Artificial Intelligence in Medicine xxx (2018) xxx–xxx

Contents lists available at ScienceDirect

Artificial Intelligence in Medicine

journal homepage: www.elsevier.com/locate/aiim

Dictionary-based monitoring of premature ventricular contractions: An ultra-low-cost point-of-care service

Bollepalli S. Chandra[a,*], Challa S. Sastry[b], Laxminarayana Anumandla[c], Soumya Jana[a]

[a] Department of Electrical Engineering, Indian Institute of Technology Hyderabad, 502285, India
[b] Department of Mathematics, Indian Institute of Technology Hyderabad, 502285, India
[c] Department of Cardiology, Maxcare Hospital, Warangal 506001, India

ARTICLE INFO

Article history:
Received 8 December 2016
Received in revised form 2 January 2018

Keywords:
Affordable telecardiology
Point-of-care service
Premature ventricular contractions
Dictionary learning
High-sensitivity detection
High-fidelity compression

ABSTRACT

While cardiovascular diseases (CVDs) are prevalent across economic strata, the economically disadvantaged population is disproportionately affected due to the high cost of traditional CVD management, involving consultations, testing and monitoring at medical facilities. Accordingly, developing an ultra-low-cost alternative, affordable even to groups at the bottom of the economic pyramid, has emerged as a societal imperative. Against this backdrop, we propose an inexpensive yet accurate home-based electrocardiogram (ECG) monitoring service. Specifically, we seek to provide point-of-care monitoring of premature ventricular contractions (PVCs), high frequency of which could indicate the onset of potentially fatal arrhythmia. Note that the first-generation telecardiology system acquires the ECG, transmits it to a professional diagnostic center without processing, and nearly achieves the diagnostic accuracy of a bedside setup. In the process, such a system incurs high bandwidth cost and requires the physicians to process the entire record for diagnosis. To reduce cost, current telecardiology systems compress data before transmitting. However, the burden on physicians remains undiminished. In this context, we develop a dictionary-based algorithm that reduces not only the overall bandwidth requirement, but also the physicians workload by localizing anomalous beats. Specifically, we detect anomalous beats with high sensitivity and only those beats are then transmitted. In fact, we further compress those beats using class-specific dictionaries subject to suitable reconstruction/diagnostic fidelity. Finally, using Monte Carlo cross validation on MIT/BIH arrhythmia database, we evaluate the performance of the proposed system. In particular, with a sensitivity target of at most one undetected PVC in one hundred beats, and a percentage root mean squared difference less than 9% (a clinically acceptable level of fidelity), we achieved about 99.15% reduction in bandwidth cost, equivalent to 118-fold savings over first-generation telecardiology. In the process, the professional workload is reduced by at least 85.9% for noncritical cases. Our algorithm also outperforms known algorithms under certain measures in the telecardiological context.

1. Introduction

Cardiovascular diseases (CVDs) are a leading cause of death across economic strata [1]. Hence a crucial healthcare objective consists in managing those diseases. In this regard, electrocardiogram (ECG) signals acquired from subjects often play a vital role. Specifically, continuous ECG monitoring is central to early diagnosis and improved clinical outcome in certain scenarios. However, such monitoring at a professional facility is often unaffordable to economically disadvantaged individuals due to high cost, low availability and other barriers. Against this backdrop, home-based point-of-care (POC) monitoring assumes significance. In this paper, we propose a POC monitoring service that is highly affordable.

Symptoms indicating CVDs often manifest sporadically. Consequently, to detect deviations from the normal sinus rhythm, subjects should ideally be monitored continuously. Especially, for patients who have suffered myocardial infarction (MI), or developed left ventricular dysfunction (LVD), continuous monitoring has proven essential in promptly detecting sudden deterioration in cardiac functions, and hence preventing mortality [2]. The aforementioned as well as various related conditions are associated with premature ventricular contractions (PVCs) that briefly interrupt the normal rhythm of the heart [3]. Although PVCs occur in healthy individuals as well, high frequency of PVCs is known to foretell serious arrhythmic conditions [4], and significantly correlate with

* Corresponding author.
E-mail addresses: bschandra@iith.ac.in (S.C. Bollepalli), csastry@iith.ac.in (S.S. Challa), laxmin56@gmail.com (L. Anumandla), jana@iith.ac.in (S. Jana).

https://doi.org/10.1016/j.artmed.2018.04.003
0933-3657/

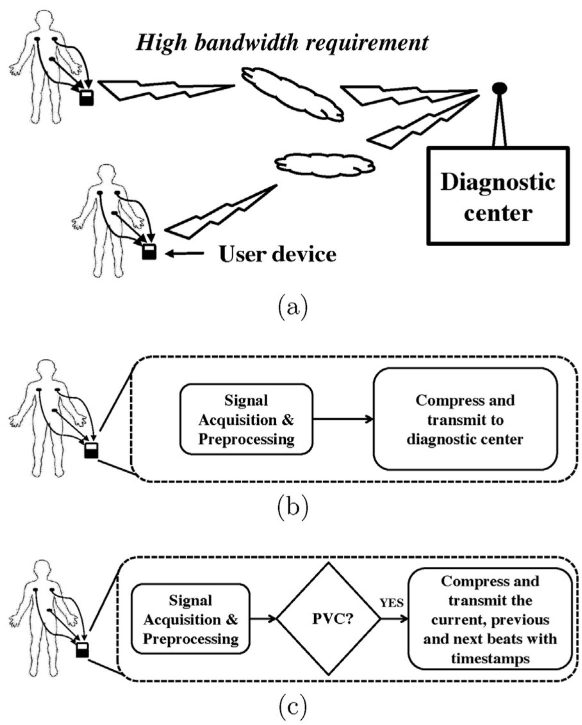

Fig. 1. (a) First-generation telecardiology architecture that records ECG signal and transmits it without compression; (b) current telecardiology architecture that compresses ECG data before transmission; (c) schematic of the proposed system with PVC detection and compressed beat-trio communication.

events of mortality [5]. In short, accurate detection of PVCs assumes clinical significance in stratifying high risk patients, and predicting medical emergencies. In this context, we propose a novel personalized service to monitor the PVC burden.

In particular, we seek to develop a POC service that would appeal to the economically disadvantaged. Worldwide, about 1.2 billion individuals live on less than US$ 1.25 per day and have little discretionary income [6]. To such individuals, the cost of professional monitoring could often be prohibitive. Further barriers to quality care could include travel and hospital expenses. Fortunately, high penetration of mobile phones even in remote communities has mitigated such barriers in certain scenarios [7]. In the present case, can the mobile network be leveraged to provide reliable PVC monitoring at an attractive cost to the communities living at the bottom of the economic pyramid [8]?

In response, we take a frugal engineering approach [9], and propose an ultra-low-cost POC service. As depicted in Fig. 1a, a first-generation telecardiology system simply records user ECG and transmits it to a diagnostic center staffed by medical professionals, where anomalies are manually detected and medical intervention is initiated, when necessary. In such systems, ECG signals are transmitted unaltered, resulting in perfect accuracy (subject only to human error), albeit with the attendant high bandwidth cost and without localizing potentially anomalous beats [10]. To reduce cost, current telecardiology systems (shown in Fig. 1b) compress data (subject to a reconstruction fidelity constraint) before transmitting to diagnostic center [11,12]. Though such systems reduce the bandwidth cost, medical professionals are still required to process the entire record for diagnosis. Against this backdrop, we propose a new telecardiology paradigm, depicted in Fig. 1c, where each user device detects anomalous beats, and subsequently compresses and transmits only those anomalous beats and delimiting neighbors (forming beat-trios) along with timestamps. Such a system would not only reduce the bandwidth requirement but also present to medical professionals only those beats that warrant closer inspection, thereby reducing their workload and potentially improving the responsiveness of the diagnostic center.

In this framework, system design involves a tradeoff among three quantities: (i) classifier sensitivity (the fraction of PVC beats correctly identified), which we take as the reliability criterion, (ii) the fidelity of reconstructed signal at the diagnostic center, which determines the ability of experts to authenticate algorithmic classification, and (iii) the transmission bandwidth, which dictates the operating cost. To ensure accurate clinical outcome, one desires both high reliability (classifier sensitivity) and high fidelity. At the same time, one also seeks low transmission bandwidth in order to operate at a low cost. The main difficulty arises due to the complex three-way tradeoff among the above quantities. In particular, the bandwidth usage increases with sensitivity and decreases with specificity, while sensitivity and specificity themselves exhibit a nonlinear inverse inter-relationship dependent on reconstruction fidelity. The above quantities are further affected by signal compression. In this paper, we study the said tradeoff, and propose a natural design framework for telecardiology systems.

None of the individual tasks, namely, classification and compression, is new in the field of ECG signal processing. In fact, numerous algorithms have been reported specifically for PVC detection. Examples include machine learning algorithms, such as mixture of experts [13], linear and quadratic discriminant analyses [14,15], support vector machine [16], and artificial neural networks [17–21]. However, such algorithms have not been designed to achieve compression as well, and are not optimized in the high-sensitivity regime. On the other hand, reported ECG compression algorithms are based on techniques, ranging from the classical time and transform domain methods [22,23], to the recent overcomplete dictionary learning [24,12]. Yet, those algorithms too were not designed to achieve the desired high-sensitivity classification. Against this backdrop, we propose a dictionary-based method that attempts to retain the best of both worlds, and achieve the desired classification and the compression goals simultaneously. The proposed approach, however, is different from the (symmetric) joint classification/reconstruction framework [25], where a combination of classification and (class-oblivious) reconstruction indices is minimized subject to a rate constraint. Instead, our setup is inherently class-asymmetric as signals detected as normal (excepting delimiting beats) are discarded, i.e., compressed to zero bits, while signals detected as PVCs are compressed at a certain rate so as to meet a target diagnostic fidelity criterion.

To this end, we propose to train separate overcomplete dictionaries for the respective classes of normal and PVC beats using labeled data. Specifically, each test beat is approximated as a linear combination of the columns of each dictionary. Intuitively, a signal should admit sparse representation only in the dictionary of the matching class. In accordance, the ratio of sparsity of representation in each dictionary is computed, and a suitable class is assigned by comparing that ratio to a threshold. The sensitivity level is then tuned to a desired level by varying such threshold. Here, the sparsity of representation is dictated by the desired fidelity of reconstruction, and in turn determines the degree of compression. Although low reconstruction fidelity would result in high sparsity (hence high compression), the resulting representation would also tend to miss the information necessary for accurate classification. Interestingly, high-fidelity regime may not guarantee accurate classification either. As the signal approximation becomes increasingly accurate, the representations based on rival dictionaries would decrease in sparsity, which in turn leads to poor classification. Consequently, our task involves choosing suitable level of fidelity so that high sensitivity and high compression are both achieved.

The efficacy of the proposed scheme is demonstrated on the standard MIT/BIH arrhythmia database using Monte Carlo cross

Please cite this article in press as: Bollepalli SC, et al. Dictionary-based monitoring of premature ventricular contractions: An ultra-low-cost point-of-care service. Artif Intell Med (2018), https://doi.org/10.1016/j.artmed.2018.04.003