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MOBILE SYSTEMS

Hiding Patients Confidential Datainthe ECG Signal viaa Transform-Domain Quantization Scheme

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Abstract Watermarking is the most widely used technology in the field of copyright and biological information protection. In this paper, we use quantization based digital watermark encryption technology on the Electrocardiogram (ECG) to protect patient rights and information. Three transform domains, DWT, DCT, and DFT are adopted to implement the quantization based watermarking technique. Although the watermark embedding process is not invertible, the change of the PQRST complexes and amplitude of the ECG signal is very small and so the watermarked data can meet the requirements of physiological diagnostics. In addition, the hidden information can be extracted without knowledge of the original ECG data. In other words, the proposed watermarking scheme is blind. Experimental results verify the efficiency of the proposed scheme.

Keywords ECG · watermarking · quantization · DWT · DCT · DFT · PQRST complexes

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Introduction

Watermarking technology is the most widely used data hiding technology in the field of multimedia. Digital watermarking technology refers to directly embedding some identification information (watermark) into the carrier (including multimedia, documents, software, etc.). It does not affect the usage of the original carrier and is hard to perceive by ordinary perception systems such as visual or auditory systems. The hidden information in the carrier can help us to confirm the content creators, buyers, and carrier's transmission of secret information to determine whether the carrier is altered or not during its transmitting process. Digital watermarking is an important research direction of information hiding technology.

Electrocardiograms (ECG) reflect the process of the electrical activity of our heart, which can be taken as a reference for the study of cardiac pathology and cardiovascular system diagnostics. With ECG signals, we can analyze and identify various heart diseases, such as arrhythmias, myocardial damage etc. ECG has high requirements for accuracy. Thus ECG is one of the very important types of bio-information to be protected.

Research on the protection of ECG information is still in its infancy, and there are some related studies. In 1998, application of watermarking techniques in medical images was proposed by Anand and Niranjan [1] to embed the patient information. Kong et al. [2] and Engin et al. [3] proposed an elementary watermarking technique for ECG signals. The main drawback is that it is non-blind.

Nambakhsh et al. [4] proposed a novel blind watermarking method combined with the EZW-based wavelet coder to embed ECG signals as a secret key into medical CT and MRI images. Zheng and Qian [5,6] developed a wavelet-based algorithm to watermark ECG signals in non-QRS complex regions to guarantee the restoration of almost un-distorted ECG signals. On the other hand, the watermark can be recognized as a media to verify whether the marked ECG signal is tampered or not, so as to achieve the purpose of protecting the ECG during the transmission. By employing multistage watermarks, Suleyman et al. [7] present a time-domain techniques that allow the embedding and retrieval of sensitive numerical data, such as the patient's social security number or birth date, within the medical signal. Kuar et al. [8] constructed a blind digital watermarking to ensure the safe transmission of ECG signals in wireless networks so that the embedded watermark can be fully removed by the receiver. Ibaida et al. [9] improved the least significant bit (LSB) watermarking technique and applied it to an ECG signal for hiding healthcare information. Ibaida et al. [10] developed a watermarking algorithm such that the ECG signals are watermarked with patient biomedical information to confirm patient/ECG linkage integrity, and are suitable for a wearable sensor-net health monitoring system in 2011. However, the embedding location selection of these two algorithms is complicated since ECG samples are rational numbers.

He et al. [11] applied wavelet-based quantization watermarking to ECG signals. Guo and Zhou [12] proposed a single channel electromyography blind recognition model based on watermarking. The host signal is transformed into the wavelet domain and the watermark with synchronization code is embedded using a quantization approach. Dey et al. [13] proposed a method of reversible binary watermark embedding into the PPG signal and a watermark extraction mechanism using a prediction error based algorithm. Dey et al. [14] proposed a novel session based blind watermarking method with secret key by embedding a binary watermark image into the ECG signal. In addition, the 'P Q R S T'-peaks are marked and stored over the entire ECG signal and the time interval between two consecutive 'R'-peaks, and intervals between other peaks, are measured to detect anomalies in the behavior of the heart. However, these two methods are non-blind. Moshaddique et al. [15] tried to raise the concerns of major social implications like privacy and security. Proper coordination between different government agencies, research institutes and manufactures is necessary to overcome these obstacles and have smooth implementation. Ayman and Ibrahim [16] proposed a wavelet-based steganography technique which combines encryption and scrambling technique to protect patient confidential data. The proposed method allows ECG signal to hide its corresponding patient confidential data and other physiological information thus guaranteeing the integration between ECG and the rest. Lu et al. [17] present an effective scheme to protect patients' personal privacy for a medical information system. In the scheme, privacy data before being stored in the database of the server of a medical information system would be encrypted using traditional encryption algorithms, so that the data even if being disclosed are also difficult to be decrypted and understood.

In this paper, we use quantization based digital watermark encryption technology on the Electrocardiogram (ECG) to protect patient rights and information. Most methods for signal watermarking can be grouped into two categories, time-domain and transform-domain. The watermark embedded in the transform domain is more imperceptible than in time domain according to theory analysis and simulation results. Three transform domains, DWT, DCT, and DFT are thus adopted to implement the quantization based watermarking technique. Although the watermark embedding process is not reversible, we evaluate its effect on the PQRST complexes of the ECG signal which concludes that the impact is negligible and the watermarked data can meet the requirements of physiological diagnostics. In addition, the change in the amplitude of ECG signals before and after watermarking is very small and does not cause too much impact in medical evaluation, which is acceptable. In the extraction process, the hidden information can be extracted without knowledge of the original ECG data. Experimental results verify the efficiency of the proposed scheme.

The organization of this paper is as follows. Section II reviews some preliminaries related to ECG signals. Section III introduces in detail the proposed scheme. Section IV gives the experimental results and discussion to evaluate the proposed scheme. Some conclusions are drawn in section V.

Preliminaries

In this section, we first review the ECG waveform and then give a possible application instance for ECG watermarking.

The abbreviation ECG denotes the electrocardiogram wave, named by the Dutch physiologist W. Einthoven(the inventor of the ECG). He divided one cardiac cycle into P, Q, R, S, and T complex waves in Fig. 1. Their meaning is discussed in the following.

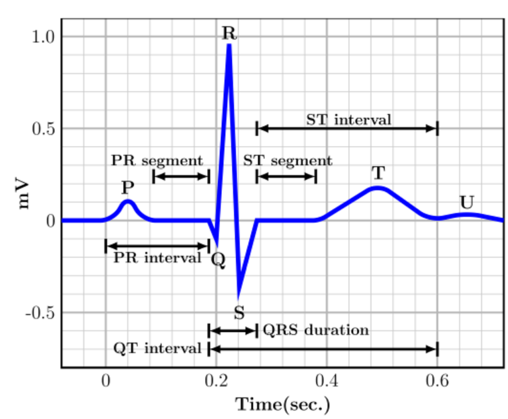


Fig. 1 PQRST complexes in the ECG waveform

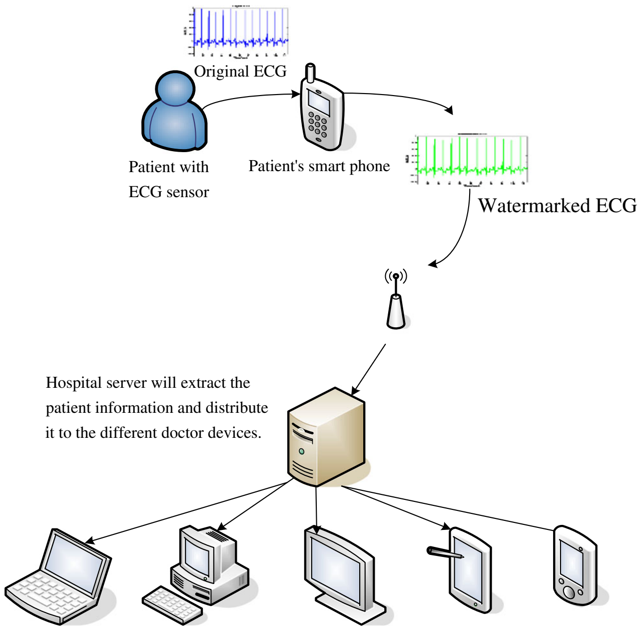


Fig. 2 Schematic diagram of ECG signal transmission

P wave: the excitation of the heart originates in the sinus node, and then reaches the atrium. The P wave is produced by the atrial depolarization. It is the first wave of each wave group and reflects the depolarization process of the left and right atrium. The first half of the P wave represents the right atrium, and the latter part of the P wave represents the left atrium.

QRS complex: a typical QRS complex includes three closely linked waves. The first downward wave is called the Q wave, followed by a high-tip vertical wave known as the R wave. The downward wave after the R wave is called the S wave. Because they are closely linked, and reflect the excitation of the ventricular electrical process, it is collectively referred to as the QRS complex. This wave group reflects the left and right ventricular depolarization process.

T wave: The T wave is located in the following ST segment. It is a relatively low and much longer wave. It is generated by ventricular repolarization.

According to the above description, the ECG diagnosis mainly depends on the PQRST waves. Therefore, when we add information into ECG signals, it is necessary to maintain the shape of these waveforms.

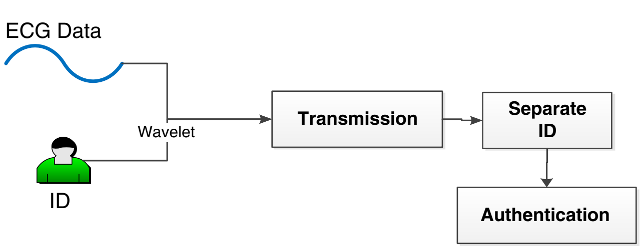


Fig. 3 An application instance for ECG watermarking

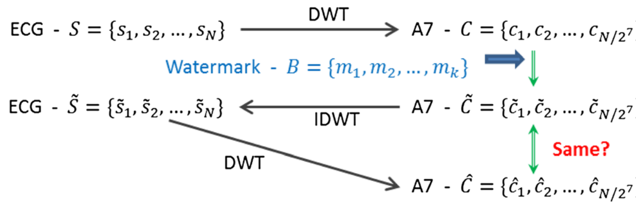


Fig. 4 The relationship between the embedded and extracting DWT coefficients

As shown in Fig. 2, we give an application instance for ECG watermarking as follows. ECG samples are initially gathered on a wireless mobile device and then are sent with patient personal information such as name, age, personal ID, etc. At hospital servers, patients' data can be extracted from the received ECG signal.

Figure 3 describes the process of using the patient's user ID to watermark the ECG signal via DWT, and the authentication is conducted after the watermarked ECG is received. Thus ECG watermarking can ensure the accuracy of the data after transmission. Of course, this is just a simple way among numerous applications. Technically there are many other applications in our everyday life. For example, academic research or medical data sharing between Hospitals A and B may use this mechanism to ensure correct ECG signal exchange. At the same time, the patient can also access his watermarked ECG data from home once the user ID authentication is verified.

The proposed scheme

The watermarking technique in the proposed scheme is based on the quantization audio watermarking technique [18,19]. In order to apply this technique to ECG signals instead of audio signals in the transform domain, pre-processing is first introduced in this section. It obviously reduces the error between original and watermarked ECG signal when the proposed embedding process is carried out.

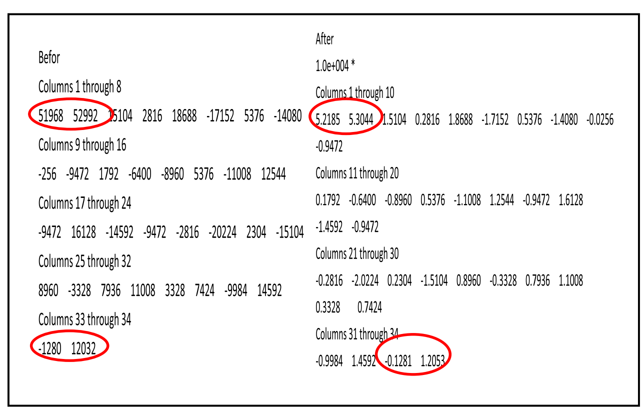


Fig. 5 The relationship between the embedded and extracting DWT coefficients using 16-bit representation

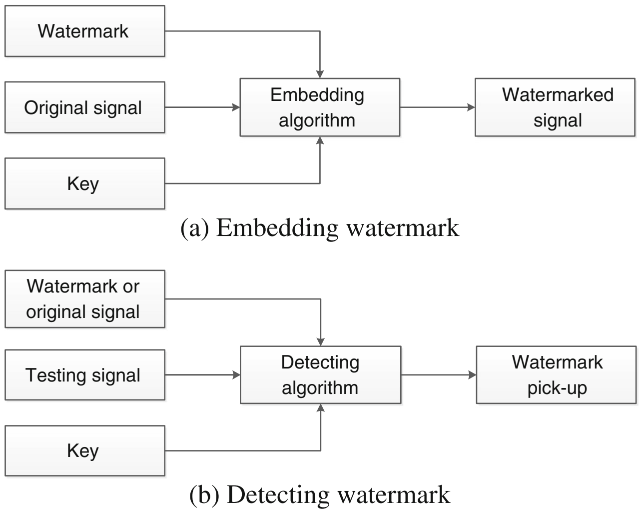


Fig. 6 The model of embedding and detecting watermarks. a Embedding watermark **b** Detecting watermark

Pre-processing

In this paper, we select the ECG data from the MIT-BIH Arrhythmia database [20]. These ECG data have a sampling rate of 360Hz and a 12-bit binary representation. Each ECG signal is first adjusted to have zero mean to eliminate DC offset. However, the resolution of 12-bit binary representation is too rough to obtain precise coefficients when embedding watermarks. As shown in Fig. 4, the error between the embedded DWT coefficient $\widetilde{c}_i$ and extracting DWT coefficient $\widehat{c}_i$ is big when using 12-bit representation. To reduce the error, each ECG signal with 12-bit binary representation is scaled to one with 16-bit representation, respectively. By using 16-bit representation, as shown in Fig. 5, the error vanishes except the first few and several later ones.

Digital watermark embedding and extraction models

Digital watermarking technology used in this paper refers to directly embedding some identifying information (digital watermark) into the digital carrier (including multimedia, documents, software, etc.), which does not affect the usage value of the original carrier and is hard to perceive or notice by people's perception system (such as visual or auditory systems). The models for embedding and detecting watermarks are given by Fig. 6.

Embedding and detecting algorithms

Let $S=\{s_1,s_2,\cdots,s_N\}$ denote an ECG signal with total length N sample points. Then, the three transforms, DWT, DCT, and DFT are independently performed on each ECG signal. After watermark embedding and inverse transform, the watermarked ECG signal is obtained and denoted by $\widetilde{S}=\{\widetilde{s}_1,\widetilde{s}_2,\cdots,\widetilde{s}_N\}$ .The watermarking scheme of each transform is introduced as follows.

Embedding quantization

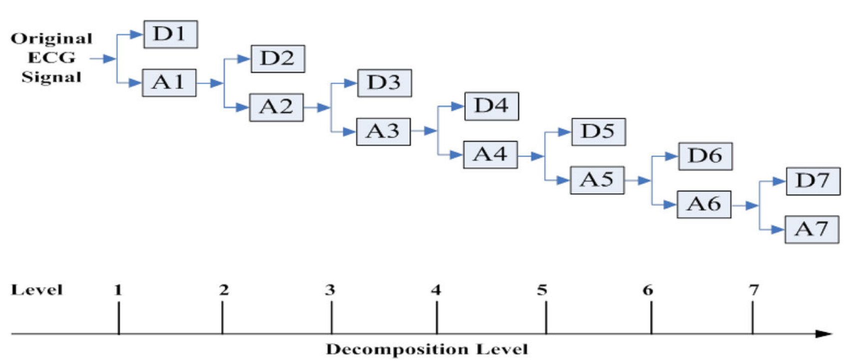
DWT: First of all, the embedding algorithm is introduced. We use 7-level Haar DWT to decompose an ECG signal into eight non-overlapping sub-bands. Figure 7 shows the structure of the 7-level DWT decomposition. Taking into account the robust performance of the low-pass filtering, we embedded the watermark (binary bits $B=\{m_i\}$) into the sub-band coefficients in the 7th level,which are the lowest-frequency coefficients. The embedding rule is based on the quantization technique[18,19]

$$\widetilde{c}_i=\begin{cases}\left\lfloor {}^{c_i}/_{Q}\right\rfloor Q+{}^{3Q}/4, & \text{if } m_i=1\\ \left\lfloor {}^{c_i}/_{Q}\right\rfloor Q+{}^{Q}/_{4}, & \text{if } m_i=0\end{cases} \tag{1}$$

where $\{c_i\}$ and $\{\widetilde{c}_i\}$ are the 7th low-frequency DWT coefficients before and after embedding, respectively; Q is the embedding strength. By applying the IDWT, the watermarked ECG signal $\widetilde{S}$ is obtained.

DCT: The embedding rule for DCT coefficients is the same as for DWT. Taking into account the robust performance of the low-pass filtering, we also embedded the watermark (binary bits $B=\{m_i\}$) into the lowest-frequency coefficients of DCT.

Fig. 7 The 7-levelDWT decomposition



DFT: Since the coefficients of DFT are complex numbers, the proposed improved rule is as follows. Again, we embedded the watermark (binary bits $B=\{m_i\}$) into the lowest-frequency coefficients of DFT.

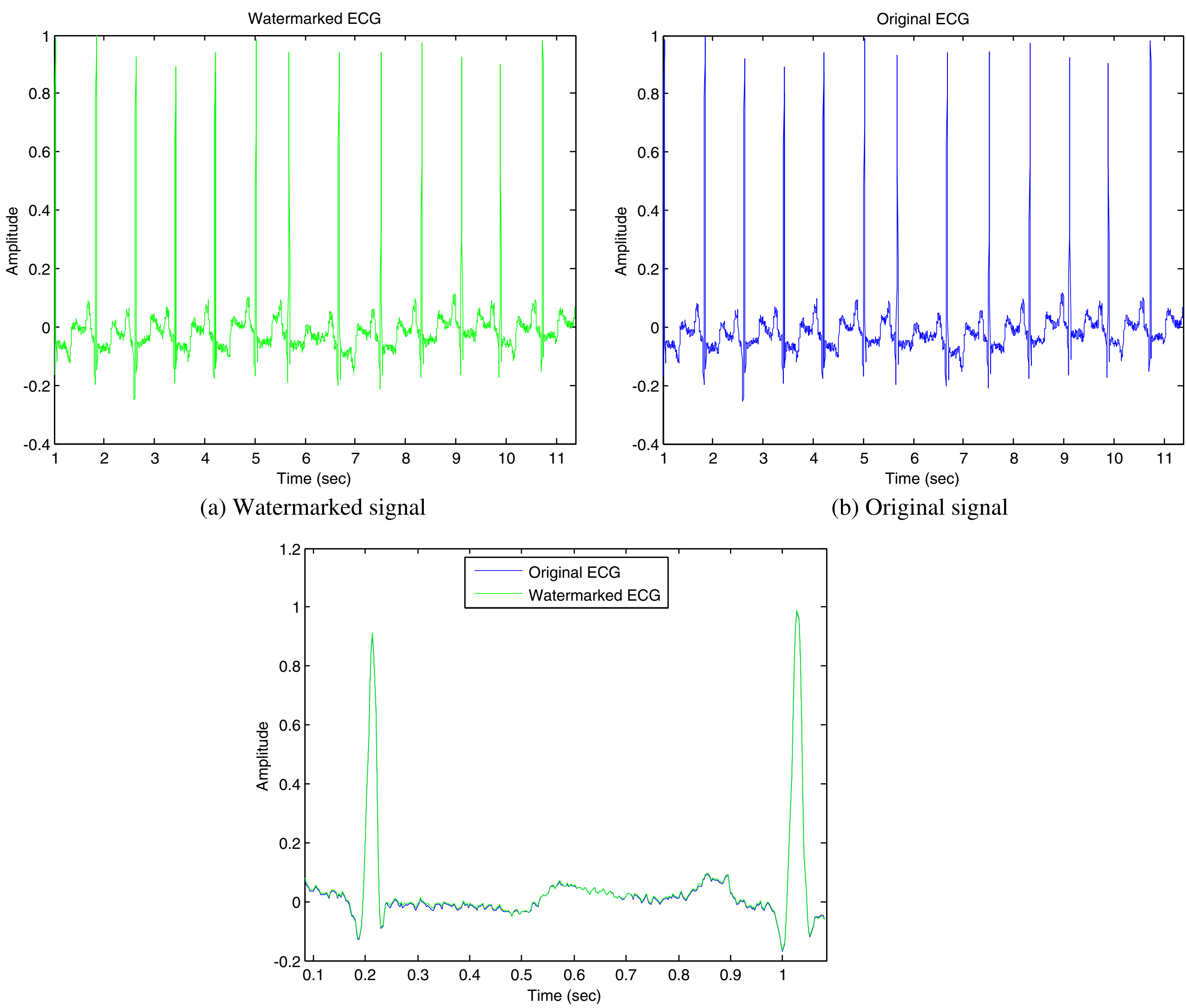
$$\widetilde{c}_i = \begin{cases} \left(\left\lfloor {|c_i|}/{Q} \right\rfloor Q + {3Q}/{4}\right)\cdot\dfrac{c_i}{|c_i|}, & \text{if } m_i = 1 \\ \left(\left\lfloor {|c_i|}/{Q} \right\rfloor Q + {Q}/{4}\right)\cdot\dfrac{c_i}{|c_i|}, & \text{if } m_i = 0 \end{cases} \tag{2}$$

where $\{c_i\}$ and $\{\widetilde{c}_i\}$ are the lowest-frequency DFT coefficients before and after embedding, respectively; Q is the embedding strength; By applying the IDFT, the watermarked ECG signal $\widetilde{S}$ is obtained.

Detection quantization

In the detecting algorithm, we first need to execute the corresponding transforms, DWT, DCT, and DFT, respectively, as used in the embedding algorithm, and then extract binary bits from lowest-frequency transformation coefficients. Suppose that $\{c_i^*\}$ is the watermarked coefficients; we use the rule in (3) to extract the binary bits $\{m_i^*\}$ of the watermark from the DWT and DCT coefficients $\{c_i^*\}$:

$$m_i^* = \begin{cases} 1, \text{if } c_i^* - \left\lfloor {c_i^*}/{Q} \right\rfloor Q \geq {Q}/{2} \\ 0, \text{if } c_i^* - \left\lfloor {c_i^*}/{Q} \right\rfloor Q < {Q}/{2} \end{cases} \tag{3}$$



(a) Watermarked signal

(b) Original signal

(c) Waveform comparison between 0.09 and 1.09 (sec)

Fig. 8 Comparison between the watermarked and original signals for dataset ID 100. **a** Watermarked signal (b) Original signal (**c**) Waveform comparison between 0.09 and 1.09 (sec)

Table 1 Experimental results for the three transforms: DWT, DCT, and DFT

ID	Domain	Interval rRMSE in ECG				Interval RMSE in ECG				Amplitude Similarity	Amplitude rRMSE	Amplitude RMSE
		rPR	rQRS	rST	rQT	PR	QRS	ST	QT			
100	DWT	0	0	0	0	0	0	0.028	0	1	0.054	14.907
	DFT	0	0	0	0	0	0	0	0	99.94	0.153	24.848
	DCT	0	0	0	0	0	0	0	0	99.7	0.060	15.805
101	DWT	0	0	0	0	0	0.002	0.002	0	1	0.132	18.197
	DFT	0	0	0	0	0	0	0	0	99.56	0.207	28.887
	DCT	0	0	0	0	0	0	0	0	99.91	0.167	19.389
102	DWT	0	0	0	0	0.035	0	0	0	99.92	0.080	14.583
	DFT	0	0	0	0	0	0	0	0	99.73	0.126	24.181
	DCT	0	0	0	0	0	0	0	0	99.84	0.085	15.362
103	DWT	0	0	0	0	0.002	0.002	0	0	99.96	0.153	22.847
	DFT	0	0	0	0	0	0	0	0	99.98	0.438	36.416
	DCT	0	0	0	0	0	0	0	0	99.77	0.233	31.356
104	DWT	0	0	0	0	0.051	0	0	0	99.8	0.450	21.987
	DFT	0.007	0	0	0	0.697	0.019	0.019	0	1	0.562	33.911
	DCT	0	0	0	0	0	0	0	0	1	0.348	23.244
105	DWT	0	0	0	0	0	0	0	0	99.95	0.076	21.130
	DFT	0	0	0	0	0	0	0	0	99.94	0.118	33.462
	DCT	0	0	0	0	0	0	0	0	99.74	0.077	21.170
106	DWT	0	0	0	0	0	0	0.003	0.003	99.99	0.024	15.671
	DFT	0	0	0	0	0	0	0	0	99.59	0.062	25.422
	DCT	0	0	0	0	0	0	0	0	99.93	0.042	16.2
107	DWT	0	0	0	0	0	0	0	0	99.96	0.087	17.488
	DFT	0	0	0	0.001	0	0	0.019	0.019	1	0.204	25.519
	DCT	0	0	0	0	0	0	0	0	99.92	0.124	18.146
108	DWT	0	0	0	0	0	0	0	0	99.94	0.010	16.678
	DFT	0	0	0	0	0	0	0	0	99.93	0.020	27.348
	DCT	0	0	0	0	0	0	0	0	99.93	0.015	17.622
109	DWT	0	0	0	0	0	0	0	0	99.94	0.067	24.874
	DFT	0.005	0	0	0	0.604	0	0	0	99.58	0.114	41.447
	DCT	0	0	0	0	0	0	0	0	1	0.070	25.924

On the other hand, we use the rule in (4) to extract the binary bits of the watermark from the DFT coefficients respectively.

$$m_i^* = \begin{cases} 1, \text{if } |c_i^*| - \left\lfloor {|c_i^*|}/{Q} \right\rfloor Q \geq {Q}/{2} \\ 0, \text{if } |c_i^*| - \left\lfloor {|c_i^*|}/{Q} \right\rfloor Q < {Q}/{2} \end{cases} \tag{4}$$

Experiments and discussion

At present, there are only three databases that are internationally recognized as the authorized ECG databases, namely, the MIT-BIH database of the Massachusetts Institute of Technology, the AHA database of the American Heart Association, and the European ST-T ECG database. In this paper, we select the ECG data from the MIT-BIH Arrhythmia database [20]. This database includes 48 groups, within two-lead ECG recordings for half an hour, a total of up to 24 hours of information. This database contains 47 individuals' ECG information (datasets ID 201 and 202 are duplicated, so we select different signal segments for our test); subjects consist of 25 men aged from 32 to 89 and 22 women aged from 23 to 89. These ECG data have a sampling rate of 360Hz and a 12-bit binary representation. For each individual, 4096 sample

Table 2 The average execution times for three different transforms

Transform	DWT	DFT	DCT
Average execution time (sec)	1.59	0.33	2.87

periods (or 12 full cardio cycles long) are obtained from the record of his/her ECG signal in the database.

Since the 7-level Haar wavelet transform is applied to the ECG signal, the lowest-frequency subband in level 7 has 32 coefficients. Accordingly, the length of watermark bits $B=\{m_i\}$ is 32. The performance of the proposed scheme is measured by signal to noise ratio (SNR) similarity, root mean square (RMSE), relative root mean square error (rRMSE), and bit error rate (BER) which are defined as follows

$$\mathrm{SNR} = -10\log_{10}\left(\frac{\sum_{i=1}^{N}\left(\widetilde{s}_i - s_i\right)^2}{\sum_{i=1}^{N} s_i^2}\right),$$

$$\mathrm{Similarity}\left(S,\tilde{S}\right) = \frac{\sum_{i=1}^{N} s_i\,\widetilde{s}_i}{\sum_{i=1}^{N} s_i^{\;2}}$$

$$\mathrm{RMSE} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\widetilde{s}_i - s_i\right)^2},\ \mathrm{rRMSE} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\frac{\widetilde{s}_i - s_i}{s_i}\right)^2}.$$

In order to compare the performance, the number of the DCT and DFT lowest-frequency coefficients is also set to 32 and the SNR is fixed for the three transforms by adjusting the embedding strength Q.

The evaluation of watermarked ECG quality

We should maintain the consistency of the watermarked signal and the original signal to the maximum extent possible since the insertion of the watermark will affect the original ECG signal. Figure 8 shows the original and watermarked signals using DWT for dataset ID 100. They look almost indistinguishable. Here the blue curve represents the original ECG signals; and the green curve represents the watermarked ECG signals using DWT.

Table 1 lists the experimental results under the two conditions, number of embedded coefficients=32 and SNR=32.One can see that both interval rRMSE and interval RMSE of the three transforms are almost invariant between the original and the watermarked ECG signal. Moreover, the similarity between original and watermarked ECG signal for these three transforms is very high.

In addition, both DWT and DCT have better amplitude RMSE and rRMSE while DFT obtains bad results.

Experimental environment and execution time

The proposed method was implemented in MATLAB (R2011a) on a standard specification PC with 3.2 GHz CPU and 1 GB RAM. The average execution times of watermarking a patient's confidential data with 4096 samples using three proposed frequency-transform methods are listed in Table 2. The quick execution time for each method shows that the three different proposed frequency-transform methods are all adaptable to doctor in cardiovascular clinic diagnose.

Conclusion

In this paper, the patients confidential data, e.g., name, age, and ID etc., are collected and treated as a watermark for medical data. We apply the quantization watermarking scheme to embed the watermark into the ECG signal. After testing with ten selected data sets from the MIT-BIH arrhythmia database, the difference between the watermarked ECG and the original one is very small and negligible for physiological diagnostics. This confirms that the transform domain quantization scheme for information protection of ECG signal is efficient and useful.

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