ECG Monitoring Systems

Subjects: Biotechnology & Applied Microbiology

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Health monitoring and its related technologies is an attractive research area. The electrocardiogram (ECG) has always been a popular measurement scheme to assess and diagnose cardiovascular diseases (CVDs). The number of ECG monitoring systems in the literature is expanding exponentially. Hence, it is very hard for researchers and healthcare experts to choose, compare, and evaluate systems that serve their needs and fulfill the monitoring requirements. This accentuates the need for a verified reference guiding the design, classification, and analysis of ECG monitoring systems, serving both researchers and professionals in the field. In this paper, we propose a comprehensive, expert-verified taxonomy of ECG monitoring systems and conduct an extensive, systematic review of the literature. This provides evidence-based support for critically understanding ECG monitoring systems' components, contexts, features, and challenges. Hence, a generic architectural model for ECG monitoring systems is proposed, an extensive analysis of ECG monitoring systems' value chain is conducted, and a thorough review of the relevant literature, classified against the experts' taxonomy, is presented, highlighting challenges and current trends. Finally, we identify key challenges and emphasize the importance of smart monitoring systems that leverage new technologies, including deep learning, artificial intelligence (AI), Big Data and Internet of Things (IoT), to provide efficient, cost-aware, and fully connected monitoring systems.

ECG | ECG monitoring system | smart monitoring | heart diseases | cardiovascular diseases | IoT | sensors

1. Introduction

The last decade has witnessed an increasing number of deaths caused by chronic and cardiovascular diseases (CVDs) in all countries across the world. These include, for instance, stroke, heart failure, heart attack, arrhythmia, coronary artery disease, cardiomyopathy, rheumatic heart disease, vascular disease, and others. According to a study from the World Health Organization (WHO), CVDs are the number one cause of death globally, with 17.9 million deaths every year [[1]]. It remains the number one cause of death of all Americans, claiming more than 840,000 lives in 2016 [[2]]. Furthermore, the European Health Network 2017 statistics revealed that CVDs cause 3.9 million deaths in Europe and over 1.8 million deaths in the European Union (EU) yearly. This accounts for 45% of all deaths in Europe and 37% of all deaths in the EU [[3]].

2. Processes, and Key Challenges

Continuous heart rate monitoring and immediate heartbeat detection are primary concerns in contemporary healthcare. Experimental evidence has shown that many of the CVDs could be better diagnosed, controlled, and prevented through continuous monitoring, as well as analysis of electrocardiogram (ECG) signals [[4][5][6][7][8][9]]. Hence, the monitoring of physiological signals, such as electrocardiogram (ECG) signals, offers a new holistic paradigm for the assessment of CVDs, supporting disease control and prevention. With advances in sensor technology, communication infrastructure, data processing, and modeling as well as analytics algorithms the risk of impairments could be better addressed more than ever done before. This, in turn, would introduce a new era of smart, proactive healthcare especially with the great challenge of limited medical resources.

As a result, ECG monitoring systems have been developed and widely used in the healthcare sector for the past few decades and have significantly evolved over time due to the emergence of smart enabling technologies [[10][11][12][13]]. Nowadays, ECG monitoring systems are used in hospitals [[14][15][16][17]], homes [[18][19][20]], outpatient ambulatory settings [[21][22][23]], and in remote contexts [[24]]. They also employ a wide range of technologies such as IoT [[25][26][27]], edge computing [[28][29]], and mobile computing [[30][31][32]]. In addition, they implement various computational settings in terms of processing frequencies, as well as monitoring schemes. They have also evolved to serve purposes and targets other than disease diagnosis and control, including daily activities [[33][34][35]], sports [[36][37][38]], and even mode-related purposes [[39][40][41]].

This massive diversity in ECG monitoring systems' contexts, technologies, computational schemes, and purposes makes it hard for researchers and professionals to design, classify, and analyze ECG monitoring systems. Some efforts attempted to provide a common understanding of ECG monitoring systems' processes [[42][43][44][45][46][47]], guiding the design of efficient monitoring systems. However, these studies lack comprehensiveness and completeness. They work for specific contexts, serve specific targets, or are suitable for specific technologies. This makes the available ECG monitoring system processes and architectures hard to generalize and reuse. On the other hand, some studies attempted to analyze ECG monitoring systems' attributes and provide classification taxonomies, supporting better analysis and understanding of the ECG systems reported in the literature. However, exiting reviews related to ECG monitoring in the literature can be intuitive and incomprehensive [[48]]. They do not consider the latest technological trends [[49][50][51]], and they target very narrow research niches, such as wearable sensors [[52][53][54][55]], mobile sensors [[56]], disease diagnosis [[57]], heartbeat detection [[58]], emotion recognition [[59]], or ECG compression methods [[60]]. Hence, there is a need to provide a comprehensive, expert-verified taxonomy of ECG monitoring systems, a common architecture, and a complete set of processes to guide the classification, analysis, and design of these systems.

Therefore, in this work, we propose an expert-verified taxonomy of ECG monitoring systems, a generic architectural model, and a complete, general set of processes to support better understanding, analysis, design, and validation of ECG monitoring systems from a broader perspective. Our experts' taxonomy is composed of five distinct, cohesive clusters. Each cluster focuses on one dimension of ECG monitoring systems, detailing the features and attributes of these systems in that dimension. These include monitoring contexts, technologies, schemes, targets, and futuristic monitoring systems. In addition to our experts' taxonomy, the proposed ECG monitoring systems' layered architecture depicts essential structural components and elements of ECG monitoring systems, their interfaces, and the data inputs/outputs of each layer. We also complement our experts' taxonomy and the generic architecture with a comprehensive ECG monitoring process model, highlighting the major processes, sub-processes, and supporting processes, emphasizing factors adding value to each process. Based on the proposed taxonomy, architecture, and common process model, we conduct an extensive, thorough analysis of the literature surrounding ECG monitoring systems, highlighting systems' categories, attributes, functions, challenges, and current trends, leading to a panorama of ECG monitoring systems. To our best knowledge, this is the most comprehensive, expert-verified review of ECG monitoring systems to date.

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