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R-Waves Localization from an Electrocardiogram Scanned Paper

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***Abstract*—**This article presents a technique for converting data of the electrocardiographic (ECG) records papers to digital ECG signals, in order to make easier the analysis by applying automatic methods to detect the characteristic waves. In addition, the files containing the one-dimensional signals are of smaller size comparing to the image ones, this will facilitate the storage of patients' databases and the records transmission, thus cardiologists can make an automatic or a remote diagnostic. A pretreatment of the binary image of the ECG record obtained by thresholding is applied in order to remove the rest of the underlying grid and to digitize the signal at the end by determining the pixel scale. In the second step, we detect the R waves of the signal and compare the results with their localizations in the original file.

The results of both files conversion technique and R-waves detection method were very satisfactory. Where the characteristic ECG waves were preserved and detected with a very small error.

***Keywords*—**digitization, image file, waves detection.

I. INTRODUCTION

THE electrocardiogram (ECG) signal measures the action potentials generated from the heart during cardiac cycles. Clinicians have used this close relationship between ECG and cardiac action to monitor the heart's health. Any distortion in the transmission of impulses through the heart can result in abnormal electrical currents, which then appear as altered and, or distorted ECG waveforms. This phenomenon was used successfully by cardiologists to diagnose most cardiovascular problems [1].

Three principal waves characterizing ECG recordings; the P wave, the QRS complex, and the T wave (Fig.1):

1) The P wave is the first deflection recorded which is small, smooth, and precedes the QRS complex.
2) The QRS complex represents the spread of electrical activation through the ventricular myocardium; the resultant electrical forces generated from ventricular depolarization are recorded on the ECG as a spiky deflection. The sharp, pointed deflections are labeled QRS regardless of whether they are positive or negative.
3) The T wave represents electrical recovery and repolarization of the ventricles, and is a broad, rounded wave. It follows each QRS complex and is separated from the QRS by a constant interval for normal ECG [3].

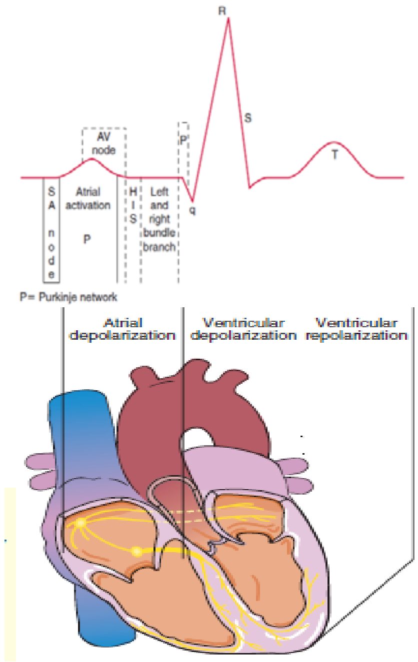

Fig. 1 Relationship between P wave, PR interval, and QRS complex and heart depolarization and repolarization (adapted from [2])

As there is a need for large storage space (each patient can have a number of ECG records to be stored); in recent years some researchers have turned to scan the paper version of the ECG recordings in order to make easy the automatic manipulations made on the signal, as [4] which uses a method for digitization and synchronization of ECG signals for use in vectorcardiography. There is another study using digitization of scanned papers in order to analyze and archive data in clinical databases [5]. But the problem is that results are not too identical to the original record. In our method, when converting image, we combine the mean and the median values to improve the results that will be used at the end in detecting R waves of ECG signal by a method based on dyadic and discrete wavelets.

These results will be compared with the paper version to check the performance of the conversion and the detection.

II. ECG PAPER DIGITIZATION

The ECG is, then, a representation of the electrical activity in the heart over time which can usually be print onto papers

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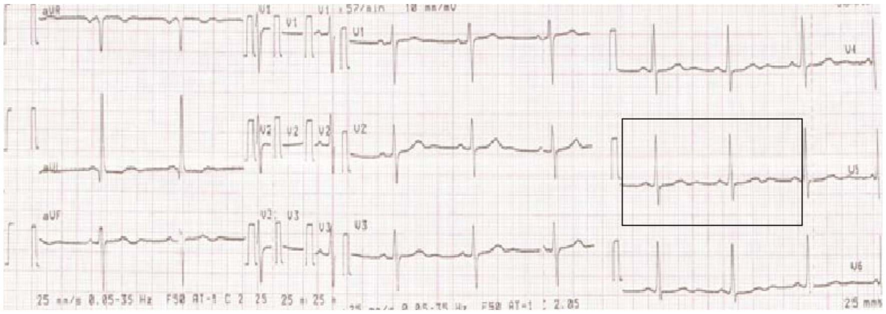

Fig. 2 A 12-lead electrocardiogram record (V1, V2, V3, V4,V5, V6, aVR, aVF and aVL) of a 61 years woman

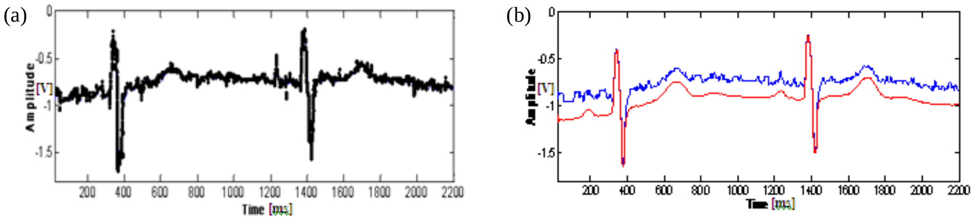

Fig. 3 (a) Filtered image and (b) ECG signal by applying mean values in red and by applying median values in blue

that have a background grid of 1 millimeter squares in vertical and horizontal directions. Almost of ECG devices represent each millivolt on the vertical axis as one centimeter and each second as 25 millimeter on the horizontal one.

A 12-lead electrocardiogram contains short segments of the leads recording (one to three heart beats). This is often arranged in a grid of four columns by three rows, the first column being the limb leads (I,II, and III), the second column the augmented limb leads (aVR, aVL, and aVF), and the last two columns being the chest leads (V1-V6) (Fig. 2).

First, the ECG paper is converted by means of a scanner to a digital image. This image consists essentially of the ECG trace and horizontal and vertical grid lines. In our procedure we used an HP 4300 CERUS scanner which gives a grayscale 8-bits image, so we will not need to convert color image of the original paper version, since the main aim is to extract the dark colored ECG waveform and exclude the rest of the details (background grid and different noises). Then, the corresponding ECG waveform is extracted as a digital data in terms of its pixels locations with some unwanted data. This raises the need for a filter to eliminate the undesirable data.

The pixel per inch (PPI) is used to describe image resolution; an image with high resolution is an image where we can perceive more details. The HP 4300 CERUS scans papers at 300 PPI and its associated software stores images in JPEG file format, which uses a lossy compression but gives a much smaller size than other image format, this will help to store more patient records. As the ECG recording is performed on a graph paper, we have to convert values in order to have a measure of pixels per millimeter (PPM) (one inch is equal to 25.4 millimeters):

$$PPM = PPI/25.4 \tag{1}$$

It is therefore essential to study the effect of converting ECG paper digitally. Where a pixel corresponds for time scale to 3.387 ms and 8.47 mV for voltage scale.

III. EXTRACTION OF ECG WAVEFORM

In the ECG waveform extraction stage data must be converted from pixels coordinates to time and voltage levels, we apply a thresholding in order to distinguish between the trace of interest and the surrounding noise such as the gridlines of the scanned gray image. The image thresholding results in the ECG waveform to be black and the surrounding medium to be white; in our procedure we use threshold level equal to 73 from a maximum grayscale of 256. Hence the ECG can be extracted easily from the thresholded image. As a result, we obtain a black and white image; the ECG waveform is characterized by black pixels which are specified by their horizontal and vertical positions (time and voltage, respectively). We can see few unwanted black dots appearing at random locations of the image. These dots produce outliers that need to be removed. A filter stage is used to remove all the outliers (cascading of 3x3 convolution filters). But, It is also, observed that at any single time (x axis), corresponds many voltage levels (y axis) (in the same vertical line, we have several dots or intensities (x,y), (x,y+1), (x,y+2), etc.).

Here, we apply the first order moment combined with the median as mathematical operators to highlight the ECG trace and eliminate the other points (Fig. 3):

$$ECG(x) = \alpha.mean((x,y),(x,y+1),\dots,(x,y+N_x)) + \beta.median\big((x,y),(x,y+1),\dots,(x,y+N_x)\big) \tag{2}$$

Where: α and β are weight coefficients and: $\alpha + \beta = 1$. The two coefficients α and β are chosen empirically to eliminate or reduce the incorrect values of the signal resulting from the mean and the median to determine, at the end, the real values of the resulting ECG.

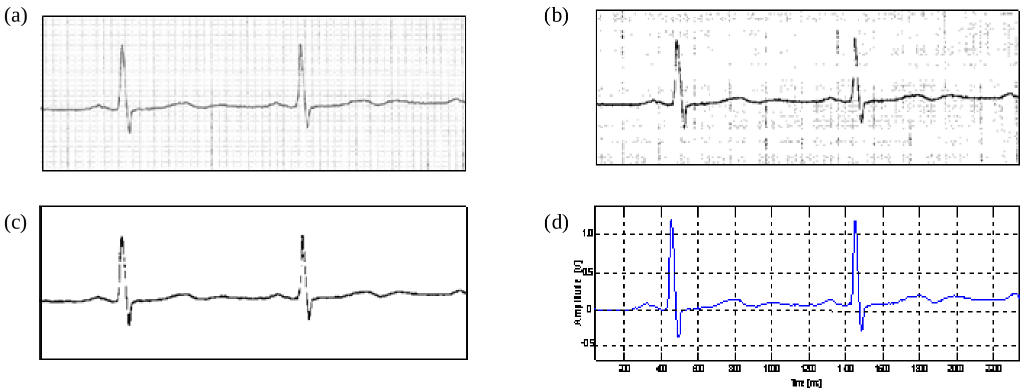

Fig. 4 Digitization results: (a) Scanned image, (b) and (c) are two filtered images in different levels and (d) resulting ECG signal

And: N_x is the number of black dots on the same x.

Figure 4 shows the different steps of our digitization procedure; where the first image is the original gray one scanned and selected to introduce it into the filtering stage which gives as an intermediate result the second image and as a final result the third, the forth signal is the resultant ECG signal which is very similar to the original.

IV. RESULTS OF DIGITIZATION

We have applied our algorithm on a scanned electrocardiogram paper of a patient of 61 years old of a female sex; by using five segments from the 12 recordings, these segments (V1, V2, V4, V5 and V6) contain two beats each. To compare our digitization results with the original graph on the scanned paper, we used a point by point and a manual verification; the applied step of comparison is equal to 1 millimeter (or 0.04 second). From Figure 5 which is the superposition of the original image and the resulting signal of the two segments of recordings V1 and V5, we can show that the two signals are almost identical (the original signal in black and the resulting one in blue). These results are confirmed by the calculation of the root mean square (RMS) error between the digitized signal and the original ECG computed from the following equation [6]:

$$RMS = \sqrt{(1/N)\sum_{i=1}^{N}\left|ECG_{res}(i) - ECG_{scan}(i)\right|^2} \quad (3)$$

Where: ECG_{res} is the resulting signal, ECG_{scan} is the scanned signal and N is the number of samples.

In Table 1 we can show that RMS error values for the five chosen recordings are very acceptable, with a mean value equal to 8.56 %. This error is due to the comparison of the original image with many points in a single instant of time with only one point of the digital signal. This also explains the big difference between the error calculated for both recordings V2 and V4; where the gap is very apparent because of the difference in width of the grid lines in the scanned graph paper (the V4 lines are very broad in comparison with V1) (Fig. 2).

TABLE I
ROOT MEAN SQUARE ERROR OF FIVE RECORDINGS

Record.	V1	V2	V4	V5	V6	RMS error Mean (%)
RMS error (%)	11.61	3.91	14.47	6.69	6.11	8.56

V. R-WAVES DETECTION

In R-waves detection procedure, we calculate the dyadic wavelet transform of the resulting ECG signal ECG_{res}, by choosing the scale 2^3 of this transform:

$$DyWT^{\psi}_{ECG_{res}}(3,k) = 2^{-\frac{3}{2}}\int_{-\infty}^{\infty} ECG_{res}(t)\,\psi(2^{-3}.(t-k))dt \quad (4)$$

The choice of this scale is due to the energy distribution mostly in the QRS interval [7]. We locate the various waves of the ECG signal by calculating the dyadic wavelet transform positive maxima and negative minima. It may be noted that the DyWT of a QRS, has the largest amplitudes in comparison with other ECG characteristic waves. Thus, one R peak is detected between this negative minimum-positive maximum couple by the direction change mark (DCM) which is sensitive to changes in direction and therefore to the presence of peaks; it is obtained using the following procedure [8] (Fig. 6):

Calculate the first approximation coefficients and the first detail coefficients of the discrete wavelet transform in order 1 of the Haar mother wavelet. Then, put all the approximation coefficients to zero. At the end, reconstruct the signal by the inverse discrete wavelet transform using the new approximation coefficients (all zeros) and the detail coefficients and thus we obtain the first level details signal (FLDS). The main property of the FLDS is that the samples are of the same magnitude and alternating signs if the slope of the wave is constant, and there is a change in direction of the latter, and in the change point, two successive samples of the FLDS have the same sign. This change of direction is marked by the DCM.

We have tested our method on the ECG signal resulting from the digitization of the five precedent segments, and obtained very satisfactory results; compared with the position of peaks and their amplitudes on the original paper (Fig. 7). For example, the two R-waves locations given by our detection procedure for recording V2 are equal, respectively, to 343 ms and 1383 ms; and have values very close to the values in the original paper (approximately equal to 340 ms for the first wave and 1372 ms for the second).

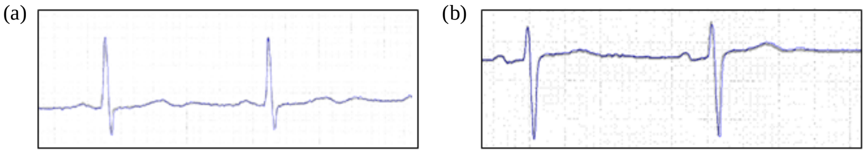

Fig. 5 Superposition of the original image in black and the resulting signal in blue of the two segments of recordings: (a) V1 and (b) V5

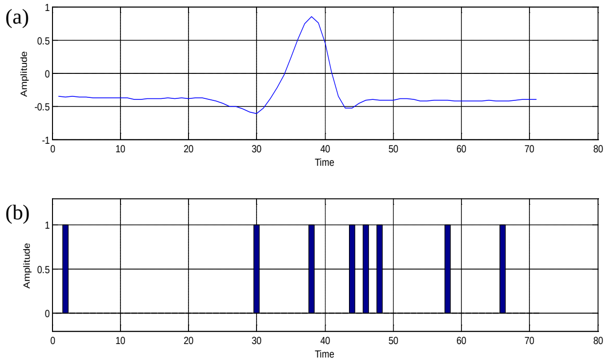

Fig. 6 Direction change mark method (a) ECG signal and (b) DCM equal to zero except at the peaks of the signal

In the same manner, the R amplitudes are equal to 0.65 mV and 0.66 mV, respectively; these two values are close to those of the original signal (approximately equal to 0.74 mV for the first wave and 0.76 mV for the second). Table 2 shows error values in the amplitude, the location and the RR period, for the five segments of the patient ECG.

TABLE II
ERROR IN AMPLITUDES, LOCATIONS AND RR-PERIODS

Recordings	Error in amplitude (mV)	Error in location (ms)	Error in RR (ms)
V1	± 0.08 ± 0.10	± 32 ± 6	± 26
V2	± 0.11 ± 0.10	± 3 ± 11	± 8
V4	± 0.19 ± 0.21	± 4 0	± 4
V5	± 0.17 ± 0.18	± 10 ± 5	± 5
V6	± 0.19 ± 0.20	± 4 ± 8	± 4

We can see from the above table that the error in the waves' locations is very small, confirming the high accuracy of our detection algorithm that produces results varying between 4 and 8 ms. However, the error in the calculation of the R-wave amplitudes is very apparent. This error is due to the thickness of the lines of the recorded signal, which is very apparent in the superposition of the ascending and the descending lines at signal peaks (in our case this error appears in R waves). Figure 7 confirms these notes; where we remark in (7(b)) that the difference between the two amplitudes is very large compared to the amplitude values for each wave. Thus, the accumulated error in the stages that precedes detection (when scanning and digitization) false final results especially for the amplitudes values. But, the principal objectives of our method is the reconstitution of the original recording with great precision and R waves localization with a very small error; and it's done. The waves' amplitudes do not affect the final diagnosis, especially, when the QRS complex shape is unchanged and similar to the original.

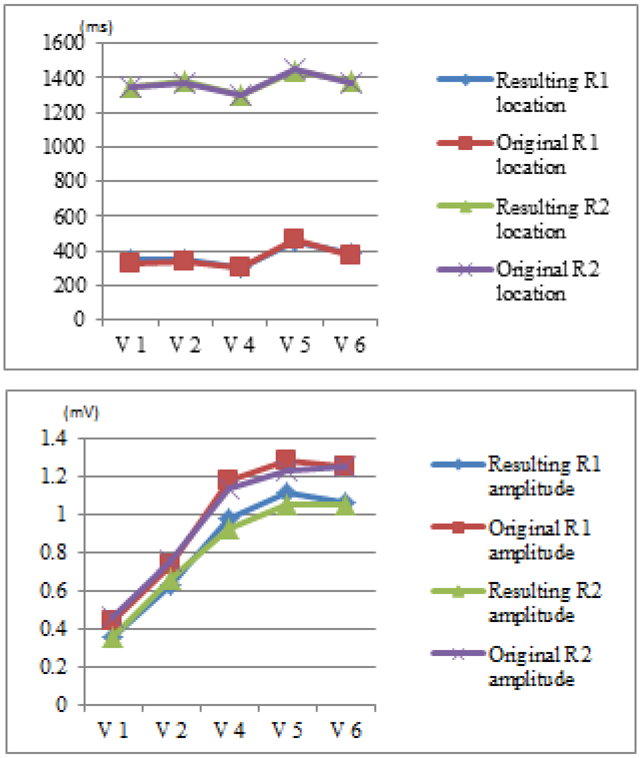

Fig. 7 Comparative curves of the locations values in (a) and amplitudes in (b) of the two R-waves of each recording

VI. CONCLUSION

In the foregoing, has been proposed a method of digitizing ECG paper using a combination between the median and the mean values of filtered black and white images to determine the most appropriate samples of the signal. At the end R-waves was detected by calculating amplitude and location with very satisfactory values using a detection algorithm based on wavelets.

Converting the digital form of ECG paper is very important because it can be easily stored, accessed, exchanged or analyzed. The results show that our technique of extraction digital data maintain the essential characteristics of the ECG waveform, and the detection method will simplify the automatic diagnosis and this with great precision.

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