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

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Abstract

Wireless 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 for 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), AFE (with high input impedance and CMRR), DAQ systems (including amplifiers, multiplexer, ADC), wireless transmission technology (IR, RF, 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 ECG systems are increasingly widespread in many application fields
- Available devices and useful electronic components are being reviewed
- Electrodes, AFE, DAQ system, 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 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 minimizing the hindrance of cables or bulky apparatuses. Furthermore, extended studies and field tests have shown how remote monitoring represents a valuable instrument 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, and hypertensive people [4].

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 [5,6]). 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 [7,8], consequently increasing the flexibility of healthcare services delivery. Furthermore, the advances in microelectronics and communication fields allow cost effectiveness and better performance of these devices, thus fostering their market penetration [9].

In this context, the trends in electrocardiographic (ECG) activity monitoring is going towards wearable [10] and/or wireless systems [11], which can even be combined (also with advanced computing technologies and artificial intelligence – AI – tools) to obtain better healthcare services. They both represent interesting fields of research, beacause of two main reasons: 1) the fact that cardiovascular diseases are very spread all around the world (17.9 million deaths from cardiovascular diseases (CVDs) in 2016, i.e. 31% of all global deaths [12]) 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 [13]. This attempts to reduce the healthcare costs [14], with a pivotal role played by wireless communication systems [15,16] enabling data transfer to the hospital/the healthcare server [17] or, more generally, to a specific base station [18] or to a smartphone application [19];
- sport applications [20], where ECG monitors report better performances than wearable devices using photoplethysmographic (PPG) signals [21], which on the other hand are prone to motion artifacts [22] and determine a quite high power consumption, contributing to the relatively short battery life of wearable devices [23]);
- fetal ECG (f-ECG) [24];
- ambulatory monitoring [25];
- 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 [26,27] 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 [28], 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", caused by a momentaneous loss of connection between electrodes and skin, as well as false peaks due to motion [29]).

Furthermore, electronics can also be embedded in textile materials, enhancing the naturalness and the comfort perception [30–34], without requiring skin preparation and avoiding skin irritation due to adhesive materials [35]. 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 [36–38], as well as causing a progressive degradation of signal quality because of the gel dehydration; therefore, many other types have been explored in the literature, even if they are not widely adopted in clinical applications and commerical systems yet.

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 realizazion 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 [39], as schematically summarized in Figure 1.

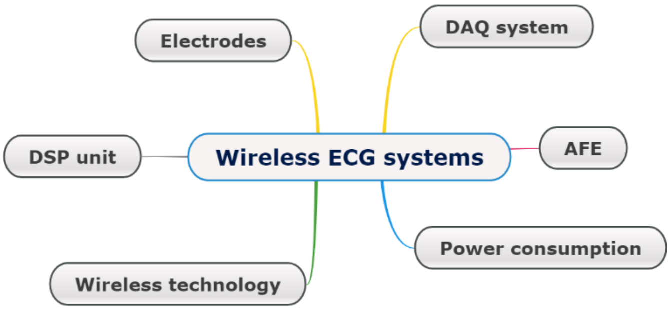


Figure 1 Wireless ECG systems: components to consider in the design process

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 reservoir [40] or superadsorbent polymers [41], 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 intantaneous changes in the contact impedance, whereas lateral motion induces triboelectric charge on the electrode surface [42]), flexible substrates (e.g. elastomeric polymer materials [43–45], where sometimes conductive materials, such as silver nanowire [46], carbon nanotubes [47], carbon black, carbon nanoparticles [35], and graphene [48] are embedded) can enhance the comformability to the skin [49,50], 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 [17]. Also conductive rubber can be used [51]. Stretchability can be enhanced with specific geometrical configurations, such as serpentine, mesh, spone, net-shaped, or spring-like structures [48,52]. These electrodes (e.g. Plessey^{TM} electrodes [53]) are capacitively coupled to the skin through a layer of insulating material [54] (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 [55]) 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 [56]. There are also insulated electrodes, with a buffer amplifier [42] and active shielding against noise [57], and non-contact electrodes (e.g. for automotive applications [57]). The latter are realized with smart tissues, such as highly conductive polymers on a cotton substrate, integrating antennas for wireless transmission of data towards external devices [58,59]. 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 material and washed without loosing their properties. Also nylon spandex [60] and chemical fibers [61] 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 [62]. Electrode arrays were realized also with Ni/Cu polyester conductive fabric tape from 3M, modelled on a thin foam pad and connected to wires [63]; three optimal electrodes for a differential 3-lead ECG measurement can be selected, then the signal is transmitted wirelessly.

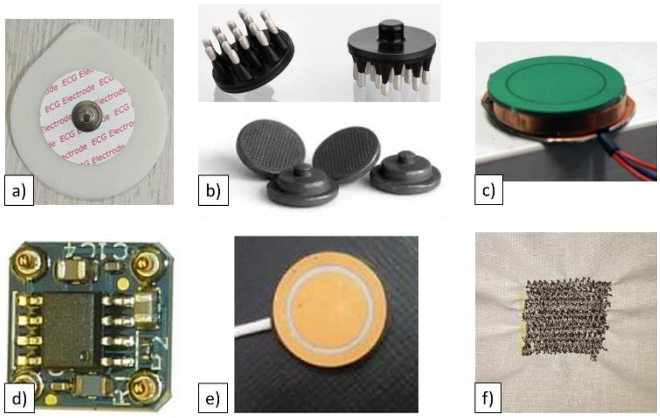


Figure 2 Electrodes examples: a) disposable wet-electrodes, b) dry electrodes, c) non-contact electrodes, d) Plessey™ electrodes, e) capacitive electrodes and f) textile electrodes

Also coincident sensing and transmitting electrodes were developed, hence simplifying the system structure [64].

Finally, conductive inks can be used to realise electrodes, such as gold nanoparticle ink [65] or medical grade Ag/AgCl ink [66], presenting a better performance than silver, both in terms of long-term drift and contact noise [67].

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 [68] or antiparallel diodes [69];
- high common mode rejection ratio (CMRR), in order to reduce motion 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 [70].

Data AcQuistion (DAQ) system. The DAQ system consists of integrated circuits, including amplifiers, multiplexers, analog-to digital converters (ADCs), and communication modules.

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 Porgrammable 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 rapid algorithm onboard essentially for noise reduction and to infer fundamental evidence on the ECG signal (e.g. detection of QRS complex and calculation of Heart Rate, HR [71,72], or short term Heart Rate Variability, HRV), whereas the latter allow to perform a deeper analysis even in more relaxed times, for example identifing all the ECG signals components [73,74]. Computing devices can also improve the SNR by filtering [75] and decomposition [76–78] techniques. Also AI technologies can be employed to reduce noise and estimate the health status of the monitored person [79,80].

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 [81];
- Bluetooth at 2.4 GHz (i.e. an ISM band), which can reach 100 m [39], at different data rates; Bluetooth Low Energy (LE) is advantageous in terms of power consumption [65];
- WiFi, for the realization of local area networks [82], with up to 100 m distance coverage and data transferrable at several tens of Mbit/s;
- RF (e.g. RFID or ZigBee), which, however, can suffer from instability and packet loss during transmission [83], thus being best used for short-range transmissions;
- GPRS [84] for long range and limited data rate communications, currently supported as a legacy technology in machine-to-machine (M2M) communications;
- ANT [54];
- Wireless mobile technologies (4G, Long Term Evolution (LTE) , Narrow Band – IoT (Nb-IoT), and the upcoming 5G, and Wide Area Networks (WAN) technologies [85–87].

Back in 2008, the IEEE issued a guidance document [88] to address the use of radio frequency (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 despite the impressive evolution of the available wireless communication technologies.

In the modern and Internet of Things (IoT)-oriented perspective [89], connected devices can have some kind of local, on-board elaboration functions (so-called edge computing approach) to pre-process raw measurement data, or act as relays of raw data towards cloud based computing platforms [90–92], 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 [93]. Years ago, Alesanco et al. [94] 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 enhance 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 [78]. An example of an efficient solution consistes in coin batteries (e.g. CR2032), representing a viable compromise between lifetime and size [29]. Harvesting techniques [72] are being developed and more commonly applied, as well as low-power electronic components [9] 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 [95]). 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. The transmission power affects the signal quality, obviously influenced by ambient conditions and eventual interfering sources; it can be reduced, for example, by employing modulation techniques robust against interference, adaptive or compressed sampling methods [96] 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.

Compact wireless ECG systems have been developed in different application fields; Lin et al. [97] 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. [98] implemented a wireless sensor network based on the MSP430 microcontroller for the acquisition (250 Hz sampling frequency) and a central ARM-based system (AT91SAM7S64 embedded microprocessor) for the monitoring; also Deshpande and Kulkarni [99] used a wireless sensor network, with system-on-a-chip (SoC) a processor at ultra-low power consumption and transmission coverage up to 100 m. Similarly, MEMSWear combines a Wireless Body Area Network (WBAN) and a PDA for remote monitoring [85]; it is able to measure not only ECG, but also oxygen saturation, temperature, and blood pressure, thanks to miniaturized sensor nodes. It includes a low-power microprocessor (MSP430FG439, with a sampling frequency of 512 Hz) and a Bluetooth transceiver [100]; moreover, the GSM network enables remote data transfer from the device; the same data can be accessed by doctors through their PDAs. A similar approach is adopted by Wu, Tang and Yang [101], proposing 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 physiological 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 Buetooth [85,102]. Aboalseoud et al. [103] 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; DSP module, converting the signal into digital form, saving it into memory, and reducing motion artifacts; 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. [9], 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. [95] 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 (at a maximum distance of 30 m from the sensor node), and a Graphical User Interface to display and analyze data on a PC, forming a compact wearable system suitable for long-term home care monitoring applications. The system achieves an optimised trasmission 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 acitivites and resting, respectively.

Modular systems enable an easy redesign, hence they are adaptable to different situations; Borromeo et al. [104] 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 [71,72,105]. 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 [106]). Tsai et al. [107] 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 [65].

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 [108]; data can be stored in memory in .csv format [109]. Different wireless protocol were tested, but WiFi seems to be more reliable [83]. 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) [110]; 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 [29].

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 [111]; Yang and Chai [112] 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 fields of smart clothing is experiencing a rapid development both in clinical and sport applications. Coosemans et al. [113] 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 receving 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). Also Le et al. [114] used coils for inductively powering a wireless ECG monitoring system.

Hsu et al. [115] 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. [116]; they employed capacitive electrodes (QUASAR [117,118]) together with an ultra-compact, ultra-low power wireless sensor node (Eco [119], including also a triaxial accelerometer and the ability to measure temperature), resulting in a power consumption lower than 30 mW, fundamental to obtain a small sensor (26 x 15 x 7 mm). ECG signals (sampled at 1 kHz) were transmitted wirelessly to a base station. Majumder et al. [11] 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. [120] used three textile active electrodes with embedded electronic boards: one with the energy components, the second with the analogic components for amplification, filtering and security ground, and the third with the DSP and wireless transmission modules. Steinberg et al. [121] realized sensors for the measurment of 1-lead ECG integrated in garments (a T-shirt for men, a bra for women), 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. [122] 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. [123], consisting in a mini-sized hardware, supported Bluetooth transmission up to 20 m.

Capacitive electrodes were also embedded on the back of the chair, with a third electrode (ground, in the form of a conductive textile) on a seat [41]; 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. [124] 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. [125] 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 [126]. 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 [127,128]; 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 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 [129] developed a retractable multi-use cardiac monitor, collecting different physiological signals, storing them in memory (e.g. RAM, EEPROM, FLASH), before sending data wirelessly (e.g. via 900 MHz radio, Bluetooth, IEEE 802.11, WLAN, Personal Area Network, TransferJet, Ultra-Wide-Band, IrDA, 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™ 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™ Performance Monitor, AfibAlert® Heart Rhythm Monitor, Color Portable ECG Recorder Dicare, and Easy ECG Monitor. The signals is 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 and H3+™ Digital Holter Recorder, which measure ECG signals and transmit them wirelessly to a central platform. 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.

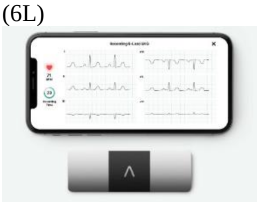
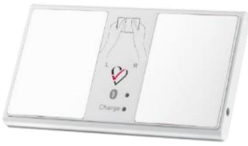
5. Electronic components

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 [130]. 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. 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

Product	Manufacturer	Price	Website
HeartCheck Palm 	HeartCheck	99 $	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©	240,0 €	https://www.alivecor.it/
HeartCheck CardiBeat 	HeartCheck	129 $	https://www.theheartcheck.com/cardibeat/index.html

BodiMetrics™ Performance Monitor 	HeartCheck	299 $	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	500,0 €	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
H3+™ Digital Holter Recorder 	Hillrom	NA	https://www.welchallyn.com/en/products/categories/cardiopulmonary/holter-monitoring-systems/h3.html
BioRadio 	Great Lakes NeuroTechnologies	8000$ (complete kit)	https://glneurotech.com/bioradio/

Table 3 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
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
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	Telit	NA	https://www.telit.com/m2m-iot-products/wifi-bluetooth-modules/wi-fi-wl865e4-p/

6. Conclusions

Today healthcare systems are experiencing great changes and facing new challenges, mainly related to ageing 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 4, evidencing pros and cons of wireless ECG technology.

Table 4 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 growing, as well as commercial devices and suitably designed electronics, witnessing the interest in the subject; more and more minaturized devices are being developed and next generation technology helps 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 prolongued measurements) to the noise shielding measures, passing through practicity, portability, power consumption, and user-friendliness of the device, as suggested in Table 5. 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.

Table 5 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

Furthermore, the differentiation among 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 fulfill distinct measurement purposes.

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