THE USE OF PREDICTIVE CODING FOR EFFECTIVE COMPRESSION OF VECTOCARDIOGRAMS

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Abstract: The paper presents a sequence coding technique applied to the compression of vectocardiograms. The loops corresponding to P, QRS and T waves in an appropriate temporal window form Groups Of Beats (GOB). All inner loops in a group are predicted using the neighboring loops' values and the prediction error is subject to encoding. The lossless Huffman coding and the lossy DCT-based coding are considered and discussed in the paper. Detailed study of various compression aspects is provided thanks to the numerical experiment carried out for a wide range of parameters. Results of both methods are quite promising: the method preserving loops identity reduces the data volume 3 times (i. e. 2000 bps) and the lossy version reaches the reduction ratio of 4.15 times at a price of 5% PRD distortions.

Introduction

The wide use of electrocardiography (ECG) and the spread of long-term ambulatory recorders need the low cost and effective solutions for data storage and transmission. The compression of the ECG signal attracts the attention of searchers all over the world and despite many interesting proposals were already published, it remains one of the hottest topic of research in biomedical signal processing.

The vectocardiography (VCG) is the conceptual and methodological extension of the ECG and performs three-dimensional imaging of the cardiac electrical field. For the lack of clear interpretation guidelines, the VCG was underestimated for years, but recently, thanks to the use of numerically supported spatial transforms, it is more and more appreciated in clinical practice. In consequence, the VCG is considered for implementation in clinical and ambulatory equipment and concerned by the data compression requirements as far as the conventional 12-lead ECG.

Motivation

Some of the features exhibited by the VCG signal are a good reason to handle the consecutive heartbeats or their parts as a sequence of events.

- In conventional 12-leads electrocardiogram the concentration of diagnostic information in the sections of P, QRS and T waves is sometimes questioned. In vectocardiograms, however, all diagnostic results are derived from the analysis of the spatial loops representing the waves.
- The role of the signal segments belonging to the waves' outside is thus reduced to continuous joint between the loops. This joint assures the correct synchronization of waves and the baseline continuity but, in principle, does not contain the electro-diagnostic data.
- In consequence, the extra-wave sections may be subject to extensive data reduction, while the waves should be processed carefully in order to maintain their's medical aspects as close as possible to the original.
- The correlation of consecutive heartbeats is very high except for occurrence of serious diseases (e.g. T-wave alternans). Our preliminary statistical studies show that the average probability of co-occurrence of two consecutive beats drops dramatically with the increase of their dissimilarity. That was the foundation of a class of compression algorithms called "long term prediction" applied to the conventional electrocardiogram [1]. Despite of high efficiency, main drawback of these methods is the ambiguous behavior in presence of high cardiac rhythm variability.

Adapting the motion compensation technique

At the origin of our approach was the inspiration by the motion compensation technique applied in the MPEG video sequence-coding scheme [2]. In fact the consecutive isolated spatial loops in the VCG recording meet all the assumptions made for the image sequence. Our algorithm consists of three stages: pre-processing, prediction-correction and error coding.

Several alterations were necessary to adapt the image sequence-coding scheme to the properties of VCG loops. Our algorithm uses three data streams for the P-waves, QRS-waves and T-waves sequence separately. The group of beats (GOB) consists of variable count of consecutive loops, because the regularity of the sinoatrial rhythm may be interrupted by the occurrence of ventricular contraction. The loops are normalized in 3D amplitude and resampled in time in order to compensate the beat-to-beat variability of heart rate. The loops bordering every GOB, the "intra-coded" or I-loops, are encoded with use of the simple differential technique, but all the internal loops are predicted and the error of the prediction is subject to encoding. Since these errors are usually expressed by low dynamic range values, the use of Huffman coding yields very interesting results. To this point only the lossless compression techniques are involved, thus the compression guarantees the identity of the original and reconstructed VCG loops.

The further research for the maximum compression ratio yielded the lossy version of the VCG predictive coding. It differs from the algorithm described above by the use of Discrete Cosine Transform (DCT) for its energy compaction properties. Allowing a certain distortion level by truncating the DCT-domain sequence of data economizes a significant amount of coefficients that do not have to be stored.

Details on the VCG-loops encoding scheme

Only the most relevant processing stages are described in this chapter. Although the processing concerns three loop sequences, the algorithm performs similarly for all of them and thus the QRS sequence only is taken into account for description (fig 1). The lossy algorithm is presented hereafter, and for the lossless compression the DCT step should be omitted.

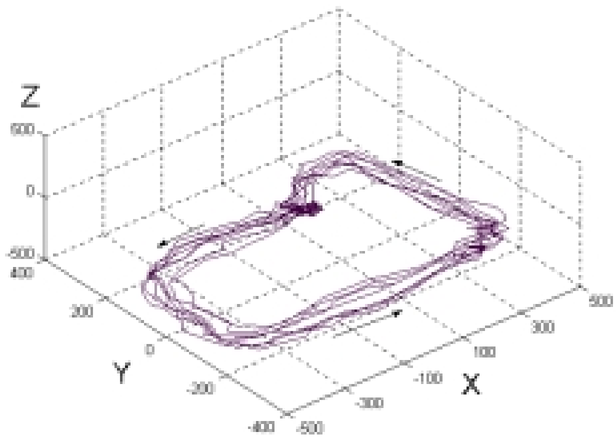

Figure 1. A 3D plot of the sample QRS-loops GOB

A. The pre-processing stage

The pre-processing stage starts with detection of the heartbeats and determination of their morphology. The sinoatrial beats are identified by the occurrence of a unique P-wave in a given time interval before the QRS-onset. All beats not complying with this rule, as well as atrial premature beats are given a distinguishing mark.

The step performed immediately after is the precise segmentation of the P, QRS and T waves representation. The baseline is then simplified as much as possible with use of the decimation technique. At the decomposition level corresponding to the frequency range of 0...2 Hz (sampling interval 250 ms) the differentiated values of XYZ-leads are stored in the output data stream.

The loop processing begins with the temporal normalization. The loop duration is re-scaled to the given count of samples and the original count is stored for correct decompression. The resampling is achieved by cubic spline interpolation of each of XYZ trace followed by sampling the interpolated sequence at the individually computed ratio. The goal of the temporal normalization is to make the loops length identical, not dependent on the actual wave duration. The normalization of the loop amplitude is the last step of the pre-processing stage.

B. The prediction-correction stage

The input for the prediction-correction stage is a GOB being a sequence of at most N loops bordered by the I-loops at each end. The GOB may be shortened by the occurrence of a heartbeat featuring the distinguishing mark. In this case the preceding loop ends the GOB. If a GOB contains less than three loops, all of them are I-loops and are encoded with use of the differential technique applied separately to X, Y and Z trace representation. Otherwise, two prediction stages are applied to the internal loops. The first level prediction loops, "coarse" or C-loops, are selected so as they were regularly distributed in a GOB. The values of C-loops are predicted basing on the I-loops values. The true values of C-loops are in turn starting points for the calculation of values for the second level prediction loops, the "fine" or F-loops, that lay in between of them (fig. 2). All the predictions involved are bi-directional, since they use past and future loops to estimate current values. Except for I-loops, in all other cases only the signals of prediction error for the traces X, Y and Z are subject to further processing.

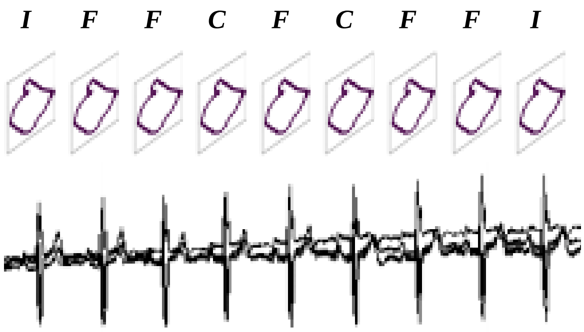

Figure 2. The loop types sequence in a GOB

The occurrence of escape beats or arrhythmia events affects the harmony of the GOB composition, forces the premature GOB's ending, increases the global contribution of I-loops and results in lower compression ratio.

As far as the lossless version of the compression algorithm is concerned, the prediction error values are encoded directly. Otherwise, an optional step is performed aiming at decorrelating the data. Thanks to the properties of the DCT, the increase of compression efficiency is expected at a price of medically negligible distortions. A set of DCT coefficients representing the prediction error values is truncated at specified energy level and encoded - instead of the raw prediction error values - using the Huffman algorithm.

C. The encoding stage

The prediction error values for the traces X, Y and Z or their DCT-domain representation are characterized by very narrow histogram (fig. 3). An optimal solution aiming at the lossless data reduction for such kind of values is the Huffman coding. Fortunately, all the data to encode are known beforehand, thus the sophisticated dynamic algorithm is not required. In addition, the statistical properties of these three traces are similar and thus the common Huffman tree is appropriate for all error values in the GOB. In this way the space required for two more lookup tables may be economized in the output string.

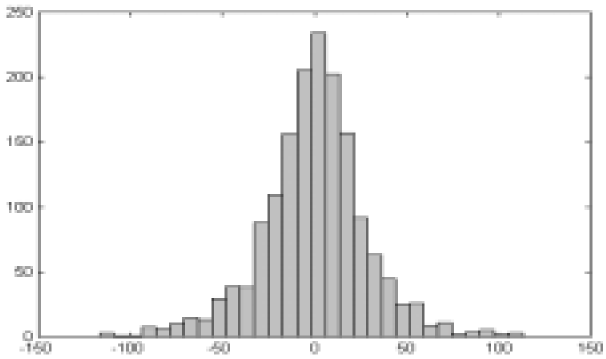

Figure 3. The histogram of prediction error values

Implementing and testing the predictive coding of vectocardiograms

Both versions of predictive coding algorithms were subject to the numerical experiment verifying their properties using a set of sample VCG signals. The source of test signals was the CSE-Multilead Database that contains 125 original 10s traces acquired with use of the pseudo-orthogonal XYZ Frank leads. The quantization level is 12 bits per value and the simultaneous sampling is done at the frequency of 500 Hz. All the procedures were implemented in Matlab, except for heartbeat detector and segmentation procedure that were obtained from the commercial ECG equipment manufacturer as executable files. Both of them comply with the CSE requirements for detection reliability and segmentation accuracy and receive wide recognition in the medical world since three years of implementation into a family of stand-alone automatic recorders.

After detection and segmentation of the heartbeats, each loop is attributed the type I C or F determined accordingly to the beats' origin. The bandwidth of the segmented signal is then split with use of seven decimation steps and Lifted Wavelet Decomposition [3] (LWD) featuring the orthogonal integer decomposition. The highpass part of the signal is reconstructed back from the detail coefficients of each step and segmented for extraction of P, QRS and T waves. The lowpass component is encoded as a continuous differential signal at the sampling rate of 4 Hz in the whole GOB.

The loops for P and QRS waves are represented by 64 samples of integer values ranging from 0 to 32767. For T waves, rarely containing high frequency components, the effective representation length was studied separately. Unfortunately, due to the use of cubic splines, the temporal normalization is the only floating-point procedure and has to be followed by the rounding the results to the nearest integer.

The prediction errors are encoded with use of the Huffman coder or, in the lossy version, are subject to the DCT. The floating-point DCT domain representation is then quantized and truncated at a level that guarantees the conservation of a given percentage of the energy. The processing ends with encoding in the Huffman coder the fixed-point DCT representation of prediction errors.

Results

Main results of the compression performance testing are given respectively: in the Table 1 for the lossless algorithm and in the Table 2 for the lossy but more efficient version. To explain the difference between the total and P, QRS and T waves distortions, the temporal distribution of distortions is displayed in the figure 4.

Table 1 Compression performance of Huffman coding applied to raw prediction errors (lossless)

CSE No	HR	CR	distortions (PRD %)			
			total	P	QRS	T
1	80	2.83	5.9	0.83	0.14	0.42
2	143	2.11	17.4	0.31	0.11	0.37
124	87	3.81	22.7	0.73	0.12	0.31
125	91	2.95	19.1	1.02	0.10	0.41
average	95	3.02	16.9	0.64	0.15	0.38

Table 2 Compression performance of Huffman coding applied to DCT coefficients of prediction errors (lossy)

CSE No	HR	CR	distortions (PRD %)			
			total	P	QRS	T
1	80	4.19	6.26	0.83	0.14	7.90
2	143	2.57	17.6	0.31	0.11	6.87
124	87	5.20	22.9	0.73	0.12	1.96
125	91	4.65	19.6	1.02	0.10	4.52
average	95	4.15	17.2	0.64	0.15	5.59

Figure 5 displays the result of linear regression of the average Heart Rate (HR) and the Compression Ratio (CR). The prediction of CR is very important for proper management of memory resources in a real application. Accordingly to our findings, it may be estimated from the HR with the confidence of 85%.

Figure 6 summarizes the compression efficiency and corresponding T wave distortions for different lengths of T wave representation used during the experiment.

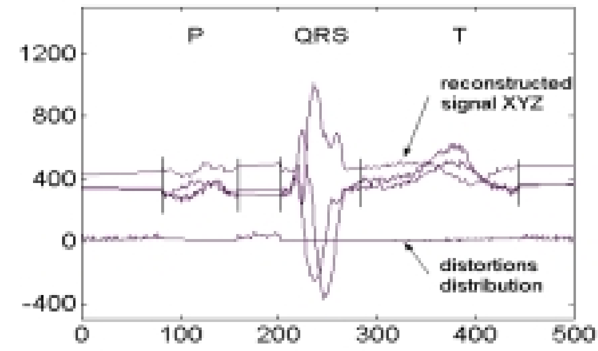

Figure 4. Temporal distribution of distortions

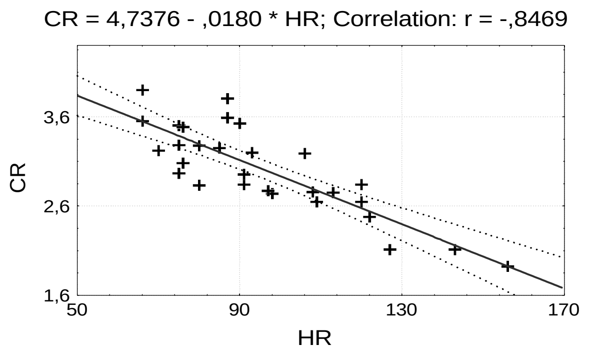

Figure 5. Heart Rate and Compression Ratio correlation

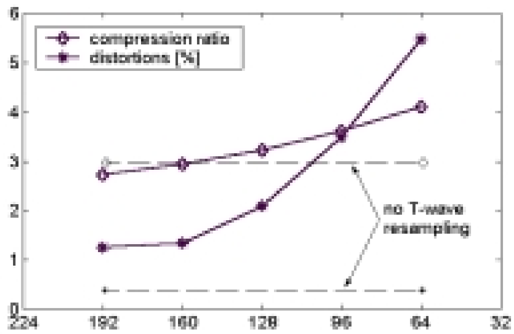

Figure 6. Compression efficiency and T wave distortions for different lengths of T wave representation

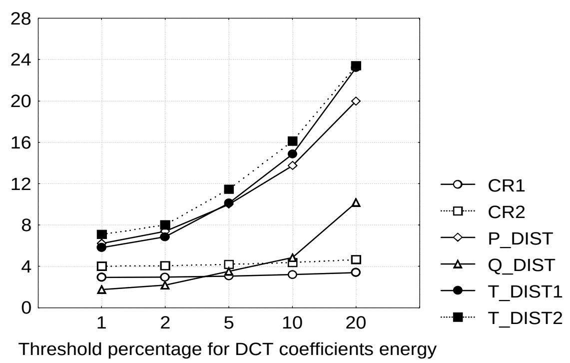

Figure 7. The compression ratio (CR) and waves distortion [%] for different threshold energy percentage in the DCT domain, CR1 and T_DIST1 are for no T-wave resampling and CR2 and T_DIST2 are for T-wave representation in 64 samples (maximum squeezing).

And finally, the Figure 7 displays the compression efficiency and corresponding distortion values for P, QRS and T waves achieved during the energy thresholding of DCT coefficients.

Discussion

The method of predictive coding for the compression of vectocardiograms was designed, implemented and tested in various aspects. The algorithm fulfils the general expectation of preserving the medical contents of the signal, and achieves highest compression ratio than other lossless general-purpose methods. That was possible thanks to the concentration of distortions in the diagnostically meaningless parts of the signal. The side effect is the high correlation of the compression efficiency to the Heart Rate.

Two ways of enhancement the value of compression efficiency were studied experimentally. The resampling of T wave yields the appreciable gain in efficiency at a price of reasonable distortion percentage (i. e. 5%) affecting the T wave only. Two sources of distortion may be distinguished in the processing:

- Quantization of the standardized waves representation (some distortion occurs also in other waves),
- Data reduction during the standardizing of the waves length (appreciable mainly for T-wave as a result of neglecting a little part of the original bandwidth).

The improvement of compression efficiency with use of the DCT is very poor due to the lowest than expected initial correlation of errors in consecutive loops. On the other hand, the rapidly growing distortion coefficient, concerning in this case all the loops, is the reason for discouragement from further using the DCT decorrelation method.

In the future, another VCG loops synchronization method, like a three-dimensional optimal superposition, should be applied in order to increase the compression efficiency without distorting the compressed signal [4].

Acknowledgement

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