HELPING PARAMEDICS IN ASSESSING A PATIENT'S CONDITION BASED ON ECG BY MEANS OF MOBILE PHONE

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ABSTRACT

One of the most common cardiovascular diagnostic test is the electrocardiogram (ECG). However, physicians' skills in ECG interpretation are far from always satisfactory. There is a problem of rendering assistance to a primary care physician in making an operative decision on the tactics of managing a patient with a cardiovascular accident, which is especially relevant in regions where specialized medical equipment has not received mass distribution. The article addresses the issue of rendering assistance to a primary care physician in making an operative decision on the tactics of managing a patient with a cardiovascular accident, if the physician has only the simplest electrocardiograph. We discuss possibility of using mobile phones for this purpose. It is proposed to use them in two ways: for the automated assessment of ECG parameters, which are promptly reported to the paramedic, as well as for transmitting the ECG image to a qualified cardiologist in order to obtain a second (advisory) opinion remotely. We have built and implemented an algorithm for assessing the main morphological parameters of the ECG on a physician’s mobile phone when taking photos of 12 leads-ECG on a phone camera. We have shown experimentally that the accuracy of evaluating the morphological parameters of the ECG when working on an image captured with a phone camera is not worse than when working on a digital signal. Using the example of typical emergency medical service scenarios, we have shown that for a consultant cardiologist to obtain an image of the patient's cardiogram with a quality no worse than that of the original cardiograph, it is enough of the phone that does not go beyond the cheap price segment. Thus, the proposed solution is quite applicable in developing countries and in provincial regions, i.e. outside big cities.

KEYWORDS

Electrocardiogram, Second Opinion, Mobile Phones, Automated ECG Processing

1. INTRODUCTION

Cardiovascular diseases rank first in the world as a cause of death [Cardiovascular]. Unlike slowly developing diseases such as oncology, cardiovascular diseases often manifest themselves as disasters, requiring the fastest possible medical intervention and, accordingly, immediate and correct decision-making.

One of the most common cardiovascular diagnostic test is the electrocardiogram (ECG). However, physicians' skills in ECG interpretation are far from always satisfactory. According to the review [Cook], the accuracy of ECG interpretation varies depending on the qualifications of the interpreter and is 48.1–63.6% for lower-level physicians, 57.6–79.5% for medical practitioners, and 63.2–86.7% for cardiologists.

This problem is especially acute in developing countries and in provincial regions, i.e. outside big cities. Here, primary care for a patient with suspected cardiovascular catastrophe is most often provided by paramedics (when calling an ambulance) or by the staff of a paramedic center who does not have professional knowledge in the field of cardiology. It is their decision that determines the choice of tactics for the further management of the patient (including such an expensive procedure as transportation to a specialized clinic) and, ultimately, his life. Thus, the significance of accuracy and reliability of urgent ECG parameter interpretation is obvious.
In recent years, methods of automated determination of ECG parameters have been actively developed [Kligfield, Kligfield, Attia]. Their accuracy varies for different monitored ECG parameters [Xie]. For example, an automated assessment of deviations from sinus rhythm can be performed with an accuracy of 99% [Sangaiah], but, while finding the sophisticated features in ECG using the standard 10 s ECG an accuracy of 79.2% is achieved [Attia]. In general, automated methods, firstly, require specialized equipment, which, as a rule, are absent in primary health care in developing countries, and, secondly, they are consultative, i.e. do not remove the need for an integral ECG assessment by a qualified cardiologist.

Thus, there is a problem of rendering assistance to a primary care physician in making an operative decision on the tactics of managing a patient with a cardiovascular accident, which is especially relevant in regions where specialized medical equipment has not received mass distribution.

The article discusses the possibility of using mobile phones for this purpose. It is proposed to use them in two ways: for the automated assessment of ECG parameters, which are promptly reported to the paramedic, as well as for transmitting the ECG image to a qualified cardiologist in order to obtain a second (advisory) opinion remotely.

2. BACKGROUND AND RELATED WORKS

An ECG (Figure 1a) is a recording of a sequence of electrical impulses corresponding to a heartbeat. Recording can be performed in several leads (from 1 to 12) and have different lengths (from 6-7 heartbeats to continuous monitoring).

![Figure 1. Fragment of ECG (a) and its characteristic intervals (b)](image)

Various assessment techniques are used for analysis and interpretation of the ECG [Xie]. In recent years, more and more methods based on machine learning have been proposed, but methods based on the assessment of ECG features, such as wavelet and statistical features, are much more widespread. However, the basic ones are morphological features (intervals) that can be directly observed on the ECG (Figure 1b). There are routine methods for their assessment, as well as tables of their normal and abnormal values. For example, going beyond the normative limits of the PR interval may be a sign of stroke [Montalvo], of the ST segment - a sign of myocardial ischemia or infarction [Hausenloy] etc.

Traditionally, obtaining an ECG is fulfilled by trained medical personnel using a special device - a cardiograph. As a rule, cardiographs record the ECG on paper. More advanced models also have a linear output for digital recording of the electrical signal from the sensors. In clinical practice, there are already models of cardiographs equipped with means of automated calculation of morphological indicators, however, as the practice of Russia shows, their distribution in developing countries is limited by large medical centers. As for the automated analysis of the ECG in general by means of machine learning, as well as wavelet and statistical features, such methods have not yet gone beyond the scope of experimental investigations.

The widespread use of mobile phones among the population has given rise to such a direction of mobile health applications as smartphone ECG monitoring [Walker, Gropler, Bansal]. Most all smartphone ECG technologies involve the use of a special device that the patient installs on the body by himself. The device communicates with a smartphone on which specialized software is installed that processes the collected data. Such implementations are widely represented on the market (see reviews [Walker, Gropler, Bansal]). For example, the Kardia Mobile device (AliveCor®, Mountain View, CA, USA) is widely popular in the United States. The device is based on the principle of plethysmography and includes a detector pad and specialized software. The signal generated by
the device is most similar to lead I on a conventional 12-lead ECG. The signal is sent to a physician through the application installed on the smartphone, and within 24 h, user receives an interpretation of the reading. On subsequent uses, the device classifies the ECG into categories: normal, interference, atrial fibrillation or undetermined, and, according to the manufacturer, a reading of AF is not diagnostic. Another example is the D-Heart device (D-Heart®, Genova, Italy) is positioned as a means of self-monitoring of ECG for regions with insufficient medical care. The kit includes the cardiograph itself, the electrodes of which the patient independently installs on the body, and software for the smartphone. The recorded ECG (from 8 to 12 leads) is transmitted via the application to the phone and from there is sent to the cardiologist, who forms a conclusion. Directly on the device (without the participation of a cardiologist), the patient is informed only of the suspicion of the presence of atrial fibrillation.

Problem-oriented analysis of the smartphone ECG technologies presented on the market shows: ECG recording in them is made using specialized devices, the signal from which is transmitted to mobile phones in digital form; the scenario of their work provides for a delayed (up to 24 hours) decoding of the ECG and the formation of a conclusion by a cardiologist; a very limited set of morphological indicators is calculated directly on the mobile phone, and the accuracy of the estimate is not indicated. Such scenarios are not actual in the provision of primary or emergency medical care in non-advanced regions (for example, in Russia - outside large cities). Here, a doctor or a paramedic most often has at his disposal only a conventional 12-lead ECG cardiograph, which records on paper and is not equipped with automated analysis or at least calculation of indicators. He must make a decision about the patient’s condition based only on his own assessment of morphological features and taking into account the integral assessment of the EEG as a whole.

The article discusses the possibilities of supporting the actions of a primary care physician in the specified scenario via a mobile phone. The authors set themselves the following tasks:

- to build and implement an algorithm for assessing the main morphological parameters of the ECG on a physician’s mobile phone when taking photos of 12 leads-ECG on a phone camera;
- to evaluate the accuracy of the constructed algorithm;
- to evaluate the possibilities of prompt transmission of the ECG image via the phone for a remote consultation of a qualified cardiologist on-line.

3. METHOD AND MATERIALS

The proposed pipeline for ECG processing using a mobile phone is shown in Figure 2. As a basic algorithm for calculating the morphological characteristics of the ECG, the MTEO algorithm [Sedghamiz] was used. This choice was due to the fact that the MTEO algorithm allows you to find the peaks of all ECG waves necessary for diagnostics (P, Q, R, S, T). For comparison, algorithms such as Pan-Tompkins [Sedghamiz2014], Nonlinear Phase Space Reconstruction [Lee], and Filter Bank [Afonso] find only the QRS complex, while the State-Machine algorithm [Sedghamiz2014a] finds only the peaks R, S, and T (see Figure 1b). Compared to other solutions that allow finding peaks of all ECG waves (for example, algorithms from the ECG-kit package [ECG-kit]), the used MTEO implementation compares favorably with a higher stability of processing ECG “edge cases”. This is important both for testing the algorithm using a digital ECG base, and for use with photographs of real ECGs, since a distortion of the signal amplitude or a rotation of the ECG relative to the horizontal position may be observed in the photograph.

The proposed pipeline for ECG processing includes the following sequence of steps. First, the signal is filtered to reduce noise. To do this, the signal is passed through a narrow notch filter, normalized, de-trend is performed, and a pass through the Butterworth filter (5-1200 Hz) is made. Then MTEO (Multiresolution Teager Energy Operator) is calculated as follows:

\[
Y_i(nT) = x^2(nT) - x(nT-kT)x(nT+kT),
\]

\[
t(nT) = \max \{ \hat{Y}_1(nT), \hat{Y}_2(nT), ..., \hat{Y}_N(nT) \}.
\]

Here \(x(nT)\) is the raw ECG signal for \(n=1, 2, ..., N\), \(N\) is the number of signal sample, \(\hat{Y}_i(nT)\) is \(Y_i(nT)\) after it is smoothed with a Hamming window of size \(4k+1\) and normalized by the squared variance at scale \(k\). For a more accurate selection of the R peaks against a noisy background, binary hypotheses are tested at the points of the MTEO graph.
\[ H_0 : t(nT) = G(nT) \quad \text{vs} \quad H_1 : t(nT) = s(nT) + G(nT). \]

Peaks P, Q, S, T are found on the basis of the peaks R found at the previous stage by an algorithmic method. For this, certain distances are plotted from the R peaks, which differ depending on the type of the sought peak (see Figure 1b). Then, in the obtained intervals, local minima and maxima are found and the necessary ones are selected depending on the type of peak.

In the filtered signal, a characteristic segment of length RR with a center in one of the peaks R is highlighted. For each type of teeth, in a certain interval from the corresponding peak, there are points of intersection of the tangent to the point of steepest increase / decrease with the isoline (see the fragment Start / END Points in Figure 2). Then the distance between the obtained points is determined in accordance with the ECG interval diagram.

The developed algorithm for translating an ECG image into a graph is implemented in the java programming language using the openimaj library. The algorithm for finding peaks and calculating intervals is implemented in the MatLab language and is integrated into the final android application using the Simulink
Support Package for Android Devices. The current version is available at: https://github.com/Pmvop19/ECG_Mobile.

Our development is focused on equipment and technologies available in Russia (see table 1). Table 1, built according to YandexMarket data as of 03/27/21, shows examples of popular phone models in the price range up to $ 50, available in Russia and satisfying the necessary characteristics for using the application.

Table 1. Characteristics of mobile phones sufficient for using the application

<table>
<thead>
<tr>
<th>Model</th>
<th>Main Camera Resolution</th>
<th>Used Data Transmission Technologies</th>
<th>Android Version</th>
</tr>
</thead>
<tbody>
<tr>
<td>INOI 2 Lite</td>
<td>5 Мп</td>
<td>2G 3G</td>
<td>7.0</td>
</tr>
<tr>
<td>ZTE Blade L8 1</td>
<td>8 Мп</td>
<td>2G 3G</td>
<td>9.0</td>
</tr>
<tr>
<td>Alcatel 1A (2020)</td>
<td>5 Мп</td>
<td>2G 3G 4G</td>
<td>10.0</td>
</tr>
<tr>
<td>Alcatel 1 (5033D)</td>
<td>5 Мп</td>
<td>2G 3G 4G</td>
<td>8.0</td>
</tr>
<tr>
<td>ZTE Blade A3</td>
<td>8 Мп</td>
<td>2G 3G 4G</td>
<td>9.0</td>
</tr>
</tbody>
</table>

Real cardiograms contain noise and interference, which makes it difficult to isolate characteristic peaks by algorithmic means. In this regard, the question arises about the reliability of calculating morphological intervals from an ECG image taken with a smartphone camera. To answer this question, a comparative assessment was made of the efficiency of calculating intervals basing on digital ECGs and on ECG images.

A dataset of Lobachevsky University [Kalyakulina] containing digital ECGs was used as a data source. From the dataset, 150 ECGs were selected with varying degrees of noise. To obtain ECG images for comparative evaluation, in the MATLAB environment, graphs of signals from the dataset were built, from which the coordinate axes and other marks were removed. The plotted graphs were photographed with a smartphone camera with the above parameters (see Table 1). Thus, we get an imitation of a high-quality image taken with a phone camera.

For a comparative assessment of the accuracy, the MAE (mean absolute error) metrics were used in milliseconds (the initial unit of measurement of ECG intervals) and as a percentage of the right border of the characteristic reference intervals ([Xie], table 1). As the analysis of cardiograms from the dataset [Kalyakulina] shows and is confirmed by real medical practice [Goldenberg], preliminary filtering of the ECG signal from noise and interference can affect the result of calculating morphological intervals, especially when finding the end of the S peak. In this regard, for a more accurate imitation of real scenarios, the MAE metric was calculated in two options: when evaluating intervals without pre-filtering and with pre-filtering. For this, appropriate changes were made to the calculation algorithm at the “Calculation of intervals” stage.

To assess the possibilities of prompt transmission of an ECG image by telephone for a remote consultation of a qualified cardiologist on-line, we considered two typical scenarios:

**Scenario 1** - taking an ECG, processing and sending the results for obtaining an advisory opinion is static - for example, at the patient’s home or in the premises of a primary medical institution. In this case, the transmission speed is taken as the maximum possible using a specific transmission technology.

**Scenario 2** - taking an ECG, processing and sending the results for obtaining an advisory opinion occurs in motion at a speed of up to 120 km / h (for example, an ambulance team is next to the patient while driving to the hospital). In this case, the transmission rate is taken as a tenth of the maximum using a specific transmission technology.

4. RESULTS AND DISCUSSION

The results of the comparative assessment of the efficiency of calculating intervals basing on digital ECGs and on ECG images are presented in Tables 2 and 3.

Comparison of the results of both tables shows that the use of ECG images instead of digital data at least does not impair the accuracy of ECG interval calculations.

Table 4 shows the typical values of the image transmission time in the implementation of the above scenarios. For the calculation, an ECG image of 200 Kb (0.195 Mb) in .jpg format was used, which is typical for the parameters of equipment and technologies presented in Table 1.
The data in Table 4 show that the image transmission time in any case does not exceed 1.5 minutes, which is quite reasonable and does not go beyond the realizable scenario.

Table 2. The accuracy of calculating morphological intervals based on digital ECG

<table>
<thead>
<tr>
<th>Reference interval, ms</th>
<th>MAE, ms</th>
<th>MAE, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>600</td>
<td>1200</td>
</tr>
<tr>
<td>PR</td>
<td>80</td>
<td>110</td>
</tr>
<tr>
<td>QRS</td>
<td>120</td>
<td>200</td>
</tr>
<tr>
<td>ST</td>
<td>60</td>
<td>100</td>
</tr>
<tr>
<td>T</td>
<td>50</td>
<td>155</td>
</tr>
<tr>
<td>QT</td>
<td>350</td>
<td>440</td>
</tr>
</tbody>
</table>

Table 3. The accuracy of calculating morphological intervals based on image ECG

<table>
<thead>
<tr>
<th>Reference interval, ms</th>
<th>MAE, ms</th>
<th>MAE, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>600</td>
<td>1200</td>
</tr>
<tr>
<td>PR</td>
<td>80</td>
<td>110</td>
</tr>
<tr>
<td>QRS</td>
<td>120</td>
<td>200</td>
</tr>
<tr>
<td>ST</td>
<td>60</td>
<td>100</td>
</tr>
<tr>
<td>T</td>
<td>50</td>
<td>155</td>
</tr>
<tr>
<td>QT</td>
<td>350</td>
<td>440</td>
</tr>
</tbody>
</table>

Table 4. The accuracy of calculating morphological intervals based on image ECG

<table>
<thead>
<tr>
<th>Data transmission technology</th>
<th>Maximum transfer rate, Mb / s</th>
<th>Transfer time for Scenario 1, s</th>
<th>Transfer time for Scenario 2, s</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5G</td>
<td>0.019</td>
<td>10</td>
<td>100</td>
</tr>
<tr>
<td>2.75G</td>
<td>0.058</td>
<td>3.3</td>
<td>33</td>
</tr>
<tr>
<td>3G</td>
<td>0.25</td>
<td>0.8</td>
<td>8</td>
</tr>
<tr>
<td>3.5G</td>
<td>0.72</td>
<td>0.3</td>
<td>3</td>
</tr>
<tr>
<td>4G</td>
<td>2.5</td>
<td>0.1</td>
<td>1</td>
</tr>
<tr>
<td>2.5G</td>
<td>0.019</td>
<td>10</td>
<td>100</td>
</tr>
</tbody>
</table>

Thus, in order for the physician or paramedic providing primary care to be able to quickly obtain data on the morphological parameters of the patient, and the consultant cardiologist to obtain an image of the patient's cardiogram with a quality no worse than that of the original cardiograph, in addition to the conventional cardiograph, it is sufficient to have a mobile phone with the following parameters:

- camera with a resolution of at least 5MP;
- operational system v. Android 6.0 and higher.

Let us emphasize that the proposed solution is highly accessible both for Russia and for other developing countries, since the required characteristics of the phone for using the application do not go beyond the cheap price segment. A big plus of the solution is the fact that no additional devices are needed to use it, except for a suitable telephone and a simple cardiograph.
5. CONCLUSION

The article addressed the issue of rendering assistance to a primary care physician in making an operative decision on the tactics of managing a patient with a cardiovascular accident, if the physician has only the simplest electrocardiograph. The article discusses the possibility of using mobile phones for this purpose. It is proposed to use them in two ways: for the automated assessment of ECG parameters, which are promptly reported to the paramedic, as well as for transmitting the ECG image to a qualified cardiologist in order to obtain a second (advisory) opinion remotely.

The tasks set by the authors of the article have been successfully fulfilled. We have built and implemented an algorithm for assessing the main morphological parameters of the ECG on a physician’s mobile phone when taking photos of 12 leads-ECG on a phone camera. We have shown experimentally that the accuracy of evaluating the morphological parameters of the ECG when working on an image captured with a phone camera is not worse than when working on a digital signal. Using the example of typical emergency medical service scenarios, we have shown that for a consultant cardiologist to obtain an image of the patient’s cardiogram with a quality no worse than that of the original cardiograph, it is enough of the phone that does not go beyond the cheap price segment. Thus, the proposed solution is quite applicable in developing countries and in provincial regions, i.e. outside big cities.

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