Image Processing on ECG Chart for ECG Signal Recovery

TW Shen, TF Laio

Tzu Chi University, Hualien, Taiwan

Abstract

Medical imaging plays an indispensable role on medical informatics. Most of imaging processing technologies is focused on the identification of the locations of diseases on MRI, CT, PET, and SPECT images. However, only a few researches focused on one dimension signal recovery or reconstruction of electronic signals. Spatial and frequency methods were provided to process on colour or gray-level electrocardiogram charts, including threshold segmentation and 2D Fourier transform techniques. Finally, the performance was evaluated by percentage of root mean square (PRD) for calculating waveform similarity. The results show that the spatial method offered better performance than the frequency method, especially if the RGB colours in chart are kept. Based on our investigation, the linear interpolation method provided the best interpolation with less overall PRD.

1. Introduction

Medical imaging plays an indispensable role on medical informatics. Nowadays, most of imaging processing technologies is focused on the enhancement and identification of the locations of diseases on MRI, CT, PET, and SPECT images [1] to assist the physicians on medical diagnosis. More and more hospitals have introduced picture archiving and communication systems (PACS) to the storage, retrieval, distribution and presentation of images, and the images are most commonly stored as DICOM (Digital Imaging and Communications in Medicine) format. A full PACS also interfaces with hospital information system (HIS), which is a comprehensive, integrated information system for hospital management and patient care [2].

Even integration with HIS and PACS systems, the technique of electrocardiogram (ECG) signal extraction from paper-written ECG image developed since 1987 [3-8] is still needed to preserve the large accumulation of ECG paper charts in some counties [3]. Some systems were developed which can transfer wave data recorded on paper to a digital time data [3–7]. In addition, the image processing techniques are able to further transfer the ECG paper charts, web-based and DICOM-based ECG screenshots, and PDF files to the digital time database for data extraction, compression, archive, and storage. Moreover, other issues, such as ECG biometrics, physiological system modelling, simulation and computer aid diagnosis (CAD), may also be concerned to help biomedical engineers for developing tools. For examples, a sudden cardiac death (SCD) simulator can be built by using Labivew program with a D/A converter to evaluate a portable ECG embedded system [9] by using real hospital paper charts. However, only several researches [3-7] focused on one dimension signal recovery or reconstruction of electrical signals from clinical paper imaging.

To retrieval ECG signal from scanned images, according to previous researches, Zhang et al. [3] obtained the ECG restoration by applied a sequential image processes (histogram filtering, gradient image and grid pattern extraction). Mitra et al. [6] generated digital time database from paper ECG records. Their method includes binarization, background separation, the thinning algorithm, and raw data extraction. After ECG data extraction, they analyzed ischemic subjects by using 2D Fourier transform method.

In general, the percentage of root mean square (PRD) is a very common index to evaluate the error of ECG data compression. It is used to evaluate on different image extraction methods, which has not yet been done in previous researches. Hence, the aim of this research is to recognize ECG phantom on charts or images, to recovery raw ECG signal, and to evaluate the performances of two different imaging processing skills.

2. Methodology

This research proposed two ECG signal retrieval techniques based on spatial and frequency oriented methods. The spatial-oriented method mainly applied histogram segmentation, missing pixel replenishment, and interpolation. The frequency-oriented method majorly applied 2D Fourier transform, 2D lowpass filter, 2D median filter, missing pixel replenishment, and interpolation. In order to evaluate two systems fairly, a standardized database for both methods is essential.

2.1. Experiment Database

The MIT/BIH Sudden Cardiac Death Holter Database is a collection of long-term ECG recordings of patients who experienced SCD during the recordings. The database contains a total of 23 complete half-hour Holter recordings which become available to researchers [10-11]. The database not only provides ECG signal at 500 Hz sampling rate, but the PhysioNet website demonstrates the ECG image (PNG format) that contains 10 second ECG. The web-ECG image database was used to develop our ECG extraction system and those images were trimmed to meet dimension at 990 x 124. These arrhythmia images include tachyarrhythmia, tachycardia (VT), ventricular flutter (VFL), ventricular fibrillation (VFib), or atrial fibrillation. For this research, the ten-second ECG image (involved before and after VF onset time or randomly selected ten-second arrhythmia for no VF onset cases) were kept in our database in order to exam both types of normal sinus and arrhythmia waveforms. Finally, the recovery results were compared with machine recording data with 500Hz sampling rate.

2.2. Spatial-oriented method

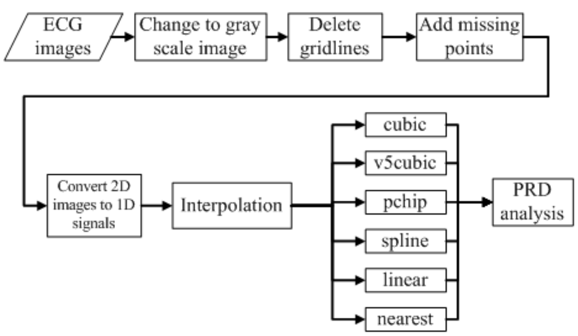


Figure 1. The flow diagram of spatial-oriented method

In spatial-oriented process (figure 1), a color image may directly eliminate the red component to remove gridlines or convert to a gray or binary tone image after selecting a suitable threshold with the help of histogram analysis. A suitable threshold selection after histogram analysis can mostly remove the background and gridlines of ECG charts. Then, the computer program searches background-removed images for missing points on the columns without any ECG pixel points. The missing point has been replenished by the darkness point of the same column on pervious gray scale image. If the same column has more than one pixel, the thinning algorithm is applied. Next, the co-ordinate of each black pixel was extracted and then the values were calibrated according to the co-ordinate system of the chart. Because of the image resolution is 990 x 124, the interpolation is applied to fill the number of points in x-axis up to 5000 points (10 sec.* 500 sps). Finally, five interpolation functions and their PRDs are calculated. The equation (1) defined PRD function which describes the difference between the reconstructed and original signal as follows,

$$PRD = \sqrt{\left\{ \frac{\sum_{i=1}^{n} [x_{org}(i) - x_{rec}(i)]^2}{\sum_{i=1}^{n} [x_{org}(i)]^2} \right\}} \qquad \ldots(1)$$

where n is the number of samples and x_{org} and x_{rec} are samples of the 1D original and reconstructed data sequences. Figure 2 shows a processing example from an original color image (figure 2a) to a 1D recovered ECG signal (figure 2d).

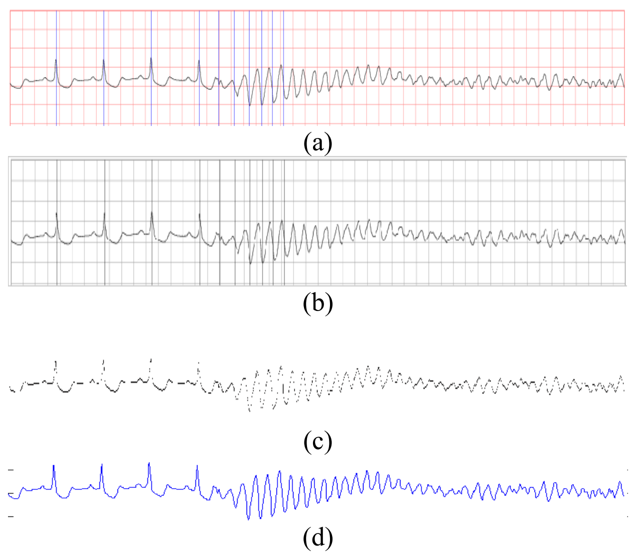


Figure 2. The procedures of spatial-oriented method: (a) an original color image; (b) a gray tone image after selecting a suitable threshold on histogram; (c) missing pixel replenishment and interpolation; (d) a recovered and calibrated ECG signal.

2.3. Frequency-oriented method

The basic idea of the frequency-oriented method is to separate the ECG image into three components in the image (2D) frequency sense, including (1) high frequency gridlines [1], (2) an ECG waveform (mainly in low frequency), and (3) noise (mainly salt and pepper noise). Hence, 2D Fourier transform (2D FT) plays an important roles in this method, which is applied on a color, gray-scale, or binary ECG image by using equation (2).

$$F(u,v)=\sum_{m=-\infty}^{\infty}\sum_{n=-\infty}^{\infty} f[m,n]e^{-j2\pi(umx_0+vny_0)} \quad \ldots(2)$$

where x_0 and y_0 are the spatial intervals between consecutive signal samples in the x and y directions, respectively.

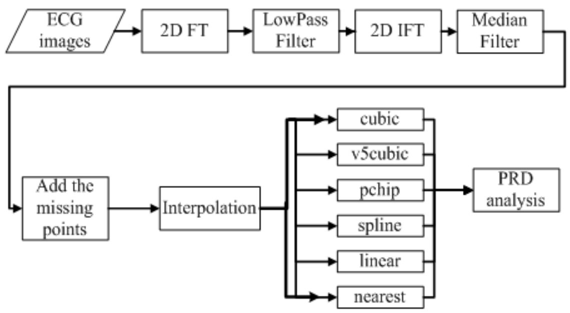


Figure 3. The flow diagram of frequency-oriented method

In frequency-oriented process (figure 3), 2D FT projects the image from spatial to frequency domain. In the frequency domain, an elliptic-shaped low-pass (LP) filter was applied on the frequency response map to omit the high frequency component as shown in figure 4. The center of frequency response map presents the low-frequency component and the outside elliptic-cycle describes the high-frequency component. Figure 5 shows the three dimension plot on the LP filter with crisp threshold on the filter edge. The formula of the LP filter is written as equation (3).

Figure 4. An elliptic-shaped LP filter applied on rectangular-shaped frequency response map

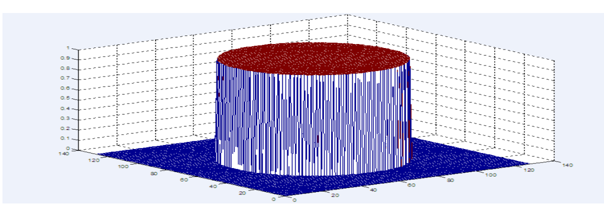
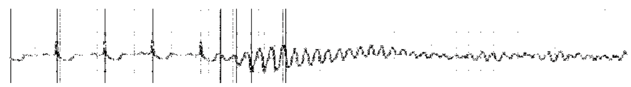


Figure 5. A 3D LP filter plot

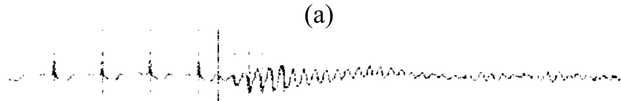
$$\frac{(u-x_{center})^2}{wide*0.4}+\frac{(v-y_{center})^2}{length*0.5}<r \quad \ldots(3)$$

where u, v are the coordinates in the frequency domain. The coordinate (x_{center}, y_{center}) is the origin of the frequency response map. The r value is suggested as 50.

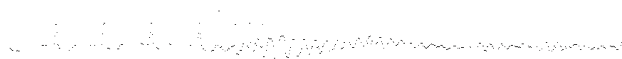
After filtering, the inverse Fourier transform (IFT) transfers frequency domain to time domain and the result shows in figure 6a. Then the median filter is applied to remove salt and pepper noise as shown in figure 6b. Also a suitable threshold selection removes the background and gridlines (figure 6c). Then, follow the procedure as pervious mentioned. The computer program searches for missing points and replenished by darkness points (figure 6d). Because this method provides more scattering noise, the dark pixel distances between adjacent columns are computed. If the same column has more than one pixel and the distance is over or below thresholds, then the pixel is eliminated (figure 6e). Next, the co-ordinate of each black pixel was extracted and then the values were calibrated according to the co-ordinate system of the chart (figure 6f).



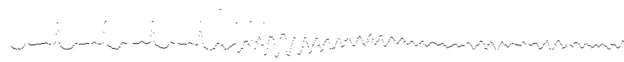
(a)



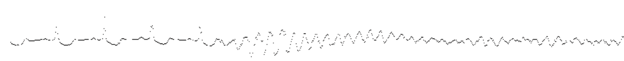
(b)



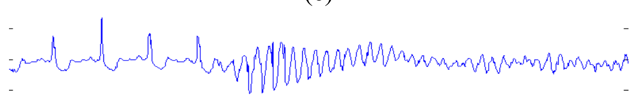
(c)



(d)



(e)



(f)

Figure 6. The procedures of frequency-oriented method: (a) an image applied 2D FT, LP, and IFT; (b) an image applied a median filter; (c) background elimination (d) missing pixel replenishment; (e) extra pixels elimination and interpolation; (f) a recovered and calibrated ECG signal.

3. Results

Our proposed methods processed on color or gray-level electrocardiogram charts. To summary, first, threshold segmentation or 2D Fourier transform were applied to remove the chart grids and marker lines. Second, column searching on missing pixels or dots was utilized, which were refilled by image matching and pixel interpolation. Then, the 2D image was converted to 1D signal by using five interpolation methods (cubic, v5cubic, pchip, spline, linear, and nearest) that rebuild sampling frequency to 500 sps. The example results are plotted in figure 7 & 8.

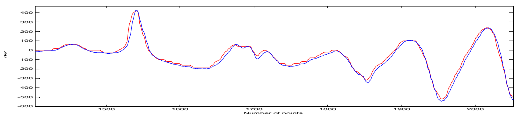


Figure 7. Spatial-oriented method – the recovery signal (red) versus the original signal (blue)

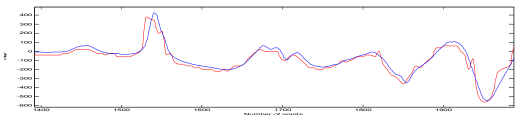


Figure 8. Frequency-oriented method – the recovery signal (red) versus the original signal (blue)

Finally, the performance was evaluated by percentage of root mean square for calculating waveform similarity. Twenty-three ten-second charts (about 990 by 124 pixels) were processed and compared with original ECG data for performance evaluation. The spatial and frequency methods provided each best result on average 45.46% and 54.33% PRD by using linear interpolation. The detail results are listed on Table 1.

Table 1. Average PRD (%) on six different interpolation methods

Average PRD (%) on six different interpolation methods			
Spatial –based method		**2D FFT based method**	
cubic	45.92 %	**cubic**	55.07 %
v5cubic	46.07 %	**v5cubic**	55.39 %
pchip	45.91 %	**pchip**	55.04 %
spline	46.09 %	**spline**	55.71 %
linear	***45.46 %***	**linear**	***54.33 %***
nearest	46.79 %	**nearest**	57.07 %

4. Discussions and conclusions

Overall, our image processing methods successfully converted 2D ECG images into one-lead ECG signals to make further CAD analysis and modelling simulation possible. The results show that the spatial method offered better performance than the frequency method, especially if the RGB colours in chart are kept. Unlike spatial method, 2D Fourier transform method contains more salt-and-pepper noise on chart images, as well as scattering noise. Our recovered signals also include amplitude displacement and inconsistent waveform phase shifting. The above factors cause the higher average PRD. However, for improving the system performance, high resolution images is a necessary condition to reduce dispensable interpolation. In addition, according to this investigation, the linear interpolation is the best interpolation method with less overall PRD.

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Address for correspondence
Tsu-Wang Shen, Ph.D.
Department of Medical Informatics
Tzu-Chi University
701, Sec. 3, Jhongyang Rd., Hualien, 97004, Taiwan
tshen@mail.tcu.edu.tw