Journal of Network and Computer Applications (1996) **19,** 295–307

A microcomputer-based prototype for ECG paper record conversion

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ECG signals (electrocardiogram) are usually recorded onto standard grid papers in hospitals as a routine clinical examination for diagnosis of possible cardiac failure. There is a need to convert the existing ECG paper records into electronic forms for efficient retrieval for clinical uses. This paper presents a system prototype designed to convert ECG paper records into electronic ECG recording forms so that they can be either efficiently retrieved as needed, or analysed by ECG signal processing algorithms, or transmitted through computer networks for clinical purposes. In the current system prototype, the scanned binary images of ECG paper records are analysed by using image processing techniques, such as filtering and thinning procedures. The extracted ECG waveforms are then stored and indexed in ASCII data files. A window based user-friendly interface is also incorporated to provide users with easy access to the system. Experimental results on sample ECG paper records are very encouraging and show promise of efficiency in ECG data storage and retrieval and easy manipulation for clinical uses. This paper also briefly discusses other possible alternative techniques such as frequency domain analysis being investigated in the current system prototyping for ECG paper record conversion.

1. Introduction

The analysis of waveforms representing electrical or mechanical activity in the human body is important in many fields of medical investigation, including electrocardiography (ECG), electromyography (EMG) and electroencephalography (EEF) [1,2]. Historically, these waveforms were actually recorded photographically or via a chart recorder, often onto standard grid papers, and then analysed by a combination of pattern recognition and manual measurements. As a result of advances in digital technology, modern equipment often utilizes computers to record waveforms in a digital format, or onto magnetic tape, which can then be played back and analysed. Non-digital equipment is still, however, in widespread use, particularly for ECG signal recording, and graphical paper records remain by far the most common mode of archiving ECG waveform data in hospitals. There are several circumstances when it would be very useful to retrieve graphical archive data in digital form. These include the analysis of historic or field data originally recorded by grid-paper-writing or photographic methods, the re-analysis of ECG data from clinical trial patients for whom outcome information has subsequently become available, and the comparison of ECG data collected at multiple instances [1, 3,4,5]. Many hospitals archives contain paper records of unique waveform shapes relating to rare conditions that if their digital values can be extracted, will be of great use as references.

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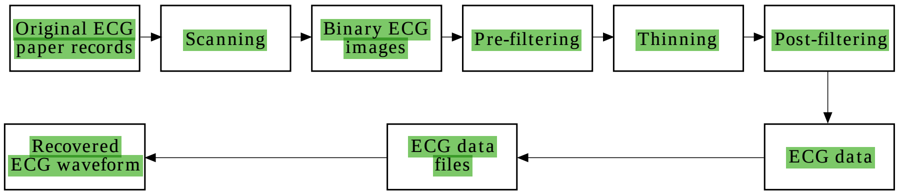


Figure 1. The functional block diagram of the system.

This paper presents a system prototype designed to convert ECG paper records into electronic digital ECG forms with a Window based user-friendly interface. ECG paper records are first scanned using a high resolution flatbed scanner. The two dimensional pixel images that are captured in digital form and stored as compressed image files in the computer. Image processing techniques [6] are then employed to remove the grid-line background and random noises in the image, and fill in any possible gaps in the image which are errors introduced during the process of scanning and digitization. Thinning algorithms are then used to derive skeletons of ECG waveforms in the images. The extracted ECG data are finally stored in ASCII data files with indexes for easy data manipulation. In the following sections, methodological details pertaining to the system prototype, the experimental results and the user interface are described. Finally, other possible techniques being investigated for current system prototyping are also briefly mentioned, which is followed by a conclusion.

2. System development

The functional block diagram of the current system prototype is shown in Fig. 1, in which original ECG paper records are scanned using a high resolution flatbed scanner to produce binary ECG images. A heuristic filtering (pre-filtering) algorithm is applied to remove the grid-line background and random noise, and to fill in possible gaps in ECG images introduced during scanning and digitization. A thinning algorithm [7] is used subsequently to find skeletons of ECG waveforms. Post-filtering algorithm traces the skeletons of ECG waveforms to extract ECG data which are then stored in ASCII data files with necessary indexes so that such waveforms can be restored with the superimposed standard grid-line pattern as needed. Details of these image processing algorithms are explained in the following subsections.

2.1 *Scanning and digitization*

The original ECG paper records are scanned using a flatbed scanner with 100% scaling and at resolution of 300 dpi. The maximum size of scanned ECG images are restricted to 640×480 pixels to fit screen display requirement. Digitization operation is performed during the scanning to obtain binary black-white ECG images. Figure 2 shows an example of scanned ECG image. If the original ECG paper is too long to fit the maximum 640×480 pixel limitation, the system provides users with file linking facility

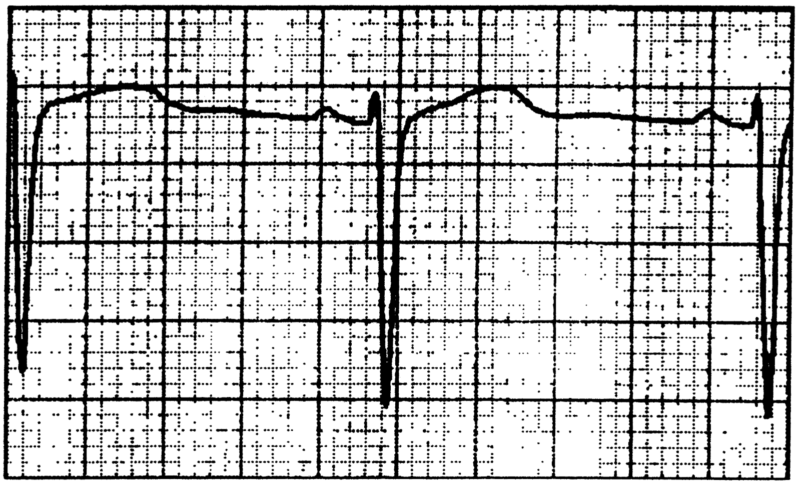


Figure 2. An example of scanned ECG image.

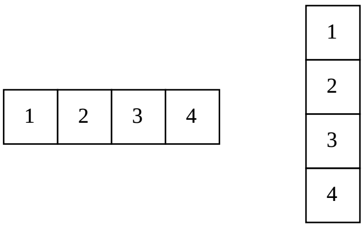


Figure 3. Example masks: 1×4 horizontal and 4×1 vertical masks.

so that the ECG paper can be scanned in parts each time and be processed respectively, and finally be linked with respective ECG data files.

2.2 *Pre-filtering I*

The primary intention of pre-filtering is to remove most of the grid-line background and random noises found in the scanned ECG images, and to fill in possible gaps in ECG waveforms introduced during the scanning process. The algorithms involved are based on heuristic methods with observations that most of the scanned ECG waveforms are thicker in pixels than their corresponding grid-line background. In some cases where part of ECG waveforms may be thinner than grid-lines, the heuristic methods introduced here may still be applied together with some related post-processing such as ECG skeleton linking operation which can be used to deal with broken ECG skeletons.

In the current system, pre-filtering uses the concept of masking. The two masks that are employed are the horizontal mask and the vertical mask. Both of these masks can be of N pixels in length. Figure 3 shows two example masks of 4 pixels in length. The process of pre-filtering is to iteratively apply these two masks over the ECG image to

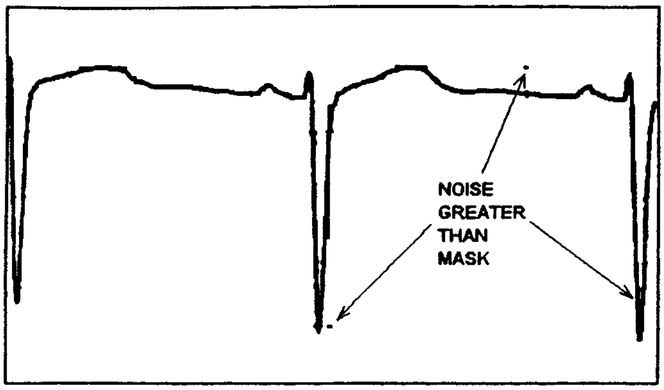


Figure 4. The resultqnt image of pre-filtering on Fig. 2.

remove grid-line background and some random noises. Taking the horizontal mask in Fig. 3 as an example, the mask is applied to the ECG image starting from the top row and from left to right to remove any noise or portions of the vertical grid lines by converting the pixels enclosed by the mask to white if the mask detects (1) the presence of white pixels at the extreme ends of the mask (location '1' and '4'), and (2) the occurrence of black pixels in the enclosed region of the mask, that is, the black pixel(s) occurred at location '2', '3', or both '2' and '3' of the mask. The similar operation is also employed by the vertical mask. The pre-filtering process by both horizontal and vertical masks is repeated until no other objects can be removed from the ECG image. Figure 4 shows the resultant image after applying pre-filtering with two masks in Fig. 3 on the ECG image of Fig. 2. It is noted that the grid-lines are removed except for some random noise.

The length of both masks can be adaptively determined according to actual width of the ECG waveform in a particular ECG image. This is achieved by randomly selecting several (3∼5) vertical scanning lines in the ECG image and finding the maximum length of continuous black pixels for each scanning line. The maximum length which falls into the normal range of ECG waveform width is chosen as the length of masks.

2.3 *Pre-filtering II*

Many different types of errors may be introduced into scanned ECG images in the scanning process due to the limited sampling rate of the scanner, global digitization set by the software associated with the scanner, and other random noises, etc. Figure 5 shows a portion of the scanned sample ECG waveform in which circles indicate gaps to be filled in and squares the random noises to be removed. Therefore, another task of pre-filtering is to fill in these gaps and to remove random noises in ECG images introduced during the scanning process. A heuristic filtering algorithm is still employed to perform the above task. A 5×5 mask shown in Fig. 7 is introduced to fill in possible gaps and to remove random noises in ECG images. With this mask, the operation to remove random noises on the scanned ECG waveform is based on the following rules:

Figure 5. A portion of the scanned example ECG waveform.

'$\wedge$' is logical 'and' operation, and
'$\vee$' is logical 'or' operation.

$$\text{R1:}\quad \wedge p_i = 1 \qquad (i = 1, 2, 8, 12, 22);$$
$$\vee p_j = 0 \qquad (j = 3 \sim 7, 13 \sim 21);$$
$$p_x = 1;$$

That is, when the mask moves over the scanned ECG waveform and the above rule R1 is satisfied, p_x is then considered as random noise on ECG waveform and subsequently set to zero. Similarly, the operation of the mask to fill in gaps is based on the rules based on R2 $\sim$ R6. Other rules are;

$$\text{R2:}\quad \wedge p_i = 1 \qquad (i = 1 \sim 5, 10, 16);$$
$$\vee p_j = 0 \qquad (j = 6, 7, 8, 18, 24);$$
$$p_x = 0;$$
$$\text{R3:}\quad \wedge p_i = 1 \qquad (i = 1, 5 \sim 8, 18, 24);$$
$$\vee p_j = 0 \qquad (j = 2, 3, 4, 10, 16);$$
$$p_x = 0;$$
$$\text{R4:}\quad \wedge p_i = 1 \qquad (i = 1, 2, 3, 7, 8, 12, 22);$$
$$\vee p_j = 0 \qquad (j = 4, 5, 14);$$
$$\vee p_k = 1 \qquad (k = 6, 20);$$
$$p_x = 1;$$
$$\text{R5:}\quad \wedge p_i = 1 \qquad (i = 1, 2, 3, 7, 8, 12, 22);$$
$$\vee p_j = 0 \qquad (j = 5, 6, 20);$$
$$\vee p_k = 1 \qquad (k = 4, 14);$$

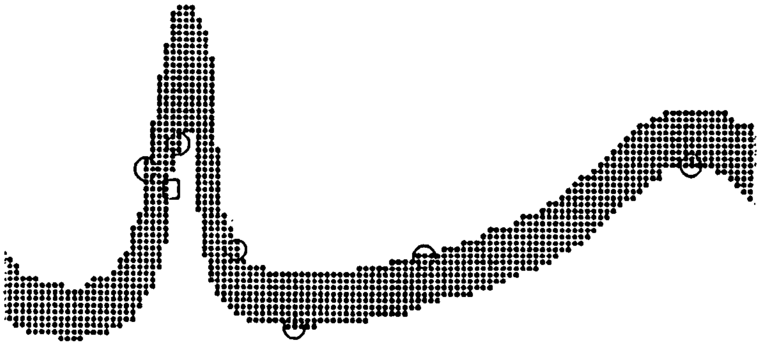


Figure 6. The result of image in Fig. 5 processed by the mask.

p_{23}	p_{24}	p_9	p_{10}	p_{11}
p_{22}	p_8	p_1	p_2	p_{12}
p_{21}	p_7	p_x	p_3	p_{13}
p_{20}	p_6	p_5	p_4	p_{143}
p_{19}	p_{18}	p_{17}	p_{16}	p_{153}

Figure 7. A 5×5 mask for pre-filtering II.

$$p_x = 1;$$

$$\text{R6:} \quad \wedge p_i = 1 \qquad (i = 3 \sim 7,\ 14,\ 20);$$

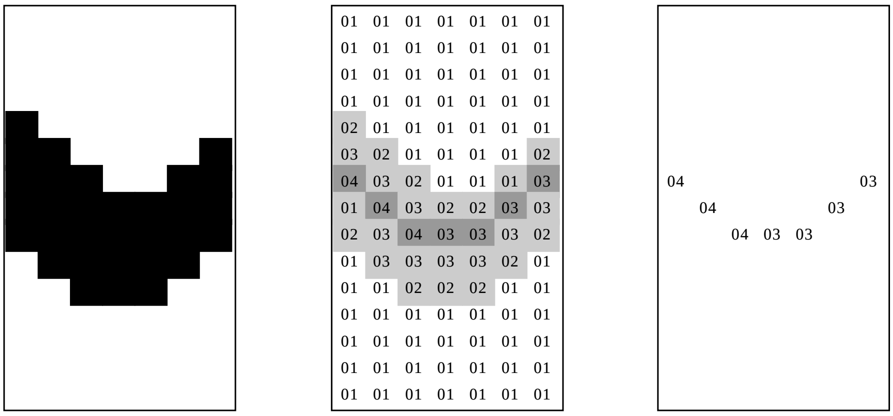
$$\vee p_j = 0 \qquad (j = 1,\ 2,\ 8,\ 12,\ 22);$$

$$p_x = 0.$$

When the mask moves over the scanned ECG waveform, and if any above rule (R2 ~ R6) is satisfied, p_x value is then set to 1, that is, a gap is filled in. In this way, the scanned ECG waveform is further filtered before a thinning algorithm is to be applied. Figure 6 shows the result of the image of Fig. 5, processed by the mask in Fig. 7 based on the above rules. It is noted that random noise in Fig. 5 processed by the mask in Fig. 7 based on the above rules. It is noted that random noise in Fig. 5 (square) is removed and the gaps (circles) are filled in.

2.4 *Thinning for ECG skeleton*

The main consideration in obtaining ECG skeleton is the preservation of shape information. Thinning algorithms can be used for this purpose in many applications [3,8–10]. There are a number of thinning algorithms available. In consideration of



(a) (b) (c)

Figure 8. An exemplified portion of ECG waveform for thinning.

characteristics of ECG waveforms, a simplified thinning algorithm similar to distance approach thinning is used to obtain ECG skeleton [3,9]. Basically, the distance approach thinning algorithm attempts to find the distance from the pixel in consideration to the nearest white pixel, by scanning radially about the pixel in question and detecting for the first occurrence of a white pixel. Since ECG waveforms span laterally as shown in Fig. 7, the skeleton of the object along each column can be defined as the innermost pixel embedded in the object. As such, scanning vertically instead of radically can effectively obtain the skeleton of ECG waveform.

The thinning method adopted in the system can be briefly described as follows as exemplified in Fig. 8, where Fig. 8(a) is an enlarged region of a portion of ECG waveform:

(a) Every column in the image, starting from the leftmost column, is scanned top-down and the distance to the nearest white pixel is calculated. Upon completion of the calculation for each pixel, the ‘distance rating’ is assigned to that pixel.
(b) The calculation of the distance rating for each pixel is based on the rule that the black pixels are assigned a value based on (see Fig. 8(b)):

$$\text{distance rating} = \text{number of pixels away from the nearest white pixel, either from the top or the bottom}$$

(c) All pixels in every column are scanned to obtain the distance rating as shown in Fig. 8(b).
(d) To obtain the ECG skeleton, every column is re-examined and all the pixels in each object, except the pixel that possess the highest distance rating, are discarded, as shown in Fig. 8(c).

The system actually does not perform step (d) until the post-filtering which is used to remove possible noises that are equal or larger than the width of ECG waveform.

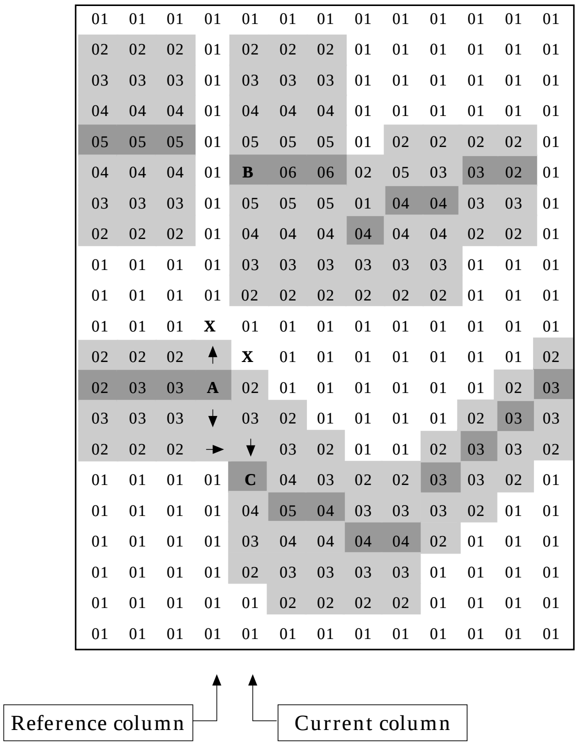


Figure 9. Illustration of waveform tracing.

2.5 *Post-filtering*

After calculating distance rating for each pixel and before actually extracting ECG skeleton based on distance rating, post-filtering procedures may be required to remove possible random noise which is equal or larger than the width of ECG waveform and does not touch with ECG waveform. As shown in Fig. 9, this operation is firstly to detect a portion of the ECG skeleton and then attempts to trace out the remaining portions of the ECG skeleton. One assumption behind this operation is that the noise is random point-like and should not touch with ECG waveform. The following is a brief description of the procedures for post-filtering:

(a) Every column in the ECG image is scanned to identify the ‘peaks’ in that column, where the term ‘peak’ refers to a skeleton of either the ECG waveform or any other objects not removed in the previous filtering.
(b) The column with only one peak is selected and defined as the ‘reference column’ as shown in Fig. 9.
(c) Waveform tracing is performed next to obtain the complete path of the ECG waveform. However, if the reference column lies somewhere in the middle of the image, the tracing can be accomplished firstly towards the right, then followed by the left. In Fig. 9, the path on the right of the reference column is traced out.
(d) At ‘A’ of the reference column (see Fig. 9), there appears to have two likely locations

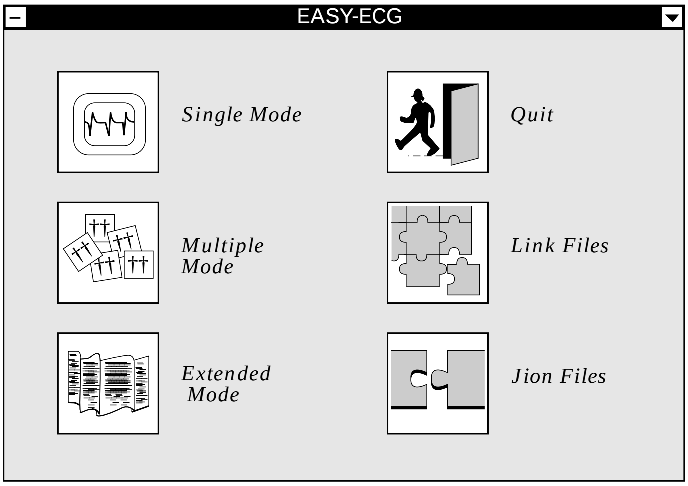


Figure 10. Illustration of graphic user interface.

in the current column ‘B’ and ‘C’, which are possibly from the next point of the ECG waveform. The algorithm firstly attempts to trace a path from ‘A’ to ‘B’ because ‘B’ has a higher distance rating compared to ‘C’. However, the path from ‘A’ to ‘B’ will be prematurely terminated due to the occurrence of the white pixels along this path. As a result, the neighbouring black pixels above and below of ‘B’ are interpreted as noise and discarded. The remaining path from ‘A’ to ‘C’ is traced to confirm that ‘C’ is indeed part of ECG waveform. Upon doing so, ‘C’ would be the new reference point for the tracing of the next point.

Upon completion of the above procedures, digital data values can be extracted from the skeleton of the ECG waveform. Based on the relationship between the scanner sampling rate used and the time and amplitude relationship on the actual ECG paper records, appropriate time and amplitude values can be assigned to each data point.

3. User interface

A window based user-friendly interface is designed for user’s easy access to the system resources. The current graphic user interface includes single mode, multiple mode, extended mode, link files and join files as shown in Fig. 10. Single mode allows users to process an ECG image file at a time while multiple mode allows users to process multiple ECG image files in sequence. Extended mode is designed to deal with long continuous ECG paper records. It separates the long paper record into parts so that they can be processed and then linked together. A user interactive cursor measurement facility is also provided to measure some of the parameters on ECG waveforms such as amplitudes and duration.

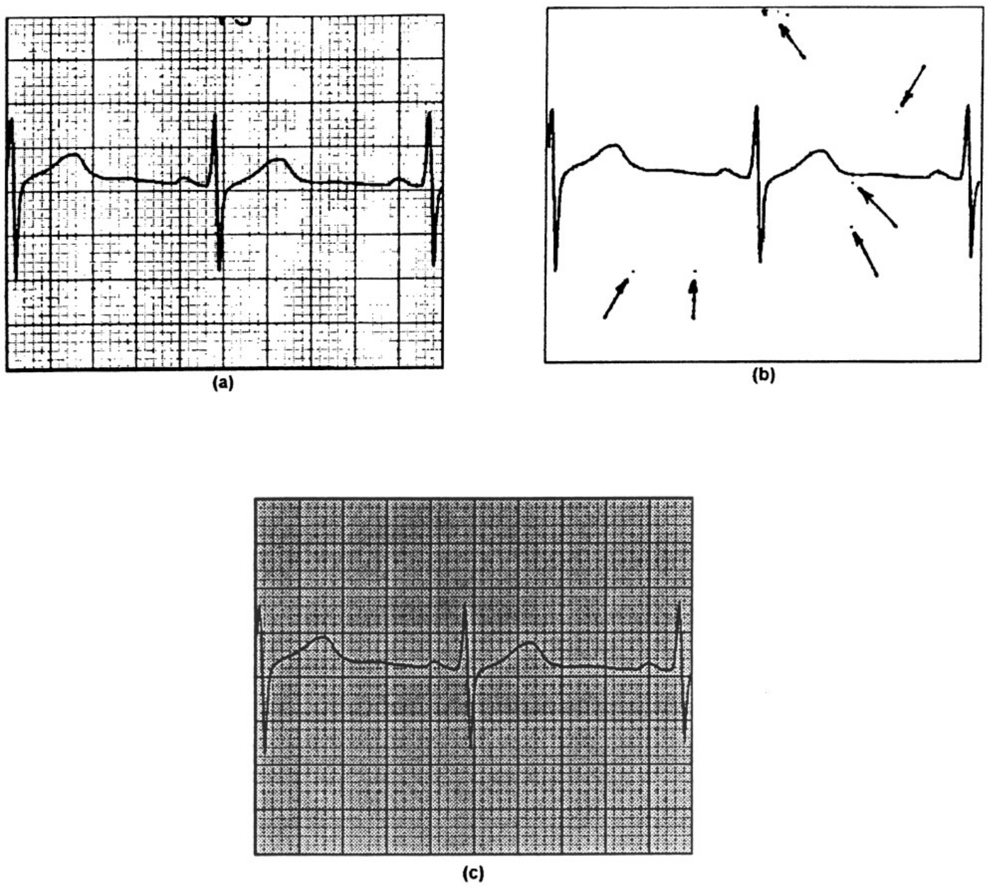


Figure 11. An experimental example.

4. Experimental results

Figure 11(a) shows an example of a scanned ECG image, and Fig. 11(b) is the resultant image of pre-filtering on Fig. 11(a), where arrows indicate random noises. Figure 11(c) is the recovered ECG waveform based on the extracted ECG data with standard grid-line superimposed for clinical measurement. It is noted that the recovered ECG waveform is thickened here for the purpose of better visualization.

The details of the data storage and format for the ECG waveform files are:

- A new file is created with ‘PCX’ file extension replaced with ‘ECG’.
- As shown in Fig. 12, the first 20 bytes in the file are reserved for ECG code word which acts as an identifier for later file retrieval by the user-interface.
- The next 108 bytes are used to store the patient’s particulars.
- A total of 128 bytes are required for ECG ASCII data file format.
- Based on the ECG records supplied by various hospitals, the conversion is able to pack all the necessary ECG signal information into an ECG file which is

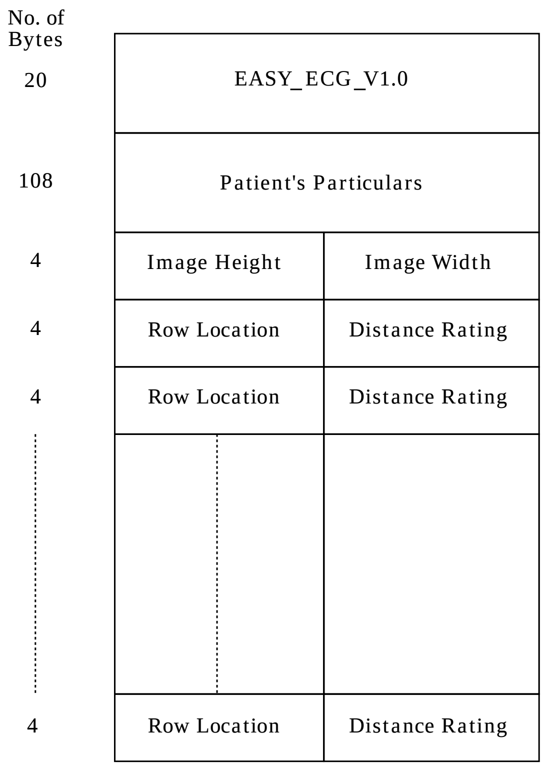


Figure 12. ASCII data file format.

approximately 10% of the original PCX file and requires approximately 2500 bytes. Total size of the file = 128 + 4 + (Image width *4) bytes.

- It is possible to directly digitize the waveform using the ADC system. There will be some quantization error in the ADC process. This error will be dependent on the type of ADC used, i.e. 8 bit or 12 bit ADC. However, the sampling rate has to be very fast to ensure that critical information is captured by the system, and this will tremendously increase storage requirements.

Typically 12 bits ADC and a sampling rate of 100 samples per second will be acceptable for discretizing ECG waveforms.

5. Discussion

Experiments on selected ECG paper records show very encouraging results. ECG skeletons can be found and their digital values can be extracted and stored in ASCII data files for each retrieval, analysis and transmission. The methods discussed here may also be used to extract other medical waveform from their graphic paper records such as EMG and EEG.

The filtering techniques discussed in this paper are heuristic in the sense that they are derived from experiments. Some assumptions include the width of the majority of the

ECG waveform in a scanned image should be greater than that of grid-line background, and the most of ECG waveforms should be continuous. These can be met in usual conditions. However, there exists the possibility that ECG waveform may be broken or its width may be less than that of grid-line background due to poor recording conditions or improper scanning operations and binarization. In this case, applying the algorithm discussed in this paper would produce broken ECG skeletons in addition to remove grid-line background and random noise. To solve this problem, some methods have to be used besides attempting to improve the scanning quality. One possible way is to combine with directional filtering techniques in frequency domain which is being investigated [11]. Another possible way is to modify the skeleton tracing algorithm so that it can identify and link those broken ECG skeletons. In addition, ECG paper records may have colour grid-line background or grey grid-line background. In these cases, using coloured ECG image or gray-scaled ECG image would avoid producing broken ECG waveforms in scanned images due to improper binarization and most of the original information contained in ECG paper records can be used to extract ECG skeleton.

In the current system, no skew correction algorithm is included. During the experiment, it is found that the skew correction is useful because it is difficult to guarantee the correct orientation of scanned ECG images especially when scanning many ECG paper records. The skew detection and correction algorithms are currently being investigated for system refinement.

6. Conclusion

In this paper we have presented a method for extracting ECG digital data from ECG paper records. With the method, ECG paper records are scanned to produce binary ECG images. Image processing techniques such as heuristic filtering and thinning algorithms are then applied to find ECG skeletons which are subsequently converted into digital values and can be stored in ASCII data files for each management and clinical use. A window based user-friendly interface is incorporated to enhance the utilities of the system. The experiments show that, under the assumptions stated in the paper, ECG data can be successfully extracted from scanned ECG images. The limitations of the current system are also indicated and possible methods to deal with them are mentioned as well. The current system is still under development and other alternative techniques such as frequency domain directional filtering and mathematical morphological operations are being tested to meet the system's technical requirements.

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