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THESIS ABSTRACT

Contributions to Remote Monitoring of the Electrical Activity of the Heart

The theme of the PhD Thesis is justified by the necessity to prevent cardiac diseases, whose frequency of occurrence is alarming, as stated by studies and statistics of institutions accredited to perform investigations in the medical domain. National statistics show the decease of a person suffering from a cardiac illness every ten minutes, a situation which does not represent a consequence of old age anymore. Worrying is also the fact that, in Romania, the age of persons prone to heart attack has dropped under 45 years. A non-invasive method of preventing cardiac diseases is constituted by the monitorization of the electrical activity of the heart, with the aid of the electrocardiogram (ECG monitoring) or magnetocardiogram (MCG monitoring).

The ECG represents a simple method for diagnosing heart diseases, each deviation from the accepted standard shape of the component segments of the ECG signal (the P-wave, the QRS-complex and the T-wave) indicating the existence posibility of a cardiac illness. Being a non-invasive clinical investigation method, the ECG is presenting some degree of uncertainty and is thus implying some risk of incorect diagnosis.

The MCG is representing a recent tehnique of monitoring of the cardiac activity, being still in an experimental stage regarding the data acquisition in an unshielded environment. MCG signals are an alternative to ECG signals, useful especially for fetal cardiac monitoring. The magnetocardiography is an non-invasive procedure of analysis of the cardiac activity, alike to electrocardiography, during which are measured the biomagnetic fields generated by the electrical activity of the heart, thus constituting a useful environment for the diagnosis of cardiac illnesses. The difference between the two techniques is given mainly by the way of acquisition of the signals: the ECG signals are recorded using electrodes in contact with the skin of the patient, while the MCG signals are recorded using transducers placed some 2-3 cm from the human body.

The MCG data used in the present thesis have been provided by the research institute *Institut fuer Photonische Technologien IPHT*, Jena, Germany during a research stage at the university *Technische Universitaet Ilmenau*, Germany The ECG data are from the Michigan Institute of Technology, U.S.A. (MIT-BIH) publicly available database.

The intensity of the magnetic fields generated by the human body being very small, very sensitive technique is necessary (the MCG technique developed at IPHT, Jena is using Superconductive Quantum Interference Devices - SQUID sensors).

The present research is aims in a first stage at offering an aid to the physician when pre-diagnosing cardiac diseases, through the amelioration of the ECG interpreting task. The second stage consists in offering the technical means to allow the remote monitoring of the electrical activity of the heart. Combining different signal processing techniques, the thesis aims at increasing of the opportunity of putting a correct medical diagnosis.

Wavelet analysis has been proposed as an alternative to Fourier analysis, the present PhD thesis aiming at the development and testing of processing algorithms for the main acquisition and remote monitoring steps: the reduction of the baseline wander of ECG and

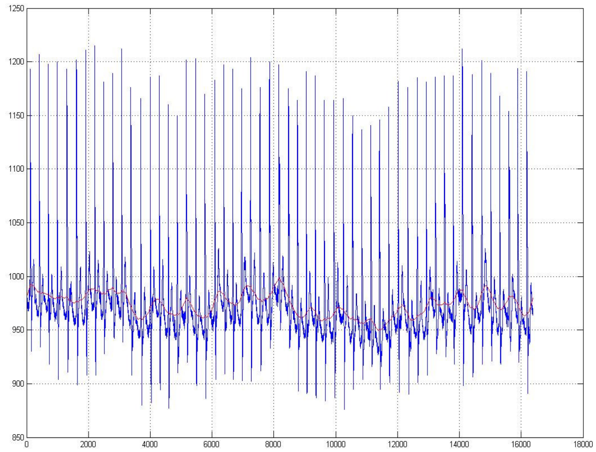
MCG signals, the reduction of the acquisition noise, the compression of the signals for their remote transmission and the reconstruction of the compressed signals. The obtained results are exemplified both in a qualitative and quantitative way, comparisons with other methods being presented in each chapter. Also, a first step for completing the research concerning the remote monitoring of the cardiac activity with an automated diagnosis system, has been proposed: a first step made in this research direction has been realized through the elaboration of a first method for the detection of the QRS complex, destined to facilitate the work of the physician and to open new research perspectives.

The thesis is structured on six chapters. **The first chapter** is an introductory one, describing the general frame of thesis.

In the **second chapter** are described the two types of analyzed signals, the ECG and MCG signals. A synthesis upon the working principle of the cardiac activity and upon the acquisition and interpretation of the electrocardiogram and magnetocardiogram has been realized, so as to exemplify some possible cardiac diseases which might be treated as a diagnosis' consequence and for allowing thus a general view upon the theme of the thesis.

The third chapter is an introduction to the wavelet theory, regarded from the time-frequency representation perspective. The main theoretical aspects of the wavelet analysis are synthesized and presented. The features of the main types of wavelet transforms are presented: the Continuous Wavelet Transform, the Discrete Wavelet Transform and the Stationary Wavelet Transform, in order to facilitate the understanding of the processing algorithms proposed in the next chapters of the thesis. Also, comparisons have been realized between the Wavelet Transform and the Fourier Transform for focusing the advantages of applying the wavelet analysis to the non-stationary biomedical signals. In case of quasi-periodical signals, like the biomedical signals are, the information contained can be accessed with more difficulty, because the time interval at which events occur is also important and modifications occur rapidly as well. Because the classical Fourier analysis allows the characterization of a signal only in the frequency domain, more general methods have been studied for the representation of the signal both in the time and frequency domain, called time-frequency representations. One of them, the *Short Time Fourier Transform STFT*, is presenting the drawback of a fixed temporal resolution of the analysis window (imposing thus certain limitations in practical use). This drawback might be avoided using the wavelet analysis. Time-frequency representations of the wavelet type may simultaneously offer information in the time domain and in the frequency domain of the analyzed signal. The basis functions of the wavelet analysis are obtained through the dilation and translation of a single function, called *mother wavelet MW,* thus segments of the signals necessitating different ways of processing may be analyzed applying to time-frequency atoms with different temporal supports, through the corresponding choice of the MW function. The specific properties of the wavelet transform, such as a good covering of the time-frequency plane and a fast implementation of the computation algorithm, recommend the use of wavelets for biomedical signals, like ECG or MCG signals.

In the **fourth chapter** have been developed and tested a series of algorithms, based on wavelets, comprising the main steps of remote monitoring using ECGs: baseline wander elimination, denoising, compression and reconstruction of ECG signals. The practical applications have been implemented using the *Matlab* environment and tested on real data, from the publicly available MIT-BIH database, facilitating thus the performance comparison of the proposed methods with other similar methods encountered in scientific literature. In the first paragraph has been proposed a method for baseline wander correction of the ECG signal, using the advantages offered by wavelets. Inspired by the procedures used for the regression of time series, the method is estimating the baseline drift using the Stationary Wavelet Transform SWT and performs the correction computing the difference between the acquired ECG signal and this estimation. The main parameters of the method are: the mother wavelet and the number of decomposition levels (iterations). A method of computing the optimal iteration number has been proposed, taking into account the sampling frequency used at the acquisition of the ECG signal and the fundamental period of the ECG signal, which may be estimated measuring the pulse of the patient. The method is taking thus a parameter of the analyzed signal into consideration. For the MIT-BIH database (the sampling frequency is 360 Hz) has been chosen a number of 8 decomposition levels. The sequence of the approximation coefficients is representing the estimation of the baseline, while the sequences of the detail coefficients are eliminated. Thus is obtained a new sequence of wavelet coefficients, from which, by applying the inverse transform ISWT, the estimation of the baseline wander is obtained. The described operation being a non-linear one, the proposed method may also be regarded as a non-linear time-frequency method. Finally, the difference between the acquired ECG signal and the estimation of the baseline wander is computed, obtaining thus a corrected ECG signal (see fig. 4.7). The estimation method proposed is equivalent to a low-pass filtering of the ECG filter using a special filter, a special method of constructing such a filter being also proposed, through the product of a prototype frequency response with scaled versions of the same function. Through the performed simulations have been proven that optimal results for the baseline drift elimination are obtained using the Daubechies 5 mother wavelets.



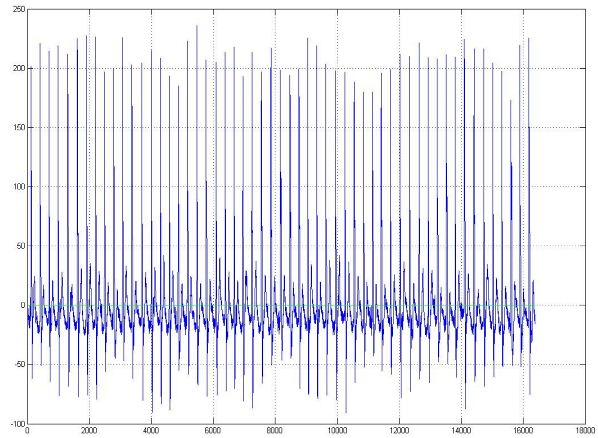


Fig. 4.7 a) ECG presenting a baseline drift b) Corrected ECG.

The second paragraph is presenting a denoising method. The algorithm of this method is exploiting the translation invariance property of the SWT. The denoising method proposed for ECG signals is taking into account the additive nature of noise, generating two results: the estimation of noise-free ECG and the noise estimation, which can be obtained computing the difference between the acquired signal and the estimated signal. The proposed algorithm is applying a *bishrink* filter in the wavelet domain, this filter being a Maximum A Posteriori MAP filter, which is taking into account the interscale dependence of the wavelet coefficients. The proposed filter has been constructed from a-priori premises regarding realistic statistical repartitions of the useful and noise coefficients. Tests upon ECG signals affected by real noise have been performed, provided by the MIT-BIH database, for evaluating the performance of the proposed method. SWT is computed using a mother wavelet with a good time-frequency localization property (like the mother wavelet with two vanishing moments, Daubechies 2), a number of 8 decomposition levels being selected. The obtained results are presented in fig. 4.23.

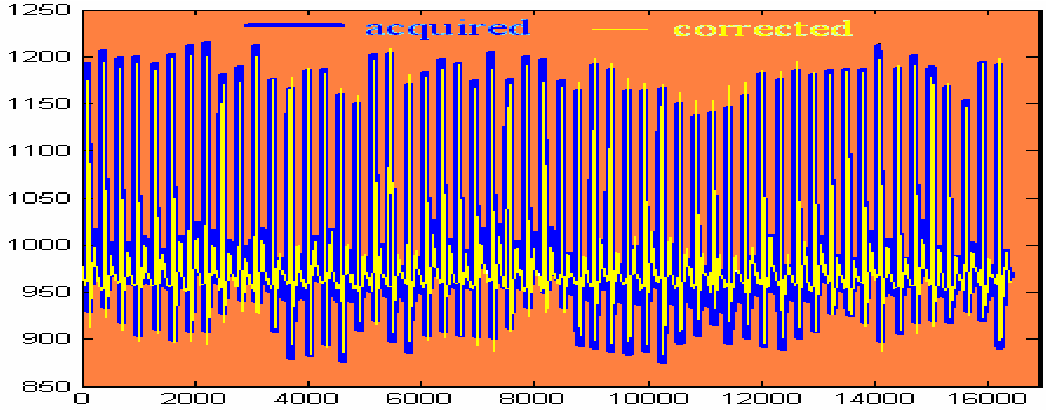


Fig. 4.23. The superposition of the original input ECG signal (blue color) and the ECG signal obtained after baseline wander correction and denoising (yellow color).

The third paragraph deals with the problem of remote transmission of the ECG signals, offering solutions based on wavelets for the compression of these signals. A long-term monitoring is increasing the chances for a timely diagnosis of a cardiac illness, but is generating at the same time an important amount of transmitted information. For eliminating this inconvenience, compression methods based on the Discrete Wavelet Transform DWT have been developed. Two compression algorithms have been proposed. The first method is presenting a simple compression algorithm of biomedical signals using wavelets. The simplicity of the concept allows an easy implementation and a good working speed. The necessity of taking into account the quantization of the wavelet coefficients has been demonstrated, the quantization operation influencing the distortion rate of the compression method. The wavelet coefficients have been quantized on 11 bits in order to keep the resolution of the original ECG signals from the MIT-BIH database. A strategy for selecting the parameters of the method has been also proposed based on the evaluation of a quality factor, dependent on the ratio between the compression ratio *CR* and the distortion factor *PRD*. The procedure allows the selection of the optimal association between the mother wavelets used at the DWT computation and the threshold value (necessary for distinguishing the useful wavelet coefficients), so as to improve the compression quality. It has been demonstrated that the *PRD* factor does not represent the best method for measuring the distortions of the ECG signal reconstructed after compression. The *PRD* may take small values for visible distorted signals. As the diagnosis for ECG signals is put on visual inspection, a visual criterion for appreciating the results seems more indicated for this kind of biomedical signals. The compression algorithm based on wavelets has been further developed. The second compression method proposed is using the subband coding property of the DWT (see fig.4.37), obtaining thus a better compression factor than in case of the method proposed in paragraph 4.3.1. Each detail subband level has been treated independently, the threshold value being chosen taking the standard deviation of the respective subband into consideration.

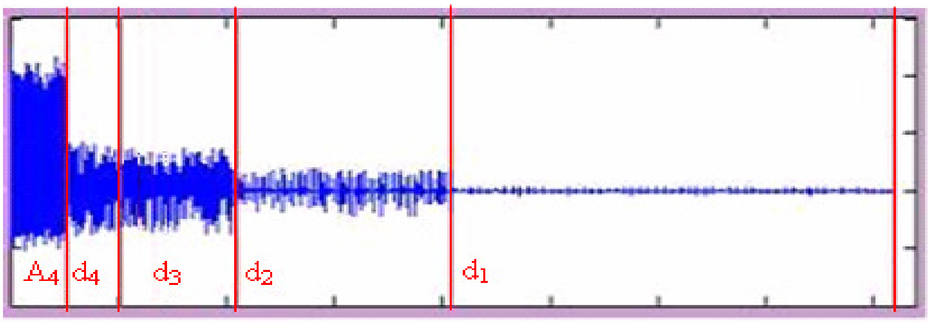


Fig. 4.37. The subband distribution of the wavelet coefficients sequence: the approximation coefficients sequence and the four detail coefficients sequences.

An optimization algorithm of the performances has been proposed, which takes into account the main parameters: the mother wavelets, the number of vanishing moments, the number of decomposition levels. The method has been tested on a significant number of ECG signals from the MIT-BIH Arrhythmia Database, considering several orthogonal and biorthogonal mother wavelets families. The three processing procedures of the ECG signal, necessary for a remote monitoring system of the cardiac activity (baseline wander correction, denoising and compression of the ECG signal) have been thus tested using both orthogonal and biorthogonal wavelet functions. A reduced number of decomposition levels has been selected (five levels of decomposition), so as to obtain a reduced computational time and a good reconstruction of the signal. The algoritm has been tested for limit situations, using strongly perturbed ECGs. The baseline drift correction method offers good results when using biorthogonal mother wavelets, the denoising method allowed the reduction of electromyographic noise and the compression results displayed a competitive compression ratio, the advantage of the method consisting in its reduced computational effort. Therefore an adaptive compression algorithm based on wavelets is useful ECG signals processing, the obtained compression ratio is around the value of 15. The adaptive compression method allows the obtaining of a significant *CR* without distorting the useful components of the analyzed ECG signal (see fig. 4.40).

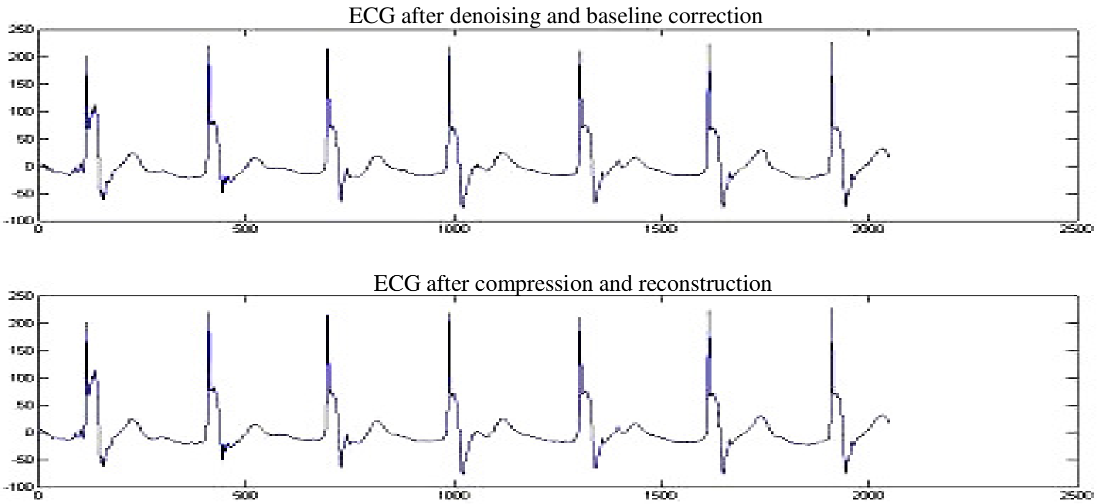


Fig. 4.40 Zoom upon seven beats of the original ECG signal 102 and the reconstructed signal.

The last paragraph of the fourth chapter is presenting a first algorithm for the automated detection of the QRS complex. Although it does not constitute the main theme of the present PhD thesis, the automatic detection of the complex is aiming at facilitating the physician’s work. The proposed algorithm is combining classical iterative methods with more recent methods based on wavelets, using the SWT. The method proposes the detection of the R-wave using one single step and taking into consideration the characteristics of the analyzed waveform: the local maximum of each segmentation block is detected, the temporal localization of the detected peak being also retained for further applications of the algorithm. The time localization is important for biomedical signals, like the ECG signal, and this property is exploited when detecting the onset and offset of the QRS complex. Both the onset and the offset of the QRS complex are detected applying to the previously detected temporal localization of the R-peak, the detection method being thus considered adaptive. The necessary number of samples for a standard duration of the QRS complex is symmetrically distributed left and right of the two minimum points framing the R-peak, determining the onset and the offset of the QRS complex, as can be seen in fig. 4.60. The validation step of the method results is aiming at avoiding detection errors or false detections. Comparisons of the proposed methods with other methods from the scientific literature have been realized, indicating the competivity of the obtained results.

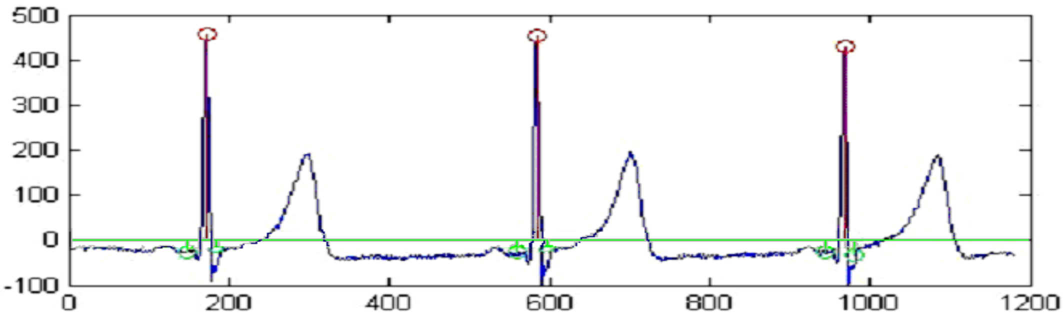


Fig. 4.60. The detection of the QRS complex for the ECG signal 113.

The fifth chapter deals with the problems specific for magnetocardiograms processing. The baseline wander reduction method based on SWT, previously developed for ECG signals has been adapted to the features specific for MCG signals, provided by the IPHT institute, Jena. As an example, the sampling frequency in this case is 1 kHz. The method’s features, the mother wavelets used and the number of decomposition levels have been adapted to the particularities of the MCG signals. The proposed correction method for the baseline wander is using the SWT, the mother wavelets Coiflet 4, 10 decomposition levels and is satisfyingly treating the baseline drift reduction problem (see fig. 5.6 respectively fig. 5.8). A reduction of the baseline drift after the application of the method may be noticed. The denoising method, based on wavelets, for the reduction of the MCG signals’ acquisition noise has also been developed and optimized, facilitating thus the putting of a correct diagnosis by the physician. The proposed method is retaining only the detail coefficients presenting higher values than a threshold value, while the other coefficients are perceived as noise and eliminated. The denoising procedure based on wavelets is reducing only biologic noise caused by muscular activity, a noise which is representing a main noise source for ECG signals, but which is not not very marked in case of MCG signals due to the more strong magnetic interferences.

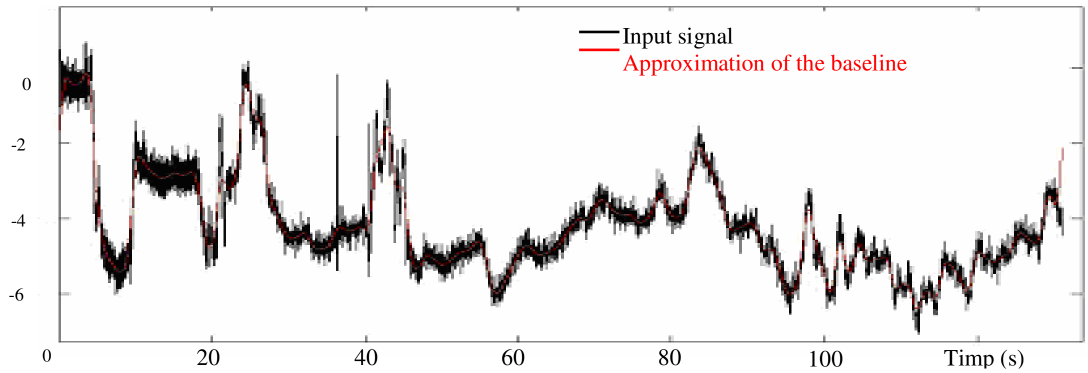


Figure 5.6. The estimation of the baseline using the Daubechies2 mother wavelets.

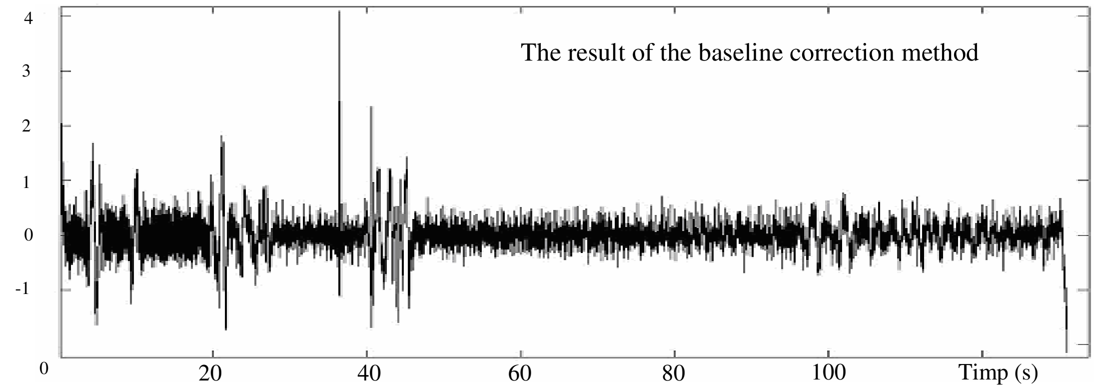


Figure 5.8. The result of the correction method for the baseline wander of the MCG signal.

The compression method based on wavelets is simple as a principle and fast and easy to implement in consequence. In chapter four has been underlined the necessity of taking the quantization of the wavelet coefficients in consideration, when analysing a compression method destined for data transmission. The quantization step is inducing some distortions in the data compression procedure. In order to reduce these distortions, the features of the method have to be appropiatively chosen: the wavelet transform used, the mother wavelet used for the computation of the wavelet transform and the threshold value. The selection strategy proposed is based on the computation of the quality factor, dependent on the compression ratio and the *PRD* factor. The compression algorithm previously developed for ECG signals (chapter 4.3.1) has been adapted, taking into consideration the characteristics of the magnetocardiograms, so as to test its performances for MCGs also. Several features of the compression algorithm have been taken into consideration, such as the mother wavelets MW used for the computation of the DWT, the number of vanishing moments of the MW and the number of decomposition levels of the DWT. The threshold value for the wavelet coefficients has been adaptively chosen as a function of the quantization step. The compression ratio obtained is around the value of 4.59, a value comparable to those obtained for ECG signals using the first compression method proposed, but the algorithm is more stable. No visible distortions of the reconstructed MCG signal may be perceived (see fig. 5.20). A quantitative measure of the results is given by the *PRD* value. The values obtained are higher than those obtained for ECG signals, but they are within the limits accepted in scientific literature. A cardiac remote monitoring system should be taken into consideration also for MCG signals for enhancing the opportunity of a timely diagnosis of an increased number of patients.

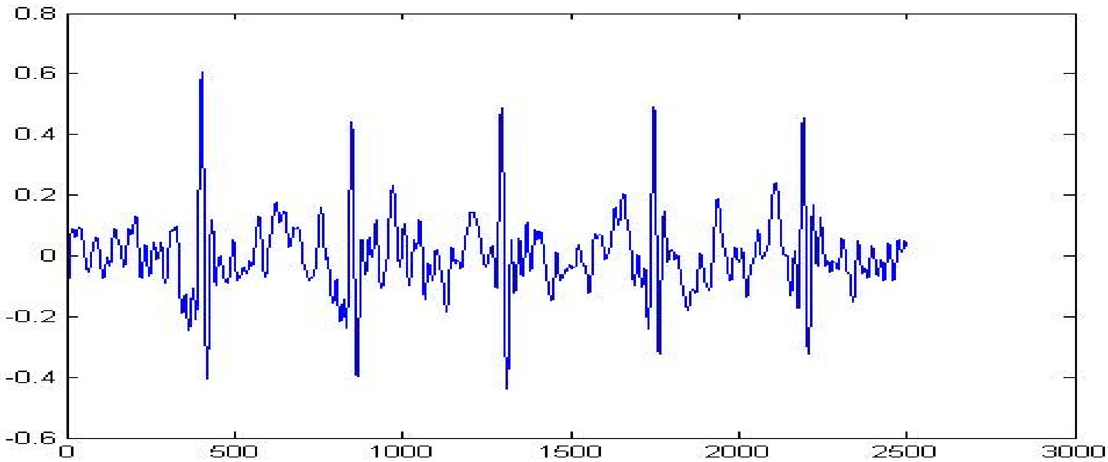


Fig. 5.20. The MCG signal reconstructed after compression using the Db20 mother wavelets and 7 decomposition levels.

As a conclusion, wavelets are offering a good flexibility and allow the development of processing methods both for ECG and MCG signals, which take into consideration the signals' characteristics for optimizing the parameters and contributing thus to a remote monitoring of the electrical activity of the heart. The three algorithms proposed in paragraphs 4.1, 4.2, 4.3 respectively 5.1, 5.2, 5.3, elaborated using the *Matlab* software have been interweaved to form an unit, the flexibility of the methods allowing the separate choice of the parameters for each stage, so as obtain optimal results. The present PhD thesis upon remote monitoring of the electrical activity of the heart may be completed with a automatic diagnosis system. A system of this kind should comprise a segmentation in the component waves (the P-wave, the QRS-complex and the T-wave) of the ECG and MCG signal and an automatic identification of pathological cases based on the analysis of the component waveforms. A first step in this direction is constituted through the elaboration of a first detection method for the QRS-complex (presented in paragraph 4.4), destined to facilitate the physician's task and to open new research perspectives.