Digitizing ECG Signal using 2D Signal Convolution Approach

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Abstracts: ECG signal printed on a graph paper has been widely used by medical examiners to analyze diseases related to the heart. Medical practitioners rely on historical records to perform diagnosis. Constantly accessing the ECG printed graph paper manually could be time consuming as there are bulk of graph papers for examination. The proposed work aims to convert the printed ECG graph paper into digitized ECG for remote diagnosis. The ECG printed graph paper undergoes conversion into ECG artifact before transforming as digitized ECG. In the initial phase, patient information in the ECG artifact is preserved by encoding into a QR Code. In phase two, preliminary processing is done on ECG artifact for removal of gridline in the background. Image convolution method is proposed as the process for background gridline removal. Then, morphological image processing is implemented to enhance the ECG artifact. In phase three, segmentation process takes place, in which the ECG artifact is divided into segments for separating the waveforms. In the final phase of ECG digitization, the location of the signal is traced for reshaping the ECG artifact as digitized ECG. The accuracy of the ECG digitization is measured through the heart rate that is calculated using our approach and compared with the one on ECG printed graph paper. The average sum of squared error of the heart rate between the ECG printed graph paper and digitized ECG is 0.005618. The digitized ECG can be useful for medical examiners and practitioners in telemedicine where remote diagnosis may be needed.

Keywords: Digitization, Image Convolution, Telemedicine, Medical, Graph Paper.

1. INTRODUCTION

In the era of post pandemic, it can be seen that there is an increase adoption in the use of digital technology in many aspects of our lives. Telemedicine for example is a communication technology that has a potential to be used for remote diagnosis particularly where rural areas are concerned. ECG diagnosis traditionally has been done on printed papers. Nowadays, although digital equipment is readily available, it may not be cost effective for purchase and placement in rural areas as specialists themselves are located only at the city hospitals. Moreover, when assessing historical records of patients, the printed ECG papers may have to be retrieved from physical storage before evaluation is done by the specialists. Having a digital version of ECG printed paper may improve efficiency in remote diagnosis such as in telemedicine with the advantage of reduction in physical storage.

The printed ECG paper has graphs that display recordings of heart electrical activities. The electrical activities are obtained by placing electrodes on the patient's body. These electrodes are placed on 12 parts on the human body and they recorded the activities of depolarization and repolarization of the heartbeat. By referring to these recorded graphs, medical specialists may identify patients' heart complications. They compare new and previous records of ECG graphs, which may be on a printed paper where it maybe a plausible situation in rural areas clinics. In the current research by [Ganesh et. al, 2021], patients' personal information is abandoned for personal data protection during segmentation process of ECG digitization. Thus, this may lead to possible loss and mismatch of information during data transport and storage due to the bulk of physical copies being digitized.

In this proposed method for ECG digitization, the patient information in the digitized printed ECG graph paper, which we call as an ECG artifact is firstly encoded into a QR Code for data preservation and artifact tagging. Then the ECG artifact will go through image processing methods using our proposed method of pixel convolution. This method is selected as it can be used to remove the background gridline during preliminary processing. Next, morphological image processing technique is proposed as a mechanism to enhanced the quality of the ECG artifact. To evaluate the accuracy of the ECG digitization process, we compare the heart rate value on the ECG printed graph paper to the heart rate value retrieved from the final digitized version.

2. RELATED WORKS

There were already several research done on ECG digitization. In [Patil & Karandikar, 2015] for example, vertical scanning was done after horizontal scanning takes place. The purpose of the vertical scanning is to identify the other pixel components that had not been identified during horizontal scanning. The vertical scanning method took place after a threshold was applied on the ECG artifact. Although the result looks encouraging but the work added complexity to the overall process due to double scanning.

On image processing work, the ECG digitization was implemented using median operator in the work by [Chebil et. al, 2008]. Median operator was used to select pixels in the ECG artifact, which also helped in reducing complexity in the signal retrieval of ECG artifact. The combination of neighborhood and median filters were used to enhanced the image quality. It was reported, the worst RMS error reaches 3% for the selected PPI range in the proposed work.

Similar to [Chebil et. al, 2008], [Ganesh et. al, 2021] also used median filter and thresholding to convert printed ECG paper records to digitized ECG. As with our proposed work, optical character recognition (OCR) was used to preserve text on the printed ECG paper records. However, their work did not encode the OCR as a QR code. The kappa statistic was found to be having average values of 0.86 and 0.72 for intra- and inter-observer correlations, respectively.

In [Sun et. al, 2019], the Sobel operator, Canny operator and LoG operator were used to measure the edges of the ECG artifact signal. The LoG operator showed positive results during digitization process of ECG. The edge detection using the LoG operator method was able to clearly identified the edges of the ECG curves. The proposed algorithm was tested on 129 actual ECG recordings of patients. The results revealed that the extracted signals retained essential features of paper ECG recordings.

In [Cabanillas et. al, 2022], the Gaussian filter and threshold parameters were set to improve the ECG image quality after conversion to grayscale. In the segmentation process, an algorithm that scanned previous lines till end of current line of the ECG signal graph was said to have helped in identifying the pattern of signal in the ECG artifact. The accuracy of the work was recorded at 95%, where it was based on the R peaks.

Similarly, in [Fathail & Bhagile, 2022] R peaks were identified and additionally the heartbeat was calculated using FFT after digitization of ECG. The results of these were sent to the medical practitioners using SMS for further analysis. However, no evaluation results were presented in the paper.

Unlike the rests, the work of [Fortune et. al, 2022] implemented a dynamic algorithm based on the Viterbi coding to get the signal waveform from ECG printed graph paper for digitization. The algorithm emphasized on getting the nearest location of the middle nodes that were set via the parameters. The sample-per-sample comparison of digitally recorded and digitized signals showed a very high correlation of 0.977 and precision 96.8%.

3. METHODOLOGY

This section explains our proposed approach on the process of converting printed ECG graph paper to digitized ECG as shown in Fig.1. A total of four phases are proposed in the ECG digitization process. These are the phases of (1) preservation patient information using QR Code, (2) preliminary processing on the ECG artifact, (3) segmentation of ECG artifact and (4) digitization of ECG. Before phase (1) takes place, the ECG printed graph paper has to be acquired as digital images. We acquired the dataset from this source [Khan & Hussain, 2020].

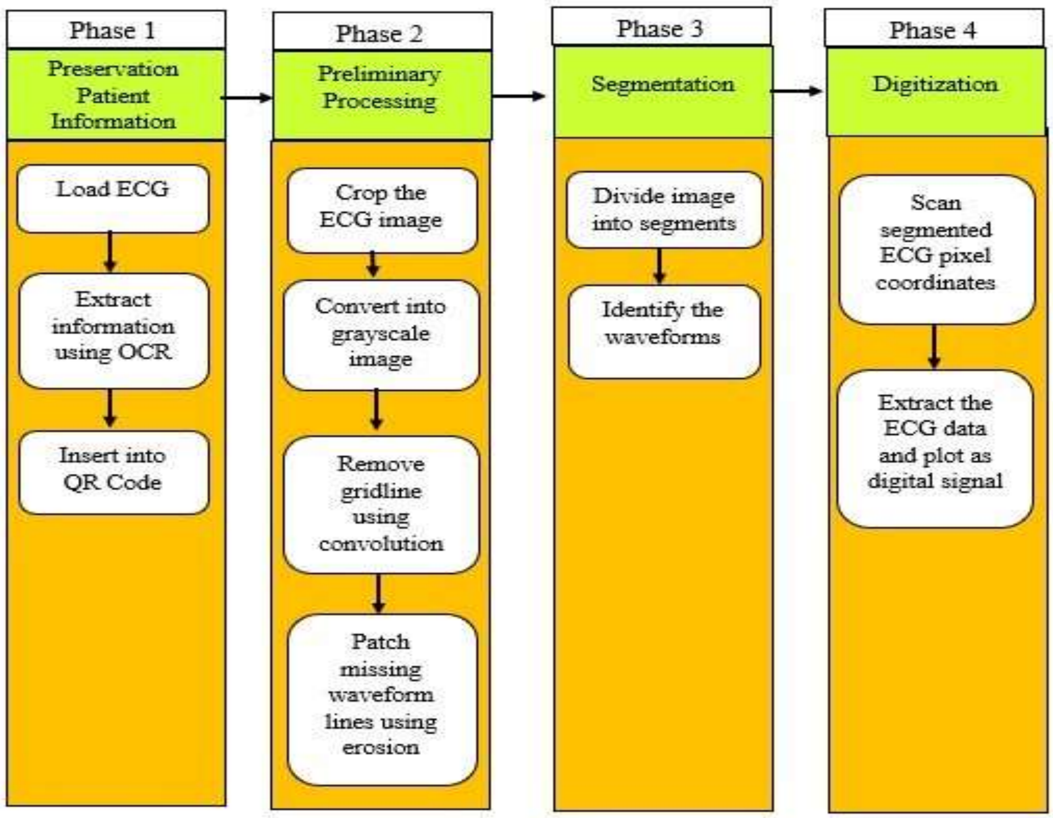

Fig. 1: The flowchart of our proposed work on ECG digitization that elaborates the process flow of each phase.

3.1. Phase 1: Preservation of Patient Information

In phase 1, patient information is kept by retrieving all the text from the ECG artifact. We make use of the Optical Character Recognition (OCR) to extract all the text from the ECG artifact. All the extracted text is then encoded into a QR Code. This QR Code will later be attached together with the digitized ECG at the end of Phase 4. Fig. 2 shows a medical image sample that contains a dataset of patients that have a normal heart beat. The ECG artifact is a JPEG format and has 200dpi. The extracted text on ECG medical image is encoded in the QR Code.

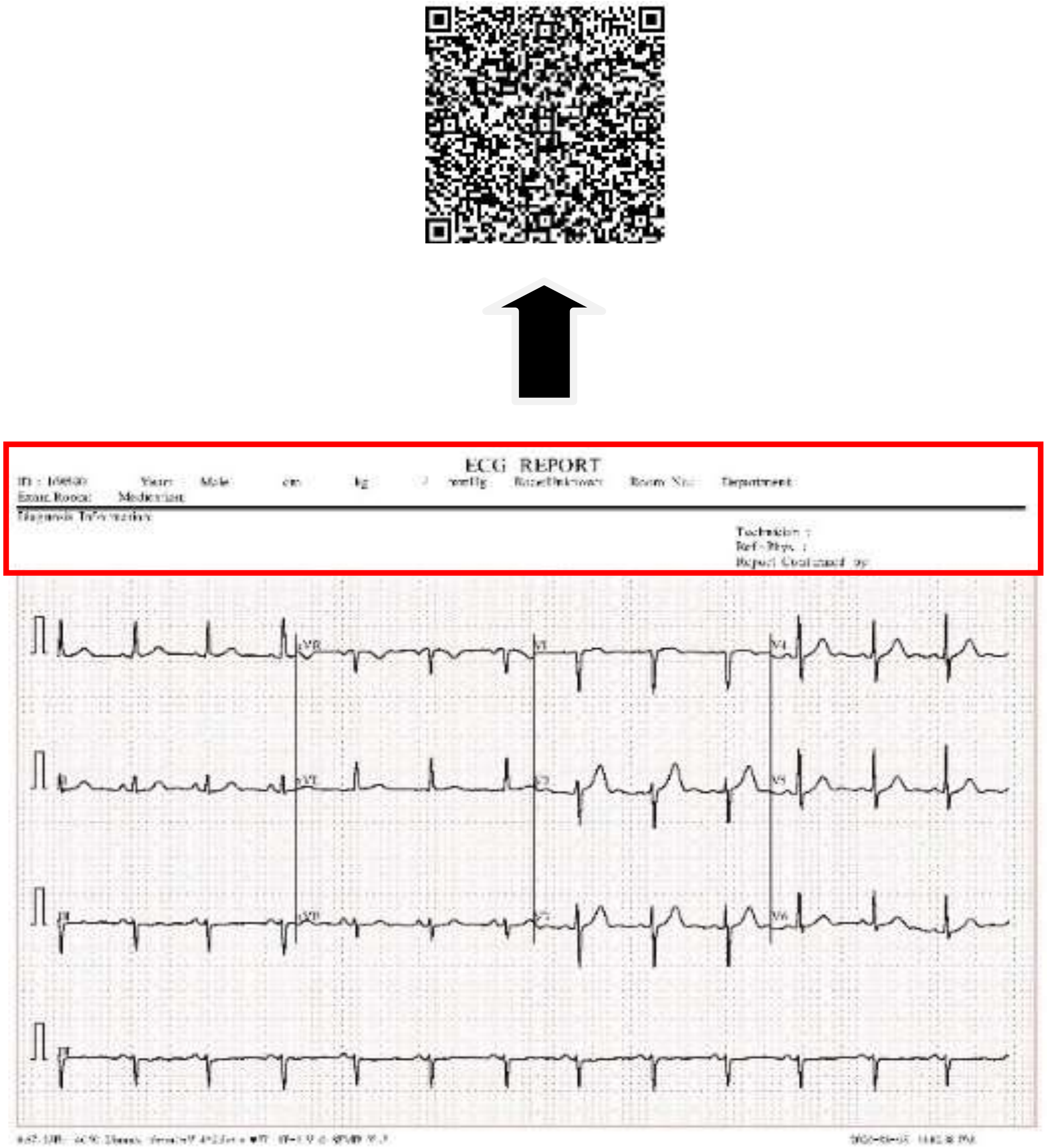

Fig. 2: ECG artifact information (text only) is transferred to a QR Code.

3.2. Phase 2: Preliminary Processing

In phase 2, preliminary processing of the ECG artifact takes place where it is cropped in such a way that the unwanted components are removed to simplify the ensuing image processing phase. The cropping is done at the top area of the ECG artifact, which contains texts such as “patient ID, Years, Exam Room number, height, weight, race, medication details, department involved diagnosis information, technician, physicians and confirmation report in charge”. Similarly, the bottom area of the ECG artifact, which consists of texts such as “frequency range, AC50 25mm/s, 10.0mm/mV, 4*2.5s, heart rate and versions” are removed during the cropping process. This process also allows for reduction in image size for the next processing.

Then, the cropped ECG artifact is converted into grayscale. This is so that we are able to get the shades of black pixels to form a binary ECG artifact. The black pixels hold the pattern of signal in the ECG artifact. Problems may arise when the background gridline is also visible as the gridline overlaps with the signal pattern.

In this research, we proposed the use of convolution method to overcome the issue of overlap between the background image and the object of the image itself. Convolution helps to remove the background gridline in the ECG artefact. However, some of the overlapped pixels of the signal waves are "erased" together when convolution is applied, which we called as an imperfect ECG artifact. Therefore, we propose to perform an image enhancement process to patch the missing components of the signal wave in the imperfect ECG artifact. This phase ends with a complete signal wave, which is an ECG artifact that is no longer imperfect.

Equation 1 shows the two-dimensional convolution formula, where Q represents the kernel and the size of image is represented as $P(i \times j)$.

$$O(a, b) = \Sigma i \Sigma j \, P(a + i, b + j) \cdot Q(i, j). \quad (1)$$

We proposed to enhance the image by implementing morphological processing method to improve the imperfect ECG artifact. One of the techniques of morphological image processing, erosion is used to remove the unnecessary white pixels surrounding the structure of the medical image. This helps in retrieval of the structure of the ECG signal wave in the medical image. Equation 2 defines the erosion of A by B which is the set of all points in z such that Bz is included in A.

$$A \Theta B = \{z \mid Bz \subseteq \mathrm{A}\} \text{ where all } z \text{ in } A \text{ such that } B \text{ is in } A \text{ when origin of } B = z. \quad (2)$$

3.3. Phase 3: Segmentation

In Phase 3, the ECG artifact is segmented into individual wave images as shown in Fig.3. We make use of a heuristic algorithm to divide into several horizontal segments. Having individual wave files allow for faster digital scanning for the final digitized ECG artifact.

3.4. Phase 4: Digitization

In Phase 4, scanning process takes place from left to right of the individual wave image. Scanning stops at the end of each segmented parts of individual wave. During scanning process, the black pixels locations are tracked and their positions are stored. The stored pixel coordinates can be restored as digitized ECG image together with its QR code.

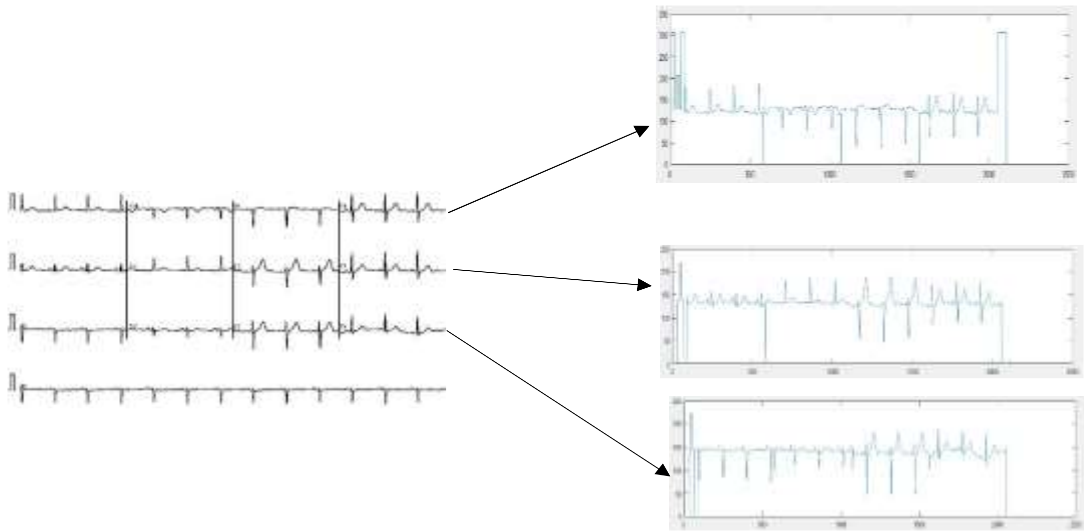

Fig. 3: Segmentation of ECG artifact into individual wave images.

4. Performance Evaluation and Results

The proposed methods were tested on 40 printed ECG graph papers. The results are shown in Fig. 4 – Fig. 7. Fig. 4 shows the Phase 2 implementation where the image is cropped so that convolution technique can take place. In Fig. 5, the result shows the image where gridlines are already removed using our proposed convolution technique and Fig. 6 shows the results of image enhancement using morphological image processing. Fig. 7 shows the final result of the digitized printed ECG paper (i.e. digitized ECG).

Visual inspection results as shown in Fig. 7 indicate that the digitized version of the ECG waveforms using our proposed method are closely similar to the one on the printed ECG graph paper. Quantitatively we made use of the heart beat rate measurement to verify our results. We manually retrieved and recorded the heart beat rate from the printed ECG graph paper and compared with the heart beat rate calculations from the digitized ECG. We measured the values of relative error, which is the ratio between the difference of the results to the total error function as given in Eq.3 as mentioned in [Ma et. al, 2020]. The results for five samples are shown in Table 1.

$$e_{rel} = e_{abs} \,/\, |x| \tag{3}$$

Table 1. Relative Error between Printed and Digitized ECG Heart Beat Rate

Patient ID	Heart Beat Count		Relative Error
	Digitized	Printed Paper	
177388	88.974	89	0.00028764
168610	52.024	52	0.00046154
168605	111.936	112	0.00057589
168513	152.193	152	0.00126974
177443	103.769	107	0.03019439

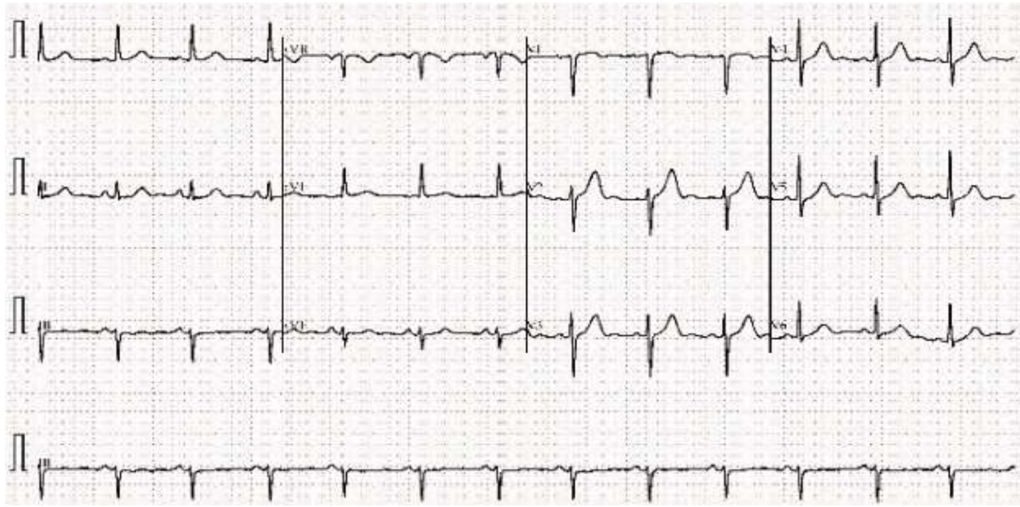

Fig. 4: An example of a cropped image after OCR encoding into QR code.

Fig. 5: The results of removal of gridlines after implementation of image convolution.

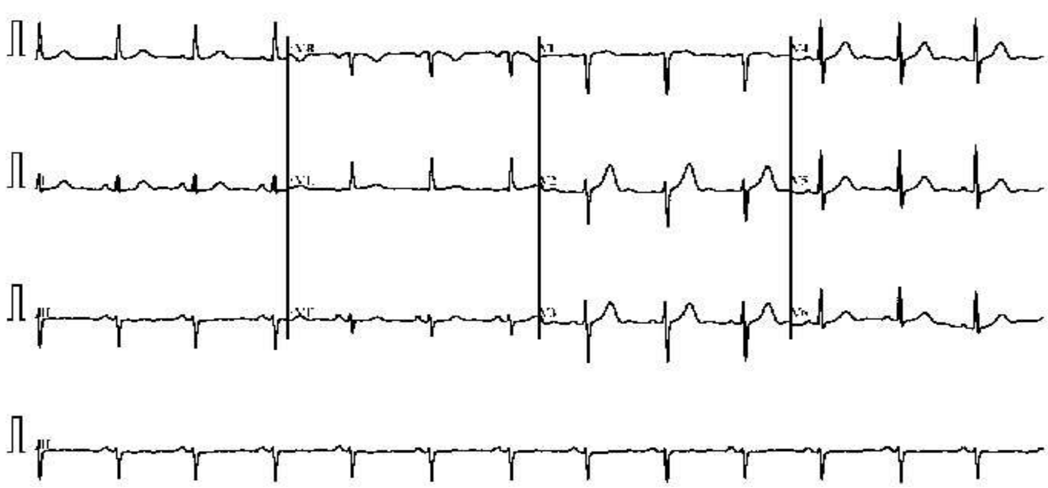

Fig. 6: The results of image enhancement of an imperfect ECG artifact.

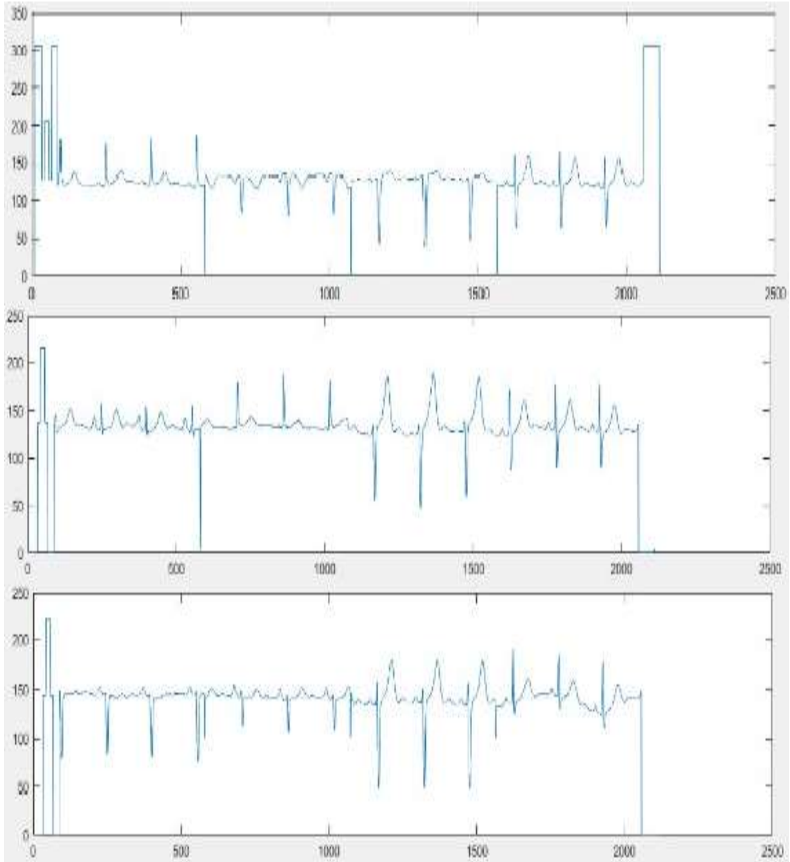

Fig. 7: An example of three individual waves as the final results of ECG digitization

The relative error represents the difference between the digitized heartbeat count and manual heartbeat count of the printed ECG graph paper. The lower the relative error value, the better the performance of the digitization of ECG. The average value of the relative error for 40 samples is 0.005618327 with the lowest relative error of 0.00028764 for Patient ID: 177388. Via visual inspection, we found that even with application of convolution, the removal of gridline using convolution techniques did not affect much on the waveform pattern. The highest relative error is 0.030194393 for Patient ID: 177443. We found that it may be due to some repetitive high peaks and irregular waveform patterns, which occurred in several waveforms. In such instance, there were significant lost patches of waveforms happened during gridline removal. However, these relative error values are considered low and acceptable and may show validity of our proposed method.

CONCLUSION

Digitization is beneficial for conversion of printed records and it allows for preservation of historical records. We proposed a method that are able to digitized ECG from printed ECG graph paper. The highlight of this research is the use of convolution technique on background gridline removal from the ECG artifact. The digitized ECG can be used for analyzing patient historical diagnosis and may help specialists in current and future diagnosis. The results show that our method has managed to convert printed ECG graph paper into digitized ECG with acceptable low error values. These digitized ECG will be requiring less storage and easier to transmit compared to printed ECG graph paper. In our future work, we shall be seeking validation of the digitized ECG results with the help of medical practitioners.

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