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Technical note

# Robust correlation technology for online monitoring of changes in the state of the heart by means of laptops and smartphones

T.A. Aliev*, N.E. Rzayeva, U.E. Sattarova

*Institute of Control Systems, Azerbaijan National Academy of Sciences, Azerbaijan*

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ABSTRACT

We demonstrate the possibility of monitoring changes in heart activity through the auscultation and analysis of heart sounds by means of a laptop or smartphone. The proposed technology allows laptop and smartphone users to create bases of reference for informative attributes in the most indicative periods of the day over the course of 10–15 days in home or work environments. During subsequent auscultation of the heart, current combinations of corresponding informative attributes are formed and compared with the reference data. If the current combinations match the reference data, a user is informed that his/her condition is within the norm; otherwise, a recommendation to see a doctor is given.



## 1. Introduction

An increasing number of people from various strata of society currently suffer from heart diseases. Modern diagnostics of these diseases are complicated by the heavy workload of physicians and the high cost of most medical diagnostic methods. In many cases, people suffering from cardiovascular diseases visit a cardiologist only when the disease is already in its explicit, expressed form; even though the disease is diagnosable by known methods, its treatment becomes substantially complicated [1].

An untimely diagnosed heart disease can cause tragic consequences for many patients, which is why many researchers and physicians focus on the diagnosis of these diseases [2–13].

Existing mobile means of monitoring do not permit online assessment of the condition of the cardiovascular system (CVS). Some systems solve this task by transmitting ECG to the server via communication channels for subsequent processing and analysis at a cardiology centre [2–13]. However, the procedure in question is quite expensive, which impedes the possibility of its mass use.

The well-known Holter monitor continuously records ECG over the course of 24 h for its subsequent analysis by a cardiologist [2]. This system detects changes in the condition of the CVS only after a certain period of time and requires the involvement of a cardiologist, which can delay monitoring results.

Another system, “Easy ECG Mobile”, records ECG, whose record is instantly transmitted via a wireless local area network or within several seconds via the Internet [3].

The “Ericsson Mobile Health” (EMH) system allows for remote monitoring of the CVS [4].

A number of papers [5–30] also have dealt with this problem.

The mobile monitoring tools described above have the following shortcomings:

- Inability to determine online, without the involvement of medical personnel, the need for a medical examination;
- Inability to carry out continuous monitoring of changes in the condition of cardiovascular patients;
- Inability to detect the initial stage of cardiovascular diseases without the involvement of medical personnel, which might help people avoid further complications if they contacted a physician in time.

In view of the above, the issue of interest here is online identification of the initial changes in heart activity based the characteristics of heart sounds, using laptops and smartphones. This will allow potentially sick people to become aware when in a home environment that they should see a doctor. Otherwise, in most cases, they will be informed based on the monitoring results that there is no need to do so, thereby minimizing the number

* Corresponding author.
*E-mail addresses:* telmancyber@rambler.ru, ulker.rzaeva@gmail.com (T.A. Aliev).

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of unwarranted visits to a doctor and saving the time of medical professionals. Patients, in turn, will be able to avoid unnecessary wastes of time, energy and finances. None of the systems described in the previous paragraphs can perform this function online and without medical personnel. The present paper addresses a way to solve this problem.

We propose technologies for robust identification of heart sounds to monitor the beginning of changes in the CVS by means of laptop computers and smartphones. This will allow users of laptops and smartphones to receive information on the condition of their heart in real time, in home or work conditions.

The proposed system does not require access to any extra medical services. It allows one to determine whether a visit to a doctor is necessary using only a laptop or smartphone.

## 2. Problem statement

As noted earlier, modern diagnostics of cardiovascular diseases are impeded by the high cost of medical examinations. Additionally, the procedure takes much time and energy from patients and doctors.

With this system, using a laptop or smartphone, one can ascertain in home conditions that no change has occurred in one's heart activity and that an expensive, lengthy and exhausting preventive medical examination is unnecessary. In other cases, the proposed system will allow for monitoring of the initial stage when the disease is easily treatable [1,10].

In view of the above, the development of such systems is of very high practical interest. This paper addresses the possible development and prospects for mass use of mobile tools for monitoring such widespread diseases as cardiovascular diseases.

A weighty argument for such systems is that heart sounds are a characteristic of the human body that can be measured and used for monitoring changes in heart activity.

However, the errors in the obtained estimates of correlation functions caused by the noise $\varepsilon_1(t)$ accompanying the useful signal $U(t)$ vary across a very wide range when heart sound is measured by means of a microphone. This is because auscultation is found in home or industrial conditions, at high or low temperatures, depending on the season, weather, vibration, shaking, etc.

As a result, during auscultation, a signal contaminated with noise $\varepsilon(t)$ arrives at the microphone input instead of the useful signal $U(t)$. The analyzed signal looks as follows in the analogue form:

$$g(t) = U(t) + \varepsilon(t), \quad (1)$$

and as follows in the digital form:

$$g(i\Delta t) = U(i\Delta t) + \varepsilon(i\Delta t). \quad (2)$$

Owing to the abovementioned reasons, both the amplitude and the spectrum of the noise $\varepsilon(i\Delta t)$ vary across a rather wide range. For the same reasons, the errors in the obtained estimates of the correlation functions $R_{gg}(i\Delta t)$ of the heart sound $g(i\Delta t)$ also vary across a wide range. Thus, we fail to provide the condition of robustness for the estimated correlation function in real-time mode—i.e., to rule out the dependence of the obtained results on the variation of the noise $\varepsilon(i\Delta t)$. This, in turn, complicates the problem of identifying heart sounds by correlation methods. Consequently, ensuring adequate identification requires that the conditions of robustness are satisfied; i.e., it requires the effects of the said factors on the errors in the estimates $R_{gg}(i\Delta t)$ to be eliminated.

At first glance, the effects of the said errors on the results of heart sound identification can be eliminated by filtering the noise accompanying the useful signal$U(i\Delta t)$. If the noise spectrum is stable, filtration usually gives satisfactory results. Under field conditions, however, the spectrum of the noise and its variance varies across a very wide range, and we cannot obtain the desired effect using filtration technology. Thus, we cannot always achieve satisfactory results through correlation analysis of heart sounds using filtration. Therefore, solving the problem under consideration first requires developing technologies that can calculate such estimates of correlation characteristics that remain practically unaffected by changes in the noise.

To that end, it is appropriate to first reduce the estimates $R_{gg}(i\Delta t)$ to a single dimensionless value by applying a normalization procedure [1,31–34]. Our analysis, however, demonstrates that the application of conventional methods introduces additional error into the normalized estimates of the correlation functions $r_{gg}(i\Delta t)$, which, in turn, also complicates attempts to ensure an adequate analysis of heart sounds. This issue will be considered in greater detail in the following paragraphs.

It is known that the normalized correlation function of the useful signal $U(i\Delta t)$ is calculated from the following formula [31–36]:

$$r_{UU}(\mu) = R_{UU}(\mu)/D_U = R_{UU}(\mu)/R_{UU}(\mu = 0), \quad (3)$$

where the estimate of the variance $D_U = R_{UU}(\mu)$ at $\mu = 0$ is determined from the expression

$$R_{UU}(\mu = 0) = D_U = 1/N\sum_{i=1}^{N} \mathrm{U}(i\Delta t)\mathrm{U}(i\Delta t). \quad (4)$$

The estimates of the correlation function $R_{UU}(\mu)$ of the useful signal $U(i\Delta t)$ at $\mu \neq 0$ are calculated from the formula

$$R_{UU}(\mu) = 1/\mathrm{N}\sum_{i=1}^{N} \mathrm{U}(i\Delta t)\mathrm{U}((i+\mu)\Delta t), \quad \mu = 0, 1, 2, 3. \quad (5)$$

It is also known that the estimates of normalized correlation functions $r_{gg}(\mu)$ of the noisy signal $g(i\Delta t)$ are calculated from the formula

$$r_{gg}(\mu) = R_{gg}(\mu)/D_g = R_{gg}(\mu)/R_{gg}(\mu = 0), \quad (6)$$

where

$$\begin{aligned} R_{gg}(\mu) &= 1/N\sum_{i=1}^{N} g(i\Delta t)g((i+\mu)\Delta t) = \\ &= 1/N\sum_{i=1}^{N}[U(i\Delta t)+\varepsilon(i\Delta t)][U((i+\mu)\Delta t)+\varepsilon((i+\mu)\Delta t)] = \\ & 1/N\sum_{i=1}^{N}[U(i\Delta t)U((i+\mu)\Delta t)+U(i\Delta t)\varepsilon((i+\mu)\Delta t)+\varepsilon(i\Delta t)U((i+\mu)\Delta t)+ \\ & +\varepsilon(i\Delta t)\varepsilon((i+\mu)\Delta t)] \end{aligned} \quad (7)$$

To ensure the adequate identification of heart sounds, the following condition must be satisfied following the normalization of the correlation functions of the signal $g(i\Delta t)$ from expressions (6) and (7):

$$r_{UU}(\mu) \approx r_{gg}(\mu) \quad (8)$$

The results of normalization obtained in expressions (3) and (6) will clearly be the same at $\mu = 0$; i.e.,

$$r_{UU}(\mu = 0) = R_{UU}(\mu = 0)/D_U = r_{gg}(\mu = 0) = R_{gg}(\mu = 0)/D_g = 1 \quad (9)$$

It is also obvious that the results of normalization obtained in expressions (5) and (7) will be different; i.e.,

$$r_{UU}(\mu) = R_{UU}(\mu)/R_{UU}(\mu = 0) \neq r_{gg}(\mu) = R_{gg}(\mu)/R_{gg}(\mu = 0) \quad (10)$$

For this reason, when Formula (6) is applied, the correct result is obtained only at $\mu = 0$. For all other cases, when $\mu \neq 0$, the results of normalizing the correlation functions of the noisy signal differ from those of the useful signal. Our experiments demonstrate that this is the main factor for the inadequacy of heart sound identification results.