THE ECG-DEDICATED COMPRESSION METHOD USING HIGH FREQUENCY PATTERNS

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Summary

This work deals with the problem of effective and lossless ECG compression. The proposed method uses pre-processed signal with delimited start- and endpoints of P, QRS and T-waves. Our method searches for non-specific patterns of time-frequency coefficients in highest three octaves in the P-QRS-T region. High compression ratio is obtained for long signals mainly (e.g. Holter recordings) due to sending or storing one pattern number per beat instead of the whole set of coefficients.

1. INTRODUCTION

In one of our preceding work we noticed that the diagnostic information is not equally distributed along the ECG's time axis. There are regions, related to the waves start- and endpoints, of highest importance than the remaining part of signal. These regions and their function of importance were identified by measurement of the electrocardiograms instantaneous bandwidth. Our first proposal [1], derived consequently from the observed nature of the data stream, consisted in encoding the highest octaves of electrocardiograms time-frequency (t-f) representation as separate signals, named "separate details" (SD), when necessary. To maintain the distortion as low as possible, the reconstruction error was continuously checked and, in case when too high, the threshold value discriminating the t-f coefficients (TFC) was modified. That first approach resulted in design of the compression method that was practically lossless in the P-QRS-T section, and lossy for the remaining part of ECG.
As we got familiar with the SD signals, containing on average 60% of all TFC stored in the output file, new idea arose allowing the improvement of compression efficiency. This idea consists in searching for repetitive high frequency patterns in consecutive beats' t-f representations. Certainly, two TFC sets, describing two beats, are expected to be close but not identical to be classified together. The value of acceptable dissimilarity is set for each frequency band separately, and depends on global energy and octave energy values. Introducing the acceptable error level will cause the whole compression process to be lossy, but the only distortion will appear in high frequencies and only when TFC do not contain much energy.
This concept is in fact an intersection of widely discussed "pattern matching" compression methods [2], [3] and recently developed in our laboratory "separate details" coding.

2. MATERIALS AND METHODS

2.1. General compression scheme using high frequency patterns coding

Although the compression is designed to work in real time, our experimental implementation process the signal stored on a hard disk. It is made in the Matlab 5.2 experiment environment. Up to present, only the methodological investigations were interested to the authors and no effort towards the speed optimisation was made. The general scheme of the compression algorithm consists of the following procedures:

- detection of the heart beats and delimitation of waves edges,
- signal transformation to the t-f domain,
- adaptive discrimination of TFC with use of local energy and error information as well as general knowledge on ECG instantaneous bandwidth,
- verification of local compression error with use of inverse t-f transform,
- one pass classification of three highest octaves' TFC strings,
- storage and management of essential signal components.

The processing scheme is presented in the figure 1.

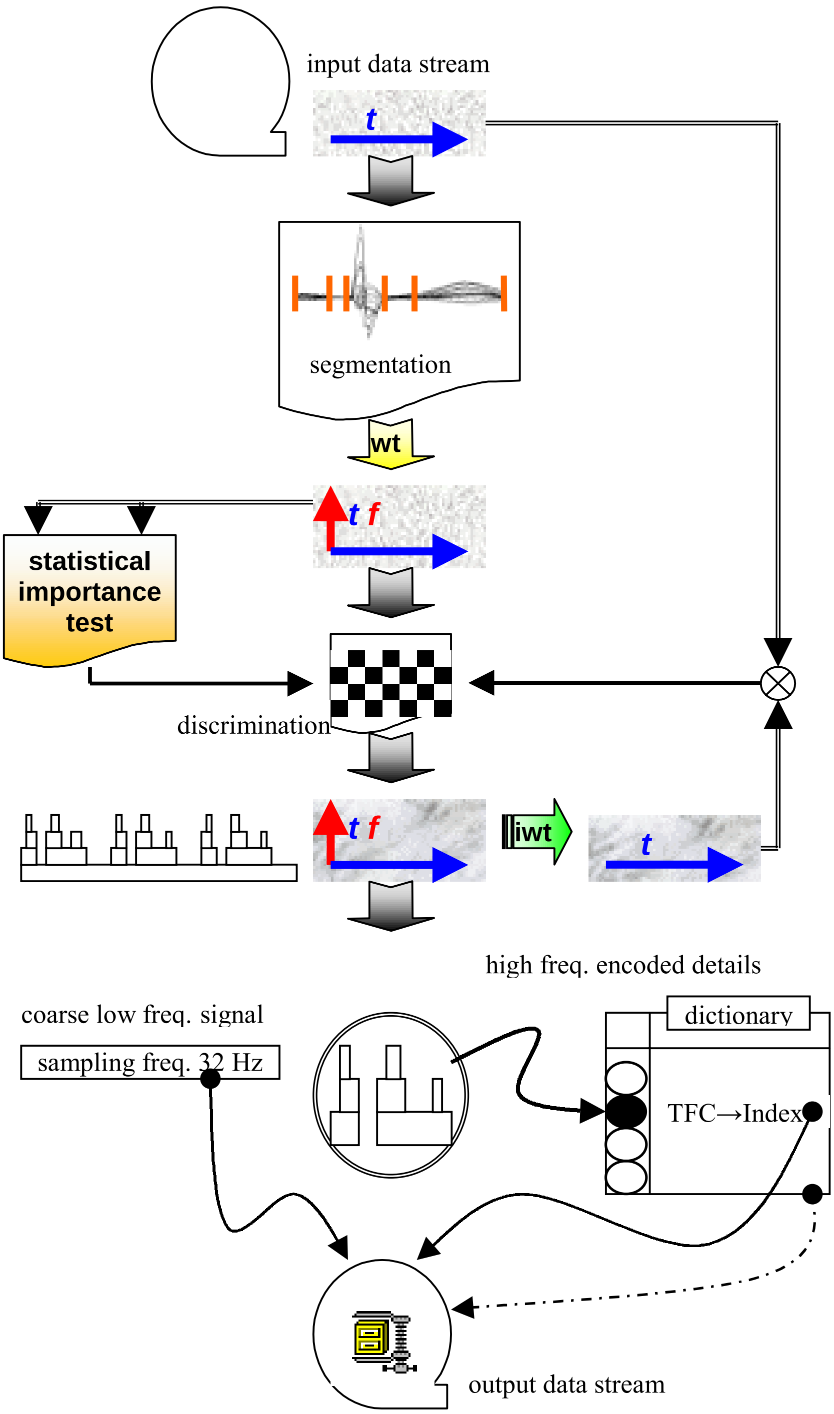

Fig. 1 The general scheme of the compression algorithm

2.2. Details on adaptive discrimination of time-frequency coefficients

Discrimination of time-frequency coefficients is the true modification of signal content. This is a very responsible task to detect the essential t-f coefficients that are indispensable for correct signal reconstruction.

Finding the right representation of the information distribution in electrocardiogram was main scientific interest of us and some other workers at our Laboratory. Several methods are still used to derive and confirm the function of local diagnostic importance of an ECG signal. Two of them are quite good converging and confirmed as appropriate also by the medical co-workers:

- local bandwidth of a typical electrocardiogram [4],
- local susceptibility to distortion caused by random cancelling of TFC [5].

Having considered all features of those, we finally decided to use the instantaneous, or local, bandwidth of ECG as source of a priori knowledge about the expected nature of an ECG. Figure 2 displays the function for an average P-QRS-T segment.

The discrimination of t-f coefficients detected as redundant and not carrying the essential diagnostic information is done in t-f domain. The input signal is decomposed and decimated down to the depth of level four. Therefore the original sampling frequency of 250 Hz results in four half-band frequency ranges of 0 ... 16 Hz, 16 ... 32 Hz, 32 ... 64 Hz and 64 ... 125 Hz. The decimation was not performed for lower frequencies because:

- the investigation showed low relationship of information density and ECG waves for low frequencies,
- the effective sampling rate was 32 Hz, that corresponds to 32 ms sampling interval, for lower sampling frequencies the waves start- and endpoints may fall in neighbour samples,
- the data stream for a signal sampled at 32 Hz is relatively low, and there is no interest for compression to modify the low frequency range.

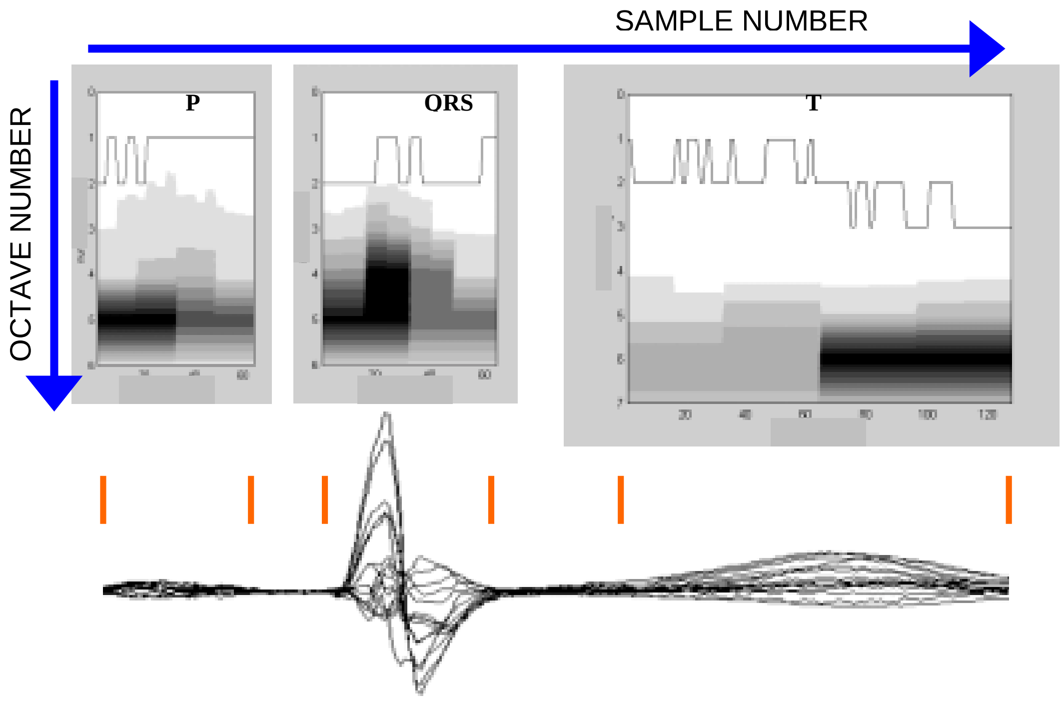

Fig. 2 Averaged normalized time-frequency planes (wavelets) of main components of heart beat along with multilead signal in time domain; black lines separate coefficients representing less than 5% of instantaneous energy; sampling frequency is here 500 Hz.

2.3. Details on reversible wavelet transform

Provided the instantaneous bandwidth is a function in t-f domain, the use of a reversible t→t-f transform is necessary. From a big choice of transforms widely used, we selected the 5-th order Daubechies wavelet transform [6]. Main reasons for that choice, except for technical, were:

- thanks to the orthonormal decomposition it fulfils the condition of losslessness, that is necessary to control all signal properties in t-f domain and guarantees that every charges in the output signal result from the manipulations done in t-f domain,
- the support of Daubechies filters is compact and relatively short, the use of 5-th order filters is a compromise between the support length and frequency bands separation.

Figure 3 shows details on orthonormal filters used in wavelet decomposition and the pyramid decimation scheme.

2.4. Pattern classification method

For each heart beat, after extraction of TFC strings representing highest three octaves, the classification procedure is executed. The currently classified beat is tested for membership in every existing class by comparing every TFC with those of class kernel.

If all values fall in expected range, an average distance beat-to-kernel is computed. The single value estimates the force of correlation of a beat to a class and facilitates the optimal choice of target class when a beat fits in with more than one class. This rather time consuming procedure contributes to maintaining the distortion at the lowest possible level.

In case of a beat not assigned to any existing class, a new class is registered unless the maximum class number is reached. Registering a new class means to create its kernel, that is equal to the first beats' TFC set, and to compute error margins for each frequency band separately. The acceptable TFC range depends on:

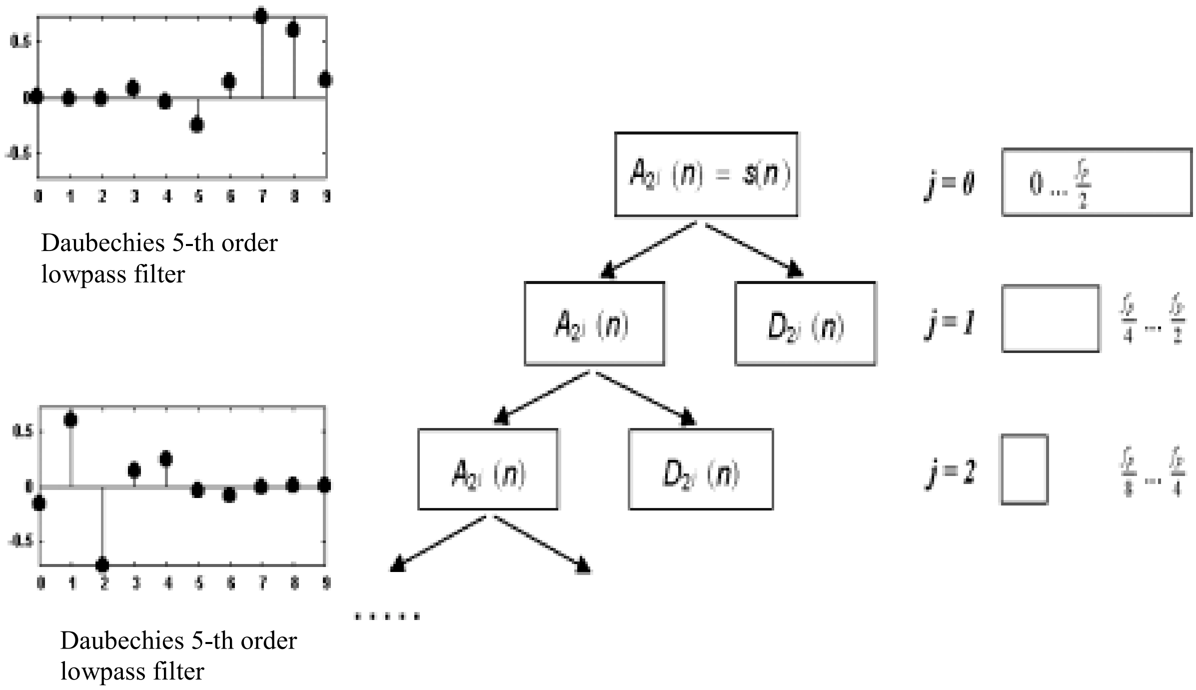

Fig. 3 The non-zero parts (support) of 5-th order Daubechies orthonormal filters and pyramid decimation scheme. On the right the signal length and its spectral contents are displayed symbolically.

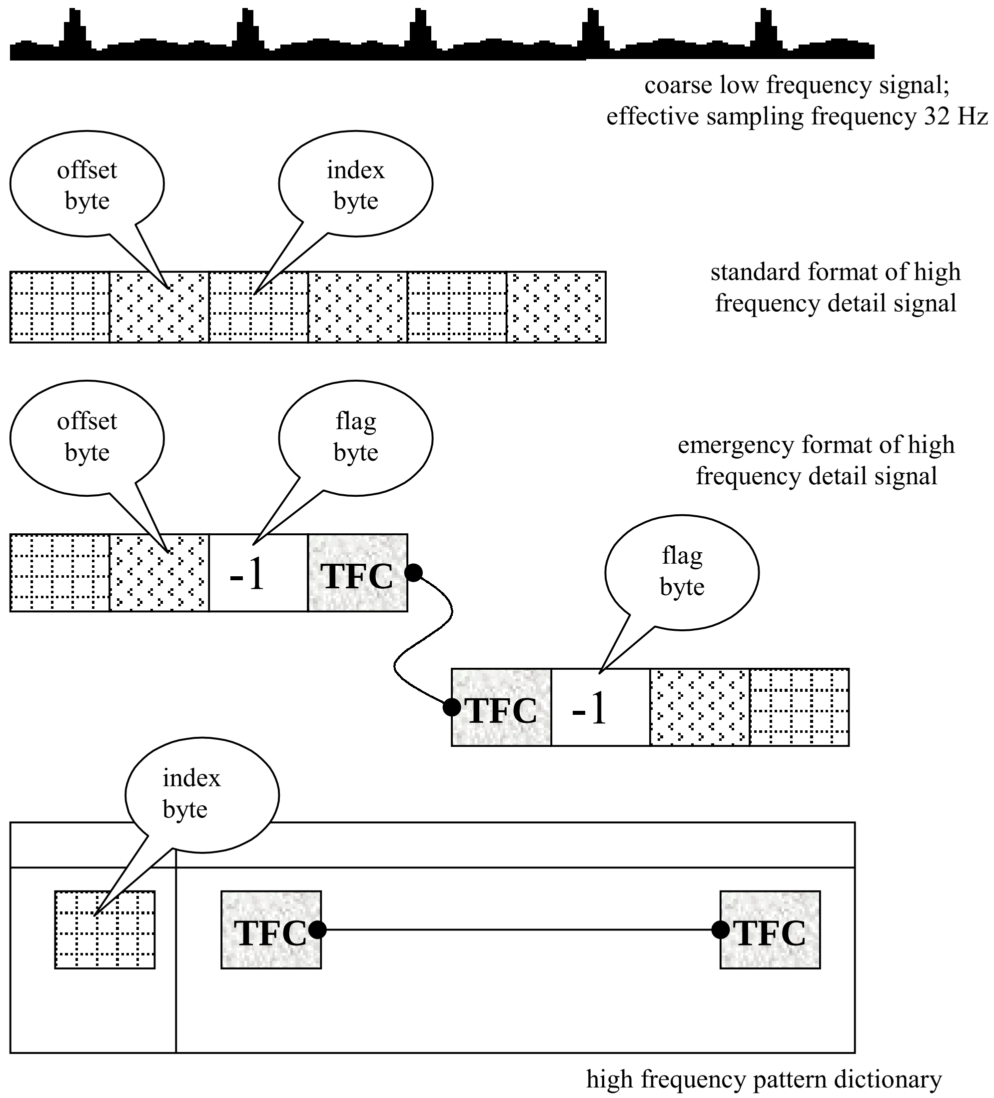

Fig. 4 Detailed structure of compressed signal

- global energy in a specified time zone for all represented frequency bands G,
- total energy, equal to a sum of all TFC in particular frequency band T,
- frequency band number B,
- global error parameter set as input value of the compression process E.

The heuristically elaborated formula for computing the TFC range ε is as follow:

$$\varepsilon = E \cdot (1 + \frac{1}{B}) \cdot (0.05 \cdot G + 0.15 \cdot T) \qquad (1)$$

This method of computing class borders was used in all numerical tests described hereby. However this highly important step influencing all the compression features is still discussed and should be considered for future investigation.

In case of very complex signal, when the maximum class number is reached and there are still beats not belonging to any existing class, the high frequency representation of those beats, accompanied by specified markers, is sent directly to the output file. That makes sure not exceeding a given distortion ratio at a price of compression efficiency, but all known compression methods fail similarly in case of noisy or unstable signals.

2.5. The structure of compressed signal

The compressed signal consists of three main components:

- continuous coarse signal,
- high frequency pattern index,
- high frequency pattern dictionary.

The main part of an ECG's energy is still stored/transmitted in the time domain. The continuous signal of a bandwidth 0 ... 16 Hz represents main ECG features and is a coarse approximation of the input data stream. Maintaining this signal in time domain in the output stream has several advantages:

- it is ready to display, no additional processing is needed if only general overview is required,
- it consists of low bitrate data stream, the corresponding sampling frequency equals 32 Hz,
- even at so low sampling rate, main ECG features are still possible to reconstruct in case of accidental pre-processing failure,
- the detailed high frequency signal can be added by simple summation of its time domain strings synchronised to the continuous signal.

The high frequency pattern index is accompanied by a synchronisation byte determining the point in the continuous signal where the beginning of detailed signal should be aligned. In case the maximum pattern number is reached, detail pattern numbers for some beats may not exist, and the raw string of TFC, marked by a leading and terminating –1 flag, is stored instead. This protects the unstable signal from being distorted. Assuming that all beats are compressed in that way, the method converges to the previously elaborated "separate details" coding.

The high frequency pattern dictionary contains the TFC patterns for all used class kernels. The pattern index refers directly to the pattern table entry. Figure 4 contains the graphical explanation of the compressed signal contents.

3. NUMERICAL VERIFICATION OF MAIN PROPERTIES OF THE PROPOSED COMPRESSION METHOD

In order to verify main features of newly proposed compression algorithm, a numerical experiment has been designed and executed. Ten examples of input electrocardiograms were taken from the MIT-BIH arrhythmia databases [7]. All experiment procedures were implemented in Matlab, except for pre-processor. The "black box" procedure was available as executable file only, and during the experiment was called from the main environment. Both recorded channels provided by database were considered for pre-processing simultaneously but once the waves were detected, the remaining part of experiment processed only one selected channel with higher signal-to-noise ratio. Investigations were expected to answer the fundamental questions for each half-hour ECG file:

- global compression ratio,
- global distortion coefficient (measured by PRD ratio),
- the amount of classes created,
- the number of pre-processor failures.

The results obtained with test ECG files displays table 1.

4. RESULTS AND DISCUSSION

Although table 1 summarises results for only 10 half-hour Holter recordings, main features of the newly proposed high frequency pattern matching ECG compression could easily be generalised:

- compression ratio is fairly high when comparing to other known algorithms,
- compression ratio depends on QRS number, class number and number of beats for that TFC are stored directly,
- pre-processor errors are very infrequent and do not influence significantly the compression ratio,
- the number of created patterns depends on signal complexity and quality, the remarkable correlation with distortion

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

MIT/BIH number	True QRS cnt.	pre-processor failures		patterns number	effective samples at output	distortion (PRD %)	compression ratio
		f p.	f n.				
100	2274	0	0	6	60330	1.17	7.46
101	1874	0	0	13	60540	3.22	7.43
102	2192	1	0	37	62641	5.70	7.18
103	2091	0	0	19	61192	3.87	7.35
104	2311	2	1	71	65449	4.57	6.88
105	2691	1	1	53	64266	3.28	7.00
106	2098	0	0	15	60940	1.33	7.38
107	2140	0	1	22	61522	2.73	7.31
108	1824	1	0	14	60414	1.81	7.44
109	2535	0	0	36	63087	2.40	7.13

coefficients should be investigated in the future.

- the maximum pattern number, set to 256, has never been reached but it may happen in case of all-day recording,
- even if the 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 5%, that is guaranteed by error checking procedure; on the contrary, this is an example of inappropriate use of PRD without taking under consideration the variability of information density.

Having completed this first try out of the high frequency pattern matching ECG compression, we feel surprised by its outstanding parameters. Although the results of our experiment are promising, we keep awareness of several difficulties that may affect its performance in a real application:

- the influence of noise and unstable signal often provided by simple portable recorders to the distortion and compression ratio; the sources of errors are: pre-processor failures, difference of signal and its expected bandwidth, huge number of patterns due to the interference of noise,
- the algorithm is very complicated and includes: beat detection, waves delimitation, forward and inverse wavelet transforms, statistical test, classification and many others; even so, we still hope for the technical reasons to implement it in a real equipment,
- the function representing the information distribution in electrocardiogram is still investigated, and may be subject of changes in the future; the general problem is here getting the objective information from the medical staff,
- problems may occur also for very uncommon and complicated signals that differ from the expectation too much to be reasonably represented by a pattern; in worst case the high frequency pattern matching ECG compression converges to "separate details" coding developed previously, with the average compression ratio of about 5; in typical Holter recordings, sections having such features do not last for long time.

The behaviour of algorithm in presence of noise and uncommon recordings should be the next task to verify the practical usefulness of our algorithm. Another positive results may maintain the hope for implementation.

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