through paramet
Savvy ECG	Bluetooth 4.0	Single lead	125 Hz	NA	Up to 7 days duration	MobECG mobile application	NA	Monitor issues (e
BioRadio	Bluetooth Classic/LE	Single lead	250-16000 Hz	NA	Rechargeable battery, up to 8 hours duration	On-board memory, BioCapture Software	Not FDA cleared	Real-tim physiolo use

Table 4 Useful electronics components for the design of a new wireless ECG system

Product	Manufacturer	Price	Website
AD8232 Single-Lead, Heart Rate Monitor Front End	Analog Devices	46.27€ (evaluation board)	https://www.analog.com/en/products/ad8232.html
AD8233 Heart Rate Monitor for Wearable Products	Analog Devices	46.27€ (evaluation board)	https://www.analog.com/en/products/ad8233.html#
ADAS1000/ADAS1000-1/ADAS1000-2 ECG analog front end	Analog Devices	199€ (evaluation board)	https://www.analog.com/en/products/adas1000.html?doc=ADAS1000_1000-1_1000-2.pdf
Low Cost Micropower, Low Noise CMOS rail-to-rails, input/output op-amp AD8617	Analog Devices	20.19€ (evaluation board)	https://www.analog.com/en/products/ad8617.html#product-samplebuy
AD8605	Analog Devices	20.19€ (evaluation board)	https://www.analog.com/en/products/ad8605.html
One-/three-/six-/five-/twelve-channel ECG board, EGxxxxx series (EG01000, EG01010, EG04000, EG05000, EG12000)	Medlab	NA	https://www.medlab.eu/english/modules/ekgmodules/eg01000/index.html https://www.medlab.eu/english/modules/ekgmodules/eg01010/index.html https://www.medlab.eu/english/modules/ekgmodules/eg04000/index.html https://www.medlab.eu/english/modules/ekgmodules/eg05000/index.html https://www.medlab.eu/english/modules/ekgmodules/eg12000/index.html
Low Power, Low Cost, Wireless ECG Holter Monitor	Analog Devices	NA	https://www.analog.com/en/education/education-library/articles/low-power-low-cost-wireless-ecg-holter-monitor.html
Ultra-Low-Power, Single-Channel Integrated Biopotential (ECG, R-to-R, and Pace Detection) and bioimpedance (BioZ) AFE, MAX3001	Maxim Integrated™	29.00$ (evaluation board)	https://www.maximintegrated.com/en/products/analog/data-converters/analog-front-end-ics/MAX30001.html
Ultra-Low-Power, Single-Channel Integrated Biopotential (ECG, R-to-R Detection) AFE, MAX3003	Maxim Integrated™	29.00$ (evaluation board)	https://www.maximintegrated.com/en/products/analog/data-converters/analog-front-end-ics/MAX30003.html/product-details/tabs-3
24-bit, 1-ch/2-ch/3-ch, Low-Power AFE for ECG Applications, ADS129x series (ADS1291, ADS1292 and ADS1293)	Texas Instruments	99.00$ (evaluation board)	https://www.ti.com/product/ADS1291 https://www.ti.com/product/ADS1292 https://www.ti.com/product/ADS1293

4-Channel/6-Channel/8-Channel 24-Bit ADC with Integrated ECG Front End, ADS129x series (ADS1294, ADS1296 and ADS1298)	Texas Instruments	199.00$ (evaluation board)	https://www.ti.com/product/ADS1294 https://www.ti.com/product/ADS1294 https://www.ti.com/product/ADS1294
Dry electrodes	Wearable sensing	NA	https://wearablesensing.com/
Dry electrodes, wireless DAQ	Quasar	NA	http://www.quasarusa.com/
Biometrics DataLog	Biometric Ltd	NA	http://www.biometricsltd.com/datalog.htm
STM32L151x6/8/B STM32L152x6/8/B Ultra-low-power 32-bit MCU ARM®-based Cortex®-M3, 128KB Flash, 16KB SRAM, 4KB EEPROM, LCD, USB, ADC, DAC	STMicroelectronics	NA	https://www.st.com/resource/en/datasheet/cd00277537.pdf
WE866E4-P fully integrated dual band, dual mode, combo Wi-Fi (802.11 a/b/g/n) / Bluetooth Low Energy (BLE) 5.0 module – IEEE 802.11 a/b/g/n & Bluetooth certified and complying with Wi-Fi Alliance & BT SIG-v5 requirements	Telit	NA	https://www.telit.com/m2m-iot-products/wifi-bluetooth-modules/wi-fi-wl865e4-p/
Versatile Bluetooth 5.2 SoC supporting Bluetooth Low Energy, Bluetooth mesh and NFC, nRF52832 – Bluetooth qualified design,	Nordic Semiconductor	≈40$ (Development kit)	https://www.nordicsemi.com/Products/Low-power-short-range-wireless/nRF52832
Advanced Bluetooth 5, Thread and Zigbee multiprotocol SoC, nRF52840 – Bluetooth qualified design,	Nordic Semiconductor	≈50$ (Development kit)	https://www.nordicsemi.com/Products/Low-power-short-range-wireless/nRF52840

6. Conclusions

Today healthcare systems are experiencing great changes and facing new challenges, mainly related to ageing of population and to the shift of care processes from the hospital to the home environment. This inevitably brings new requirements for remote monitoring and the possibility of employing wireless instrumentation is undoubtedly contributing to this direction, as shown in Table 5, evidencing pros and cons of wireless ECG technology.

Table 5 Comparison of wireless ECG systems with respect to traditional ones

	Wireless ECG	**Traditional ECG**
Characteristic	**Pros**	
	Portability	Cumbersome equipment
	Relatively low-cost	High-cost
	Wireless communication	Stable data transfer through cable
	Usability outside clinical environment	Hospital/ambulatory measurement
	Possibility of remote monitoring	Necessity of the clinician during the measurement
	Possibility of long-term measurement	Acquisition limited in time
	Cons	
	Exposure to interference issues and link instability	Cabled connection

	Electrodes biocompatibility for long-term monitoring	Suitability of standard electrodes (relatively short-term measurement)

This paper aims to highlight how the literature on the topic of wireless ECG systems is moving forward, as well as commercial devices and suitably designed electronics, witnessing the interest in the subject; more and more miniaturized devices are being developed and next generation technology enables to realize comfortable wearable devices for continuous monitoring of vital signs. However, systems are not mature yet and there is still room for a lot of hugely improving research, starting from the sensing electrodes (particularly the materials to manufacture them, aimed at biocompatibility, which is essential even more for prolonged measurements) to the noise shielding solutions, passing through practicity, portability, power consumption, and user-friendliness of the device, as suggested in Table 6. Also, data security aspects should be thoroughly taken into account, considering the related data protection standards to guarantee that data access and handling are properly managed.

Undoubtedly the market in this field is continuosly growing and evolves fast, offering not only new products but also innovative (and often miniaturised) components useful for research purposes. The different solutions reach different market portions, from healthcare professionals to simple citizens wishing to track their fitness activity.

Table 6 Not-mature aspects that can be improved through research

Not-mature aspect	**What can be improved**
Electrodes	Biocompatibility, electric contact goodness
SNR	Shielding and filtering technologies
Portability	Miniaturisation of the system
Power consumption	Optimisation of data transmission, low-power components, harvesting techniques
User-friendliness	User interface, easiness of use

When medical applications are considered, it is worthy to mention that most of these devices are intended for arrhytmias screening and monitoring, with a particular focus on fibrillations (also common smartwatches have been used for their detection [166], hence underlining how technology is fastly improving in this field, with reliable and accurate solutions able to support medical decisions). On the other hand, there is an increasing tendency to make data available to users by sharing them on dedicate clouds; this highlights once again the importance of security and protection of data, offering at the same time big amounts of data to analyse, leading to the development of advanced algorithms for prediction of significant parameters thanks to AI technology [167]. Furthermore, the peculiarities of different application fields (e.g. ambulatory monitoring, home assistance, and sport applications) will lead to the development of devices with different metrological characteristics (and, consequently, diverse costs), matching specific users' requirements to fulfil distinct measurement purposes. If the target use of the device is clinical, the device should be obviously more accurate and precise, requiring high level hardware and software components, whereas for daily life applications (e..g fitness tracking) the specifications can be more "relaxed". Even the tolerable rate of lost data or communication link interruptions due to reliability issues in the wireless transmission technology must be carefully evaluated, in order to avoid their detrimental impact on the quality of the measurement data but also on the clinical procedures established within hospitals or healthcare institutions. Indeed, it is worthy to underline that the clinical usability of such devices is critical, since the often non-conventional electrodes positioning provide signals that need to be interpreted. Moreover, the correct positioning of the device should be thoroughly described in the user manual, possibly providing a simple test for its verification. This undoubtedly requires a valuable contribution from medical experts, comparing these data with those obtainable from standard ECG systems, in order to establish correspondences but also differences for a reliable interpretation of the measured signals [168].

Proper guidelines should be proposed in this perspective, hence providing the clinicians not only with sensing devices designed for continuous monitoring of their patients, but also with proper valuable means and procedures to evaluate the obtained results, thus being effectively supported in their decision-making process, also thanks to proper AI algorithms able to provide hints on symptoms detection and diagnosis. Furthermore, regarding the correct positioning of electrodes, it is important to underline how much adhesion can interfere with the quality of the measured data, since motion artifacts can undoubtedly play a key role in the signal acquisition and noise generation, hence demanding proper test to verify its correctness (e.g. electrical impedance measurement to control the contact impedance). Motion-related noise is even more significant when wireless ECG systems are used in daily life; algorithms have to be employed in order to properly filter noise [34,169] and, when not possible, to discard the spoiled signal portion.

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