A Novel Method for Digitizing Standard ECG Papers

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Abstract

Conversion of ECG papers into digital form is very important for both clinical and research purposes. This paper proposes some improvements to the existing digitization process by selecting appropriate image resolution during scanning and using neighborhood and median approach during the extraction and digitization of the ECG waveform. Results indicate that the developed software preserve the essential features of the ECG waveform.

I. Introduction

Monitoring the electrical activity of the human heart for clinical diagnosis is a common practice which often relies heavily on electrocardiography. Most of the public hospitals in Jordan use electrocardiogram (ECG) papers for the study of heart conditions of patients. However, few private hospitals employ commercial equipments that can provide a standard ECG traces on graph paper and digital signal which can be stored in a local archive. During the last decades, huge amount of ECG traces were produced, unfortunately, most of these traces were either lost or not archived properly. A digital database for ECG traces in most hospitals in Jordan can be a valuable asset for both clinical and research purposes. Thus, the data can easily be accessed, exchanged or analyzed. Therefore, there is a need to devise a method for developing an ECG database in Jordan. As a first step in this direction, this paper addresses the issue of converting ECG traces to digital form which can be either stored digitally or be used for automatic diagnosis of heart conditions.

In this study, a method is proposed for converting a lead II ECG paper into digital form. The method can be generalized for the other 11 leads ECG. The paper is organized as follows. Section II discusses the process followed in the digitization of the EGC papers. The description of the methodology implemented by this study is given in Section III, whereas results and discussion are presented in Section IV. Finally, Section V concludes the paper.

II. DIGITIZATION OF THE ECG PRINTOUT

Digitization of an ECG printout refers to the process of assigning discrete time-voltage values to the pixels of an image corresponding to a signal from the printout [1]. From [2-4], it can be deduced that the major steps needed to accomplish this task should follow the block diagram in Figure 1.

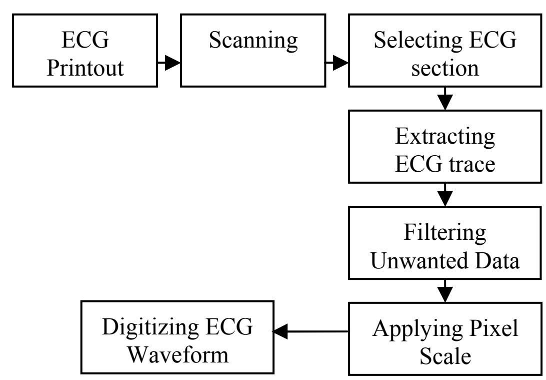

Figure 1. Main processes required by the digitization of an ECG paper.

In the first stage, the ECG paper is first converted into a digital image by using a scanner. A typical ECG image includes ECG black waveforms that appear on a background red grid having horizontal and vertical grid lines as shown in Figure 2. These ECG waveforms represent 12 lead printouts along with three continuous recordings of lead II, V and VI. During the scanning stage, three main issues have to be considered: the image resolution, the bit depth, and the output file format. Although these issues are important in the digitization process, little attention was paid to them. These issues will be discussed further in Section III.

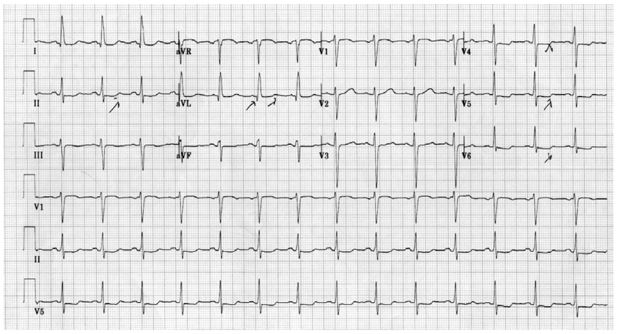

Figure 2. ECG image shows 12 lead printout for a heart patient along with 3 continuous recordings.

In the second stage, a portion of the image is selected such that it only includes the recording of one lead. Then, the corresponding ECG waveform is extracted as a digital data in terms of its pixels locations accompanied with some unwanted data. This raises the need for a filter to eliminate the unwanted data. In the next stage, the data must be converted from pixels coordinates to time and voltage levels using pixel scaling technique. Finally the digitized ECG waveform is obtained and saved in a data file.

In [3] [4], The extraction of the ECG waveform was done by using image thresholding. The ECG paper is scanned as gray image. Then, a gray scale level was selected as threshold to distinguish between the trace of interest and the surrounding noise such as the gridlines. The implementation of image thresholding results in the ECG waveform to be black and the surrounding medium to be white. Hence the ECG can be extracted easily from the thresholded image. Paterni *et. al.* [5] suggests using the first order absolute moment as a mathematical operator to highlight the ECG trace. This method is more complex and require more computer computational time.

The pixel scaling technique depends on the relationship between pixels and actual time-voltage values which is given in all ECG printouts, that is, 10 mm/mV and 25.0 mm/sec. Therefore, identifying the pixel equivalent of 10mm/mV and 25.0 mm/sec provides the relationship between pixels and time-voltage values. Morales et al.[2] determine the pixel scale manually, whereas, Badilini et al. [4] uses the scanner resolution to determine the pixel scale.

Few problems associated with this process were not fully addressed. First, the sampling rate of the produced digitized data might not be adequate and some of the important information might be lost from the ECG signal. A sampling rate less than 300 Hz might not be sufficient since the bandwidth of typical ECG signals is in the range of 0.05- 150 Hz and it might even be higher in some pathological cases [6]. For the second problems, the ECG trace might have more than one voltage-pixel for a particular time-pixel. Therefore, there is a need to reduce the effect of these two problems. This study will develop software procedures which are needed to convert past ECG signals from graph papers into digital form with the best possible accuracy. The next Section will discuss the methodology followed in this research.

III. METHODOLOGY

The methodology followed in this study is similar to what has been described in Section II, however, some modifications are introduced in the scanning procedures, and in the extraction and digitization of the ECG waveform. These modifications are explained in the next subsections. All the digitization procedures will be implemented using MATLAB software.

A. Scanning Procedure

Scanning is one of the important stage during the digitization process. Three main issues have to considered image resolution, bit depth, and output file format. The image resolution depends on the number of pixels, or picture elements, which are the building blocks of all digital images. The pixel per inch (PPI) is used to describe image resolution [7]. For example, a 4" x 6" photograph digitized at 300 PPI would result in a 1200 x 1800 pixel image. Higher PPI settings will result in images which are able to contain more details per inch while increasing the file size of the resultant image. Larger file size results in higher computational capabilities when the image is processed. Concerning the ECG images, the selected image resolution specifies the number of pixels/mm since 1 inch=25.4 mm

$$Number\ of\ pixels / mm = \frac{PPI}{25.4} \qquad (1)$$

Thus the relationship between pixels and time-voltage values can be determined from the PPI. For example, a 300 PPI corresponds to 11.81 pixels/mm. This means that one pixel corresponds to 3.387ms for time scale and to 8.47 μV for voltage scale. Thus, the sampling rate is close to 295 Hz. It is therefore crucial to investigate the effect of converting ECG paper into digital form for various PPI values and select the appropriate image resolution that best fit this application.

The second factor that must be considered is the bit depth which is the number of bits used to describe the color of each pixel. Greater bit depth allows a greater range of colors or shades of gray to be represented by a pixel. Using multiple bits increases choice and variety, at the expense of increased file size. Grayscale 8-bit images are most useful for the conversion of ECG paper since the main aim is to extract the dark colored ECG waveform and exclude the rest of the details.

File format is the third factor that needs to be considered before scanning. File formats encode information into a form which is intended for processing and used by specific combinations of hardware and software [7]. Fortunately, the current technology trends of interoperability and compatibility have led to many file formats being supported on a variety of hardware and software platforms. In this study, images are processed using MATLAB software which can support many file formats such as Windows Bitmap (BMP), Joint Photographic Experts Group (JPEG), Tagged Image File Format (TIFF), Graphics Interchange Format (GIF), Windows Paintbrush (PCX) *et al.* [8].

The scanner used in this study is Epson of type Perfection 2480 Photo. Its associated software can support BMP, JPEG and TIFF file format. It has a wide range of PPI values from 100 to 4800 and the grayscale 8-bit is available. Images have been generated for an ECG paper using the three formats with the same PPI and bit dept. It is observed that the quality of the BMP and TIFF files are superior to JPEG, however their file size are larger. This is expected since the JPEG employed here uses lossy compression whereas the others use lossless compression. Since the aim of this study is to produce ECG waveform in data files and discards the generated images, the BMP format is selected to guarantee better distinction between the ECG waveforms and the grid lines. The TIFF file format associated with the scanner is not favored because it uses LZW-compression which is not supported by MATLAB.

Figure 3. Lead II ECG image for a heart patient

B. Extraction of the EGC waveform

In this paper, the ECG waveform is obtained by using image thresholding technique which is explained in Section II. Figure 3 shows a lead II ECG image with its referencing pulse. For the threshold value, an appropriate gray scale level was selected. The application of the image thresholding technique on Figure 3 produces a black and white image where the ECG waveform is black and the rest is white as shown in Figure 4. The ECG waveform is characterized by black pixels which are specified by their horizontal and vertical positions. In some cases, it is possible to see few unwanted black dots appearing at random locations in the image. These dots produce outliers that need to be removed.

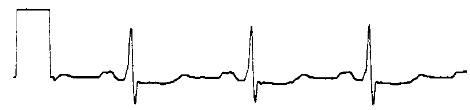

Figure 4. Thresholded image of Figure 3.

The ECG waveform can be extracted from the thresholded image by transforming its coordinates from image form to Cartesian. The new coordinates (x, y) of the extracted ECG waveform are expressed in terms of the corresponding pixel locations of the waveform as shown in Figure 5.

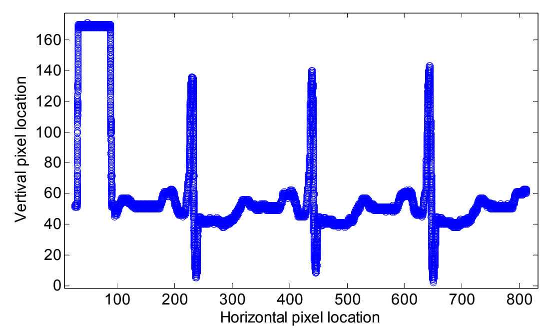

Figure 5. ECG waveform in terms of its horizontal and vertical locations of its pixel

In order to convert the extracted data into its final form in terms of time and voltage levels, there is a need to solve some of the problems associated with the extraction of the ECG waveform. To illustrate these problems, Figure 6 shows a zoomed portion of the QRS wave of Figure 5. It is observed that at any single time in the x-axis, corresponds many voltage levels in the y-axis. This problem is unavoidable since the ECG curve is represented by a number of pixels at any particular time. The number of pixels increases as the PPI increases. This problem can be solved by selecting a single value by using either median or average operator. The second problem is present if there is a sharp increase or decrease as demonstrated in the QRS wave of Figure 6. This is due to the inherent quantization errors that occur during the conversion of a continuous image, the ECG curve in this case, into digital image. This can be reduced by increasing the image resolution during scanning. Finally, the problems of outliers can be resolved by using neighborhood and median approach.

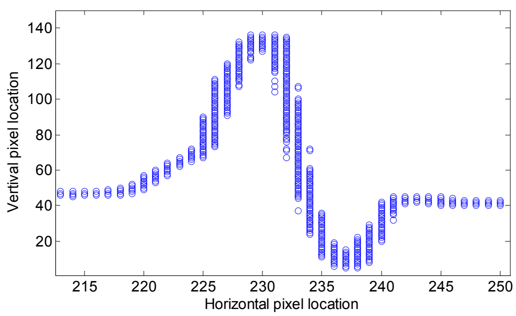

Figure 6. Portion of the QRS wave from Figure 5.

C. *Digitization of the ECG Waveform*

The transformation of the extracted data into its final digital form in terms of time and voltage levels is done in three steps. First, the referencing pulse is used to locate the zero voltage level. Second, at any single value in the x-axis and after the referencing pulse, the median of the corresponding y-axis is considered. The median is preferred over the mean operator since it avoids the effect of isolated outliers. The remaining unwanted data are removed by using the neighborhood approach. The resulted data from this stage represent the refined x-y coordinates of the ECG waveform in terms of its horizontal and vertical pixel location. Finally, the pixel scale is computed from the image resolution PPI which is obtained from the scanning stage as explained earlier. The pixel scale along with the zero voltage level is applied on the data obtained from step 2 to produce the discrete times and corresponding voltage levels of the ECG waveform.

D. *Determining the minimum required PPI*

Higher image resolution during scanning produces a better accurate ECG data but with undesirable higher computational load. Since the analysis of ECG data does not require exact reconstruction, it is therefore sufficient to find the minimum PPI so that the extracted ECG data retain all the important features of the ECG signal. This can be achieved by comparing the accuracy of ECG parameters obtained from the extracted data for various PPI. The minimum acceptable PPI will be selected.

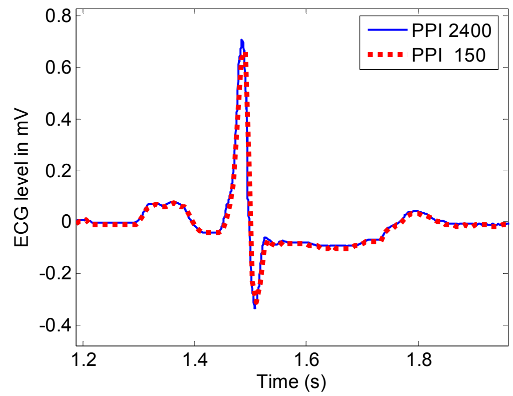

Figure 7. ECG data extracted from Fig. 2 using PPI values of 150 and 2400.

IV. RESULTS AND DISCUSSIONS

The developed software was tested on the second lead (II) of 12 ECG papers. Two traces are normal and the rest are obtained from patients with different types of heart disease. For each trace, the extracted ECG data were obtained for 7 cases, where the image resolution during scanning ranges from 150 PPI to 2400 PPI. Figure 7 shows an example of the extracted ECG data using 150 PPI and 2400 PPI. In this case, the ECG curves are very close most of the time except at sharp edges such as the peak values of the QRS wave. The same observation is true for all the extracted data from the ECG papers with 150 PPI and 2400 PPI. As the value of the image resolution increases, the difference in sharp edges becomes smaller and the accuracy of the ECG data gets better. This is expected because higher PPI value produces data with higher sampling rate, and hence less quantization errors during the digitization process. Therefore, it is anticipated that the extracted ECG data with 2400 PPI will have the best accuracy among the seven cases of PPI values. To verify this assumption, some measurable features are obtained from the digitized data and from the ECG paper and a comparison is made between their values. The ECG paper provides the recorded values of the heart rate, PR interval, QRS duration and QT interval. The same features are measured from the digitized data with 2400 PPI. The comparison is made by computing the percentage of relative error between the recorded and measured values of these features using 5 ECG traces of type lead II. The result is given in Table 1 which shows that the relative errors are very low and it is within an acceptable range in all 5 cases. This certainly confirms the good accuracy of the extracted ECG data when the image resolution is 2400 PPI.

TABLE 1. RELATIVE ERRORS (IN %) OBTAINED FROM 5 ECG TRACES.

	Heart Rate	**PR Interval**	**QRS Duration**	**QT Interval**
ECG 1	0.56	0.66	0	0.25
ECG 2	2.39	2.14	0	1.89
ECG 3	0.89	0.7	2.5	1.10
ECG 4	1.39	0	2	0
ECG 5	2.11	0	1.06	0.93

As mentioned in Section III, higher value of PPI results in higher computational cost and there is need to find the minimum acceptable PPI. For this reason, the root mean square (RMS) error between the digitized signal and the best estimated ECG data is computed from the following equation [2]

$$RMS = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left|v_e - v_d\right|^2} \qquad (2)$$

where v_e is the best estimated ECG level and v_d is the digitized signal. Figure 8 shows the results of the RMS error calculation for the 12 ECG papers using PPI values of 150, 300, 400 and 600. It can be seen that the RMS error generally decreases as the PPI value increases; however, the error is quite comparable if the PPI value ranges between 400 and 600. Therefore, the image resolution during scanning should have a PPI value in that range. In addition, in all cases, the worst RMS error reaches 3% for the selected PPI range which is much below the 12% value found by Morales *et al.*[2] for ECG lead II. This indicates the improvement made to the digitization process.

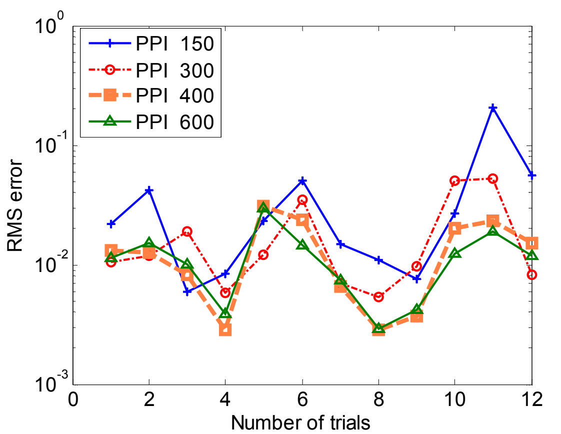

Figure 8. Comparison between the RMS errors obtained from 12 ECG papers (lead II) using PPI values of 150, 300, 400 and 600.

V. CONCLUSION

The conversion of ECG papers into digital form is very important since it can be easily stored, accessed, exchanged or analyzed. This paper proposes some improvements to the existing digitization process by selecting appropriate image resolution during scanning and using neighborhood and median approach during the extraction and digitization of the ECG waveform. In addition, the relationship between pixels and time-voltage values is automatically determined. The study also focuses on determining the minimum PPI value to reduce the computational load required by the digitization process. Results show that the extracted digital data preserve the essential features of the ECG waveform.

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