Analysis of ECG Bandwidth Gap as a Possible Carrier for Supplementary Digital Data

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Abstract

This paper presents the use of bandwidth gap for embedding supplementary digital data into the ECG record without changing its ability to diagnose. The gap results from overestimation of the constant sampling frequency which is greater than the local bandwidth of cardiac components in large parts of the ECG record. The proposed algorithm starts with conventional beat detection and wave delineation procedures. Next the time-frequency representation is determined and a standard ECG bandwidth function is used to separate the area occupied by cardiac components. The remaining parts, roughly extending from QRS-end to QRS-ons in the 1-st scale and from T-end to P-ons in the 2-nd scale, contain noise and artifacts of given statistical properties. Analysis of these properties opens the opportunity to hide the supplementary digital data stream into variable-size sectors of values having similar statistical properties.

The usability of the method is twofold: (1) for transmission (or storage) of multimodal data through an ECG channel and (2) for hiding sensitive data into a standard record. In the latter case, the record may be recovered (up to 78 characters per heartbeat) or not, depending only on reader's privileges.

1. Introduction

Fast development of telemedical applications for cardiology and common access to the digital content raise questions of data integrity and protection from unauthorized access and modification. Additionally in medicine the records made in a particular patient are further reused in different contexts for epidemiological, statistical or scientific purposes.

Therefore the most useful coding scenario is expected to meet two contradictory criteria: provide integrated, non detachable data fields for storage of fragile content and hide the existence of these field to the eyes of unauthorized user (steganography). Besides the possible encryption, this method additionally protects the data by bringing in question the usefulness of unauthorized access.

This kind of data protection, also referred to as 'watermarking' is commonly used in digital image or audio content and uses the specificity of the data format (JPG, GIF, MP3 or WMA). For medical applications, such data integration is partly supported by DICOM. In case of electrocardiogram, using time series of sample values as most common data containers, it is particularly difficult to hide the existence of supplementary digital data without influencing the diagnostic results. However, certain progress has already be made thanks to the research of Bender (Patchwork) [1], van Schyndel (LSB) [2], and Chen (QIM) [3]. The early watermarking methods were summarized by Kong and Feng [4]. Recently an implementation of low complexity high capacity ECG watermarking was published also in CinC proceedings [5].

The particular idea of hereby presented method is, however, based on the paper by Engin, Cidam, and Engin [6] proposing an implementation of a wavelet based watermarking technique for ECG signals. These authors decomposed the cover-medium ECG with Discrete Wavelet Transform (DWT) and calculated the average power in each of 8 equidistant frequency bands. These values were then used as threshold parameters to select subband-specific values of a hidden message. At the end they used an inverse DWT to reconstruct the ECG signal being stego-medium. Their algorithm is robust, however, they don't use any temporal information accessible in time-frequency domain.

The idea of bandwidth gap results from the research on instantaneous bandwidth of the ECG related to the positions of P, QRS and T waves in the heart cycle [7]. The use of constant sampling frequency of a value appropriate for QRS complex (lasting for ca. 15% of beat's length) leads to oversampling of cardiac components in large remaining parts of the ECG record. This gap was previously explored for possible perceptual compression [8] and denoising of the ECG [9], but it also has a considerable storage capacity. This data carrier may be used for embedding of supplementary digital data into the ECG record without changing its diagnostability.

2. Material and methods

2.1. Analysis of the bandwidth gap

The bandwidth gap extents between the actual bandwidth of cardiac components present in the record and the maximum frequency allowed by sampling theorem (also referred to as Nyquist frequency). Except for experimental applications all recorders use constant sampling frequency adjusted to the component of highest bandwidth, a QRS complex. Consequently, in remaining time (up to 85% in case of NSR), the high scales contain extracardiac noise (e.g. of muscular origin) that could be replaced by a hidden message of similar statistical properties. However, the capacity of such data container depends on two factors:

– length of cardiac cycle, or precisely the distance from the QRS endpoint of the previous beat to the P onset of the subsequent, and
– level of high frequency noise.

Therefore, embedding the hidden message must be preceded by signal analysis aimed at beat detection and determination of selected fiducial points. These procedures are part of standard medical interpretation of the ECG, thus various implementations can be found elsewhere [10, 11]. For sections Q-end-P-ons, additional statistical signal analysis is performed on the first scale of time-frequency signal representation being a carrier for supplementary data. To remain invisible, these data must mimic the noise statistics what limits the coding bit depth to the value used by noise and consequently determines the storage capacity. For example with amplitude resolution of 0.25 μV/LSB, and the noise level of 10 μV, the storage space is 5 bits per sample.

2.2. Processing scheme

The proposed algorithm starts with two steps typical for medical interpretation: heartbeat detection and delimitation of selected wave borders. Next, the Discrete Wavelet Transform (DWT) is performed and the content of the 1-st scale is analyzed between the Q-end and the P-onset of adjacent beats. The analysis yields three beat-specific parameters describing the band gap container for a hidden message:

– the beginning with respect of precedent R peak,
– the length, and
– maximum coding bit depth.

The hidden message, or its part is then coded using selected bit depth and these samples replace lowest significant bits of the consecutive time-frequency coefficients in 1-st scale. First coefficient modified by the message is pointed by the container beginning parameter. If the message is shorter than the container capacity, the container length is adjusted respectively.

Next the container description is coded along with the key pattern accordingly to the format described later in section 2.3, and the inverse DWT recovers the electrocardiogram to the time domain (fig. 1).

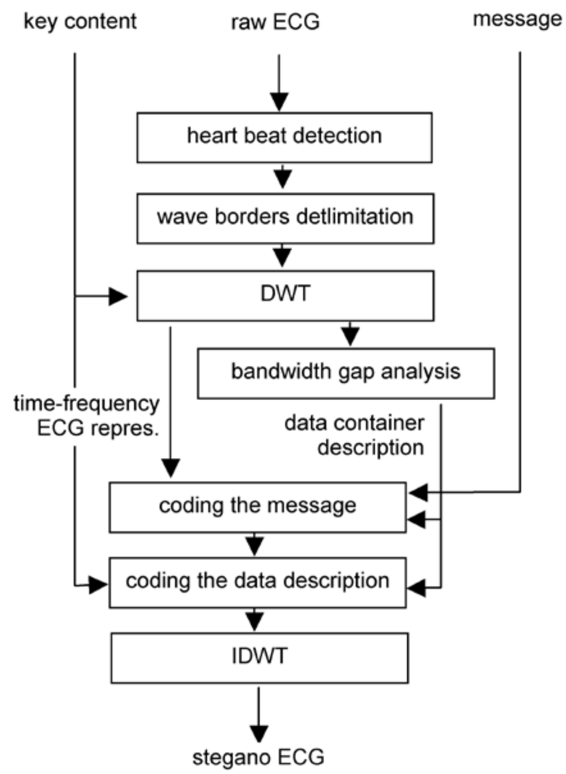

Figure 1. Block diagram of the processing scheme for supplementary digital message encoding.

The decoding algorithm starts with beat detection and positioning of R-wave peak. The signal within the QRS is not affected by the hidden message, consequently positions of R peaks are determined precisely. Next the DWT is performed, and the key pattern is identified in the lowest significant bits of the 2-nd scale coefficients. In case of no matching string could be found, it is assumed that no message has been encoded in this heartbeat for this particular user. Otherwise, data container parameters following the key pattern are used to point and interpret the significant bits of the hidden message.

2.3. Embedding the hidden message

The hidden message is entirely embedded in time-frequency coefficients of the highest scale. The second highest scale is then used for a data description layer. It enables message identification and storage of three descriptors of the data container: relative container beginning (6 bits), container length (9 bits), and message coding bit depth (3 bits). These beat-specific data are preceded by key pattern (up to 12 bits) corresponding to the respective key section. This identification tag is encoded using a simple LSB method in time-frequency coefficients of the second scale and occupies 30 consecutive samples (i.e. 240 ms @ 500Hz). The key pattern starts in a specified R-to-Key (RK) distance from the peak of R wave (fig. 2).

As the term suggests, the key is a fundamental element in embedding the hidden message into the electrocardiogram. To increase the data protection, we use third protection scheme accordingly to Key Steganographic Schemes Classification [12]. Therefore the key consists of three sections with the following functions:

- specification of the wavelet used,
- specification of the RK distance,
- key pattern.

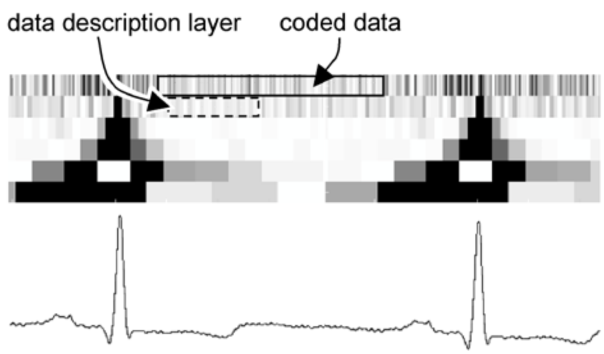

Figure 2. Scheme of data embedding in ECG bandwidth gap.

2.4. Test signals and messages

The proposed algorithm was tested accordingly to the industry standard with use of files from CSE Multilead Dataset 3 [13] recommended by IEC60601-2-51 [14] for the repeatability of wavelength calculation in dependence of supplementary data density. The database contains 10 s Multilead records (leads were used as independent signals) and provides reference wave border points.

The messages used for testing were random series of bytes of length ranging from 16 to 128 bytes. Such storage capacity is expected as corresponding to a 10 s record in case of 1 to 5 bits coding respectively.

We used the commercial IEC-certified interpretation software to assess the influence of supplementary digital data to the accuracy of the wave's delimitation. According to the recommendation, maximum accepted values of inaccuracy were 10 ms (for QRS, PQ and P lengths) and 30 ms (for QT length). Additionally, we calculated the PRD value for the purpose of evaluation of our method in context of other works. Since the size of hidden data container adapt to the ECG content, it is not necessary to separately test the method for various beat types.

3. Results

Main results of testing are deviation values for global durations and intervals for biological ECGs measured accordingly to IEC recommendation (tab. 1).

Table 1. Standard deviations for global durations and intervals for biological ECGs (accordingly to IEC) and average PRD values

coding depth [bits]	deviation of interval duration [ms]				PRD [%]
	P	PQ	QRS	QT	
0 (orig. ECG)	4.51	3.93	3.55	9.82	0
1 (0.5 μV)	4.55	3.79	4.16	10.5	0.03
2 (1.0 μV)	4.81	3.98	4.39	12.3	0.06
3 (2.0 μV)	6.93	4.12	4.89	15.1	0.13
4 (4.0 μV)	9.11	4.33	6.16	18.9	0.27
5 (8.0 μV)	12.5	4.52	8.88	27.1	0.51

First row of table 1 presents inaccuracy of interval measurement of the software used with regard to the reference length calculated from the fiducial points provided by the CSE database. These values, obtained for original database records are in turn references for the assessment of influence of the hidden message coding to the accuracy of diagnostic results.

4. Discussion

Since the average noise of CSE database signals falls slightly above 10 μV, and the signal resolution is 0.25 μV/LSB, coding depth of 5 bits doesn't deteriorate the signal significantly. From the IEC recommendation viewpoint, the acceptable values of standard deviations for global durations and intervals are not exceeded. In case of larger densities, the supplementary data start changing the noise statistics and consequently (1) are more pronounced in statistical parameters and (2) systematically degrade the cardiac components.

Due to the adaptation of hidden data container to local ECG properties, its capacity may be only roughly determined. In the electrocardiogram sampled at 500 Hz with amplitude resolution of 0.25 μV/LSB (where 16 bits correspond to ±8.2 mV) representing a Normal Sinus Rhythm of 72 bpm and average P-QRS duration of 250 ms, the coding depth of 5 bits represent the data stream for hidden message of 725 bps (i.e. 9.1% of the carrier ECG data rate).

Three features of the proposed method are worth highlighting:

- the method doesn't assume a uniform coding of a hidden message, but adapts the container size and modulation depth to best mimic the noise present in the original electrocardiogram,
- each heart beat constitutes an independent data container - by using various combination of RK distance, and key pattern, messages hidden in the record may be selectively accessible to the users of various privileges,
- the hidden message coding doesn't affect the most informative (i.e. medically important) sections in the electrocardiogram (see tab. 1 column PQ).

Future development of the use of ECG bandwidth gap as a possible carrier for supplementary digital data might include efforts towards improvement of data security. These includes data ciphering and usage of fourth protection scheme [12] i.e. influence of key on a message signal bits selection and distribution per container.

Alternatively, the proposed method is simple enough to be suitable for telemedical applications. The usability of the method is twofold: (1) for transmission (or storage) of multimodal data through an ECG channel and (2) for hiding sensitive data into a standard record.

Acknowledgements

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