Physiological ECG Compression Based on Integer Time-Frequency Pattern Matching

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Abstract
This paper deals with the problem of effective and low-distortion ECG compression. The principle of our algorithm is the local adaptation to the medical contents of the signal rather than to its technical features. The data reduction ratio is modified accordingly to pre-detected time-domain signal events such as P, QRS and T waves. This approach maximizes the signal diagnostability, often not concerned by technical measures of distortion. The output bit rate is modified with time - the most natural for processing is thus the time-frequency domain. Our method identifies and correlates patterns of time-frequency coefficients representing the consecutive heartbeats gathered from highest three octaves (16-125 Hz) in P-QRS-T surroundings. High compression ratio is obtained in particular for long signals due to representing the whole coefficients set by one item of the dictionary. The test against the standard MIT-BIH Arrhythmia Database results in average compression ratio 7:1 (425 bps) and the distortion coefficient PRD rarely exceeds 5%.

Introduction
In the course of our research into the ECG signal, we focused on the variability of diagnostic information distribution along the time axis. In some regions of the signal, related to the waves start- and endpoints, its content is diagnostically more important than in the remaining part. These regions and the function of importance variability can be identified by measurement of the electrocardiograms instantaneous bandwidth [1]. To determine the parts of heart's evolution particularly sensitive to distortion, we carried out an experiment consisting in windowed random canceling of t-f representation and tracking the changes in diagnostic parameters quality [2].
The discrete ECG signal can be split into two components:

- the continuous low bit rate coarse approximation (CA) signal,
- the separate detail (SD) signals carrying the complementary high frequency information for more important signal sections.

Assuming the correct synchronization between the consecutive beats, the corresponding time-frequency coefficients (TFC) sets have high degree of similarity. Thanks to a low but non-zero dissimilarity level one high frequency pattern (HFP) from the dictionary is representative for several sets of TFC. The storage of all TFC for a SD component is no longer necessary, since the index in the HFP dictionary is sufficient to correctly reconstruct the ECG content from archive. Comparing to various wavelet-based algorithms published before [3,4,5], the superiority of our method consists in the priority of the medical parameters of the signal over its technical features. These features are extracted with use of the segmentation subroutine, designed for diagnostic purpose, in a new unusual function: as compression pre-processor. The detected wave borders modify the processing indirectly. They are temporal reference points for the generalized expectations on the ECG signal contents in the following domains:

- expected instantaneous bandwidth,
- vulnerability of derived medical data to local distortions,
- expected dynamic range of TFC.

Consequently, the algorithm achieves high efficiency in the non-relevant segments of the signal (e.g. baseline) and preserves the signal quality in the regions of high medical importance (P, QRS and T waves).

Method

The target application of the compression algorithm is a real time DSP-based portable ECG recorder, however at the experimental stage, the methodological design is made in the Matlab environment. The general scheme of the compression algorithm consists of the following procedures:

1. Detection of heartbeats and delimitation of P, QRS and T waves edges (also called pre-processing),
2. Normalization of the P-T section in temporal domain,
3. Deriving the t-f representation (TFC) of the P-T section with use of a transform grid synchronized with the R-wave,
4. Adaptive discrimination of TFC based on local energy and error information (the set of threshold-passed TFC is the HFP representing a particular heartbeat),
5. Verification of local compression error with use of inverse t-f transform,
6. One pass HFP classification,
7. Storage and management of all the signal components

To avoid multiplying spare patterns representing similar heartbeats in the dictionary of TFC, we determine a synchronization point for every heartbeat in the ECG signal. The numerical investigations justified the R-wave peak as the optimal choice of such point. Since the HFP contains TFC for three upper octaves only, we set the corresponding synchronization point in the t-f plane as so it begins the t-f atoms in all these octaves. Such points occur in the interval of the third octave's atom length - in our example every 64 ms (the signal sampling frequency 250 Hz). In consequence, the decomposed signal section must always start at a multiple of 64 ms before the R-wave peak.

Discrimination of TFC is a particularly difficult and sensitive task aimed at identifying all the essential TFC that are indispensable for correct signal reconstruction. As we attempt to manipulate the contents of the signal that may be life-critical, special attention must be paid to the distortion checking procedures:

- inverse time-frequency transform;
- quasi-continuous time-frequency domain model of the noise.

The discrimination of TFC is immediately verified by comparison of the modified time-frequency signal representation to its original version and the parameters of compression process are corrected if the threshold distortion ratio is close to be exceed. Additionally, the instantaneous signal quality is verified by beat to beat measurement of the frequency contents in the baseline section. This measurement updates the quasi-continuous model of the ECG-noise and modifies the threshold distinguishing the essential TFC values and the TFC representing the noise.

Making for the final implementation in a DSP chip, the programmer’s point of view should no longer be neglected. For this reason, we decided to use a lifting wavelet transform that maps integers to integers [6], fulfills the orthogonality and the compact support requirements and is feasible in the hardware. The transform properties depend on the filter orders and the number of lifting steps. Considering the hardware implementation we used the simple Haar filters and 5 iterations of lifting that corresponds to a canonical wavelet of 5-th order.

Every heartbeat represented by the TFC set subjects to the classification that aggregates similar beats and in consequence represents them by a common pattern. The classified beat is tested for best suitable membership in every existing class by comparing every TFC with the corresponding TFC of class kernel.
If all TFC values fall in expected range, the average distance beat-to-kernel is computed. This single factor expresses the degree of correlation of a beat to a class and is used for making the optimal choice of the target when the beat fits in with more than one class. This optimization contributes to maintain the distortion at the lowest possible level.
In case of a beat can not be successfully assigned to any existing class, new class is registered unless the maximum class number is reached. Registering a new class consist in creating its kernel, being equal to the first beats' pattern, and in computing TFC error margins for each frequency band separately.
In case of a very complex signal, even after the maximum class number is reached, there are still patterns not assigned to any existing class. That involves the use of substitute storage format: patterns, accompanied by specified flags, are sent directly to the output file. In such cases the compression efficiency drops giving priority to keeping the given distortion ratio.

Results

A numerical experiment has been designed and carried out aiming at the verification of main features of the newly proposed compression algorithm. The input electrocardiograms were taken from the MIT-BIH arrhythmia database [7]. All experiment procedures were implemented in Matlab, except for pre-processor obtained from the commercial manufacturer as executable file. Investigations were expected to answer the following fundamental questions for each half-hour ECG file:

- global compression ratio,
- global distortion coefficient (measured by PRD ratio),
- the amount of created patterns,

The abstract of results obtained for test ECG files are displayed in table 1 (the whole table has 44 entries).

Tab. 1 - Main features of high frequency pattern matching ECG compression tested with use of the signals from MIT-BIH arrhythmia database

MIT/BIH number	true QRS count	number of patterns	distortion (PRD %)	compression ratio
100	2272	6	1.17	7.46
101	1865	13	3.22	7.43
102	2187	37	5.70	7.18
103	2084	19	3.87	7.35
104	2228	71	4.57	6.88
...	...	...	...	...
232	1780	22	2.73	7.31
233	3078	14	1.81	7.44
234	2753	36	2.40	7.13
average	**2488**	**31**	**4.77**	**7.07**

Discussion

Although table 1 displays results for only eight half-hour Holter recordings, main features of the newly proposed time-frequency pattern matching ECG compression could easily be generalized:

- compression efficiency is fairly high taking at low distortion level for P-QRS-T section,
- even if the global distortion coefficient exceeds 5% (as in case of file 102), the most important sections of signal containing P-QRS-T segments do not differ from the original by more than 1.4 %, that is guaranteed by the error checking procedure
- compression ratio depends on the QRS number (HR), class number and number of beats requiring direct storage of TFC patterns (substitute format)
- the number of created patterns depends on signal complexity and quality - the remarkable correlation with distortion coefficients should be investigated in the future
- the maximum pattern number, set to 256, has never been reached.

Comparing to the ASEC algorithm [8], yielding the best compromise of storage efficiency and signal quality, our results are similar for high transmission rates (425 bps, PRD = 4.7%). The behavior of our algorithm in presence of noise and uncommon recordings should confirm the practical usefulness of our algorithm. Its main advantage is the physiology-based control of distortion distribution in time. In consequence, samples are economized mainly in the non-relevant sections of the signal and the medical contents remain almost untouched.

Acknowledgment

This project was funded by AGH Univ. of Science and Technology, grant No: 10.10.120.39

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