Testing Biorthogonal Wavelets on Magnetocardiogram Processing Algorithms

B. Arvinti, M. Costache and R. Stolz

Abstract The paper studies the influence of biorthogonal wavelets upon several steps of the processing of magnetocardiograms recorded in stress conditions: baseline drift correction, denoising, and compression. The implementation of a novel technique implies the performance of several tests in order to define the optimal parameters of the algorithms. Therefore, simulations have been performed using several biorthogonal families of mother wavelets. Analyzing the results, we notice that even a high baseline drift is properly corrected and that the denoising performances are better, compared to orthogonal wavelets. Also, there has been obtained a significant improvement of the compression ratio, enabling the development of a more competitive monitoring system.

Keywords Wavelet analysis · Magnetocardiogram · Biorthogonal wavelets

1 Introduction

Magnetocardiograms are an investigation tool suited for evaluating the well-being of the human heart. Electrocardiograms (ECGs) and magnetocardiograms (MCGs) provide similar information, but MCGs are better suited for fetal investigations, as they are not influenced by the protective substance covering the fetus skin [1].

The MCG method is a passive, noninvasive one, the signals being acquired using a measurement system based on SQUIDs (**S**uperconducting **QU**antum **I**nterference **D**evice) in order to measure the magnetic field produced by the human body [2]. The human heart generates electrical signals, with a specific shape

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(Fig. 1). The form, time extend, and recurrence of the P wave, QRS complex, and T wave provide vital diagnosis information [3, 4].

- P wave: describes the depolarization process of the atria and presents the following characteristics: it is rounded, symmetrical, positive, monophasic, showing an amplitude between 0.1 and 0.2 mV and a time length of 0.1 s.
- The QRS complex: corresponds to ventricular depolarization and presents three phases, being composed of two negative waves with small amplitude and one high amplitude positive component. The complex is having an amplitude of 1–2 mV and a duration smaller or equal to 0.1 s.
- The T wave: represents the terminal point of the ventricles' repolarization. It is rounded and asymmetrical in shape. The amplitude is approximately 1/3 of the QRS complex. The time is 0.15–0.25 s.
- The U wave: corresponds to the complete relaxation of the ventricles and usually is not to be seen on ECGs.

This activity can be captured and outlined using either ECGs or MCGs. Usually, a timely diagnosis might prevent the evolution of heart diseases, a fact clinically important especially for fetal recordings. Before the implementation of each novel technology, extensive tests have to be performed so as to choose the optimal parameters. Wavelet algorithms are suited also for the design of automated systems, which can improve the benefits of modern medical care. An automated system needs the preselection of certain features in order to show the best performances, the main feature of wavelet analysis being the mother wavelet.

The wide use of MCG technology in clinic environment was restricted through the necessity of cryogenic equipment and through the presence of magnetic disturbances usually of much higher amplitude than the signals to be measured. To overcome the disturbance, magnetically shielded rooms can be used, but it would imply the design and construction of a special room for the acquisition of MCGs. This would limit a large-scale utilization of the method in any hospital or medical environment.

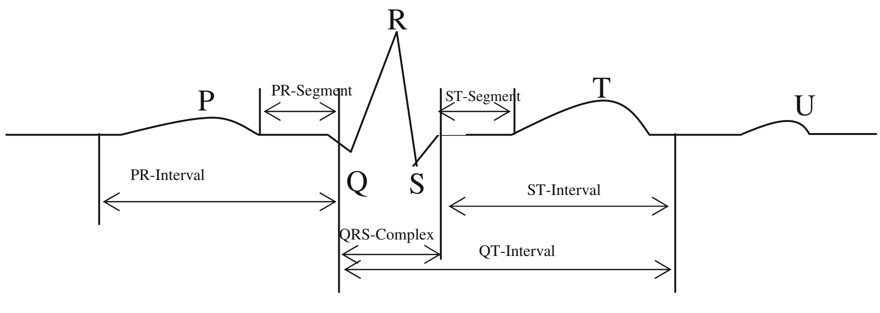


Fig. 1 Standard ECG

Therefore, the MCGs used in the paper were acquired in an unshielded environment, using intrinsic first-order gradiometric sensors based on low temperature superconductive DC SQUIDs manufactured in standard all-refractory Nb/AlO_X/Nb technology developed at IPHT Jena [5].

Several wavelets-based signal processing methods to reduce noisy interferences (which cause baseline drifts and artifacts endangering the putting of a correct diagnosis) have been tested on real data. Previously obtained results using orthogonal wavelets [6, 7] showed the need of further improvement and therefore another class of mother wavelets has been taken into consideration.

The design of specialized software and the performance simulations ensure a correct implementation and help the development of the considered diagnosis technique.

2 Wavelet Analysis

Wavelets are useful mathematical functions used for the multiresolution decomposition of a nonstationary signal, aiming at studying each component with the desired resolution. They present a specific way of adapting themselves to the spectral and temporal changes of an input signal, through translation (i) and dilation (j) parameters applied to a basic function. Therefore, any signal might be described as a wavelet-type time–frequency representation adapting the analysis function (the analysis window, called mother wavelet (MW) $\psi(t)$) at the requirements in time or frequency domain of the analyzed signal $s(t)$ [8]:

$$W_{\psi}s(i,j) = \langle s(t), \psi_{i,j}(t) \rangle, \quad i > 0, j \in R \tag{1}$$

Wavelet analysis allows the localization of a signal also in the time domain and not only in frequency domain (as does Fourier analysis); an important property for biological signals aiming at a diagnosis where time localization is important.

Biorthogonal wavelets use a biorthogonal base which allows a better reconstruction of the analyzed signal, compared to orthogonal wavelets, due to the use of different reconstruction and decomposition filters [9]. There have been taken into consideration compactly supported biorthogonal spline wavelets for which symmetry and exact reconstruction are possible with FIR filters (in orthogonal case, it is impossible except for Haar) [9]. Several main families have been tested: Villasenor, CDF (spline biorthogonal filters proposed by I. Daubechies), Deslauriers. Before the final putting of a diagnosis, there are several operations to be performed (Fig. 2): acquisition of the signal, baseline drift correction, noise filtering, compression, data transmission, and reconstruction.

The baseline drift correction method proposed uses the Stationary Wavelet Transform (SWT) for decomposing the signal into approximation and detail wavelet coefficients, the performance of the method being enhanced using the appropriate number of decomposition levels. The estimation of the baseline drift

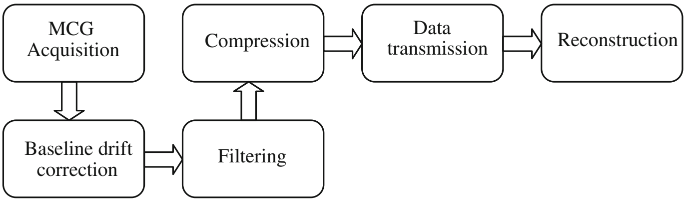


Fig. 2 Main steps to be performed before putting a diagnosis based on MCGs

(obtained using the approximation coefficients only) is subtracted from the original signal, the corrected MCG being reconstructed using the inverse transform ISWT [6].

The denoising procedure is using a MAP filter, an interscale dependance between the wavelet coefficients and a statistical estimation of the useful and noise-affected coefficients [6] assuming a Laplacian distribution for the useful coefficients a:

$$s(a) = 3/\left(2\pi\sigma_a^2\right) \cdot e^{-\left(\sqrt{3}/\sigma_a\right)\left(\sqrt{a_1^2+a_2^2}\right)} \tag{2}$$

and a bivariate Gaussian for the noise coefficients b with the noise variance σ_b^2:

$$s(b) = 1/\left(2\pi\sigma_b^2\right) \cdot e^{-\left(b_1^2+b_2^2\right)/\left(2\pi\sigma_b^2\right)} \tag{3}$$

where a and b represent two component vectors whose elements represent couples of detail wavelet coefficients for the noiseless and noisy components having the same spatial coordinates situated at two successive decomposition levels.

The MCG compression algorithm proposed is based on the wavelets' ability of analyzing the signal using different resolutions. The original signal has been decomposed using the Discrete Wavelet Transform on seven decomposition levels, the magnitudes of the wavelet detail coefficients obtained at each level are compared with an adaptive threshold value correlated with the quantization step q and the coefficients smaller than the threshold are put to zero [7]. The Compression Ratio (CR) is defined as the ratio between the number of bits of the original signal and the number of bits of the compressed signal.

The diagnosis being put through the visual checking of a physician, the first evaluation measure of the algorithms' performance has to be qualitative. In the present paper, we propose also a better quantitative evaluation tool for the performances of the simulation results, using the Signal-to-Noise-Ratio (SNR) improvement SNR_+ [10, 11], seen as the difference between the SNR of the output signal and the SNR of the input signal. Prior results obtained with orthogonal mother wavelets provide good performances for baseline drift reduction [6], but only medium performances for denoising and compression [6, 7]. Therefore, we study the influence of another class of MWs, so as to be able to propose a more competitive MCG monitoring system.

In the present paper, we have studied how the choice of the defining parameter of wavelet analysis (the mother wavelet) might significantly influence the algorithms' performances. Therefore have been taken into consideration several biorthogonal MW families: Villasenor (Vil), CDF, Deslauriers (Desl).

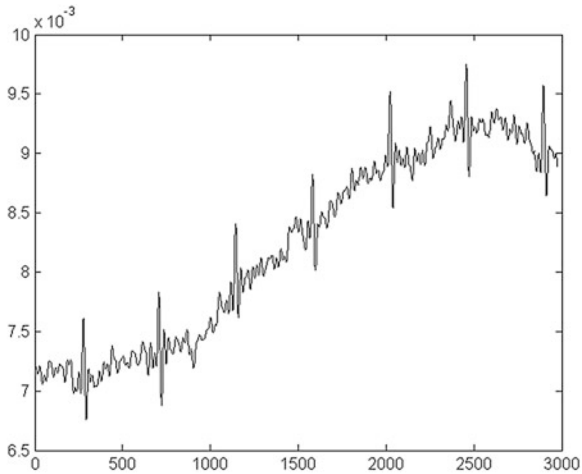
We hope that the present work gives an accurate insight of the application of biorthogonal wavelets to MCGs, enabling future comparisons with other techniques. Also, comparisons have been made with the results previously obtained using orthogonal MWs for MCG processing [6, 7]. Through the appropriate selection of the parameters of the MW, the performances of the algorithm are enhanced.

3 Experimental Results

For the first step of baseline drift removal, in the present paper we test several biorthogonal mother wavelets. The MCG system has been developed at IPHT Jena and the signals have been acquired under stress conditions, in an unshielded environment, in order to test better the performance of the proposed algorithms. The original signal is affected by noise, showing a significant baseline drift (Fig. 3).

The correction method previously described has been applied aiming at a reduction of the baseline drift without causing distortions. The method has been tested using biorthogonal MWs with different decomposition and reconstruction filter lengths on seven decomposition levels, the results being displayed in Figs. 4 (bior1.3), 5(bior2.2), and 6(bior6.8). The baseline drift has been corrected and there are no visible distortions to be perceived in none of the cases, proving also the stability of the proposed algorithm.

Fig. 3 Original MCG signal



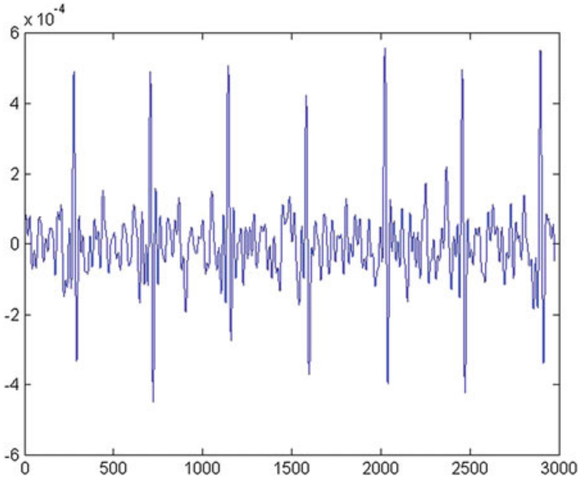


Fig. 4 Baseline drift correction using the bior1.3 MW

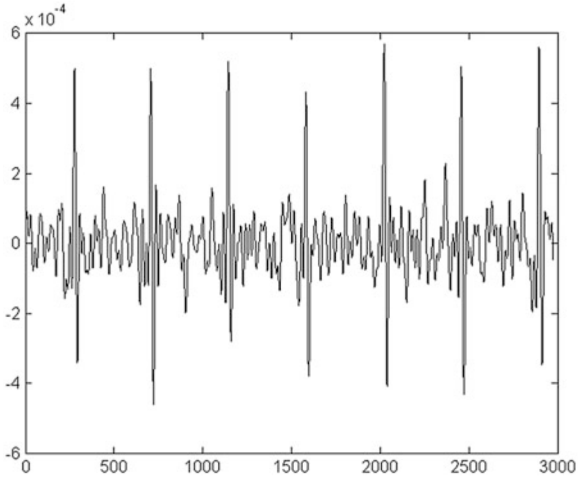


Fig. 5 Baseline drift correction using the bior2.2 MW

The denoising and compression algorithms have also been tested using MWs belonging to the Villasenor, Deslauriers, and CDF family of biorthogonal wavelets. The same initial values have been considered as in case of the orthogonal wavelets [7], so as to allow a correct comparison. The results are evaluated both qualitatively and quantitatively. The reconstructed signal after compression is represented in Figs. 7, 8, and 9 for the Villasenor3 MW, Deslauriers MW, and CDF1.3 MW. Checking the results, we conclude that the threshold level of 40 * *q*, established as an optimum between CR and Percentage Root Mean Square Difference (PRD) in case of orthogonal MW is not suited for biorthogonal wavelets, as important

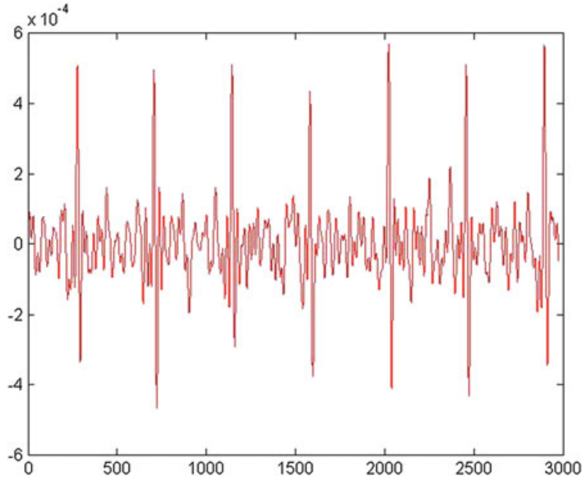


Fig. 6 Baseline drift correction using the bior6.8 MW

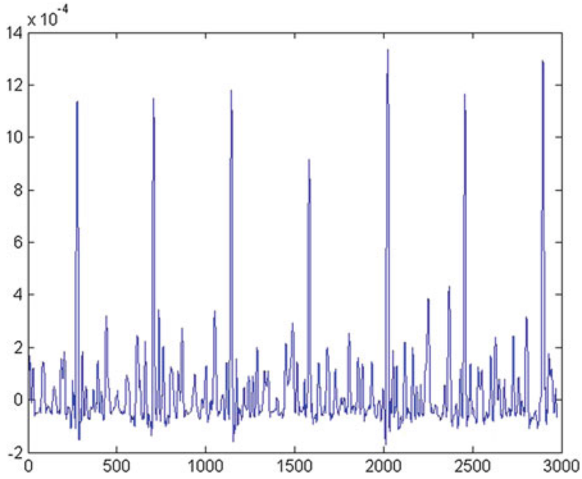


Fig. 7 Reconstructed signal after denoising and compression using the Villasenor3 MW, and a threshold of 40 * q

distortions are to be perceived. In order to obtain better results, the quantization step has to be increased. Performed simulations have displayed a quantization step about 10 times greater (in case of biorthogonal wavelets compared to orthogonal wavelets) as an optimum. Testing several MWs, we also conclude compared to [6], that the denoising performance is more influenced by the appropriate choice of a biorthogonal MW than in case of orthogonal MWs.

The best results have been obtained using the biorthogonal MWs proposed by Daubechies. The performance is influenced also by the chosen filters length. In

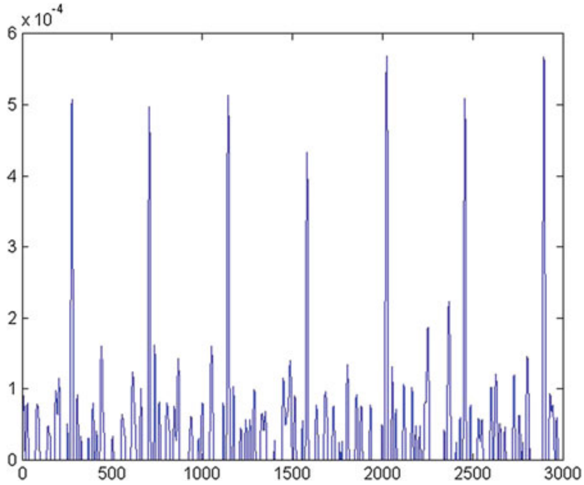


Fig. 8 Reconstructed signal after denoising and compression using the Deslauriers MW, and a threshold of 40 * *q*

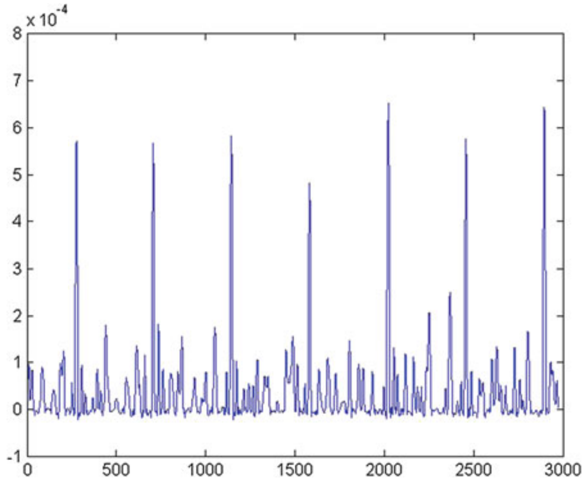


Fig. 9 Reconstructed signal after denoising and compression using the CDF1.3 MW, with a threshold of 40 * *q*

Figs. 10, 11, 12 are displayed the results obtained for CDF MWs: CDF1.3, CDF2.2, CDF2.6. Similar results have been obtained with Villasenor4 MW (Fig. 13). We notice clearly outlined QRS complexes in each case, enabling thus also a heart-rate determination.

A high compression ratio increases the risk of inducing distortions, therefore the CDF1.1 and CDF1.5 MWs have been rejected as not being suited for the compression and reconstruction of biomedical signals, upon visual checking.

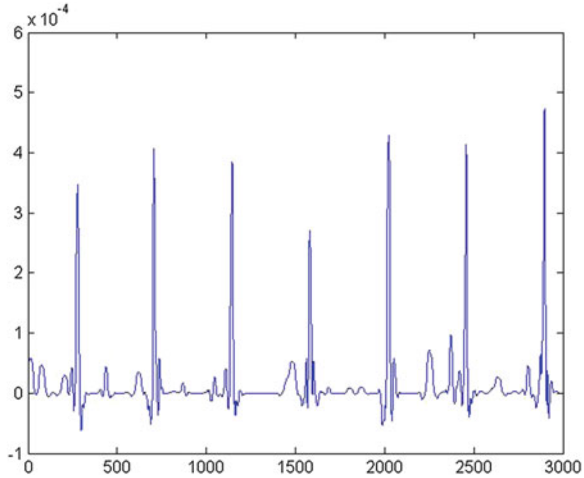


Fig. 10 Reconstructed signal after denoising and compression using the CDF1.3 MW, with a threshold of 400 * *q*

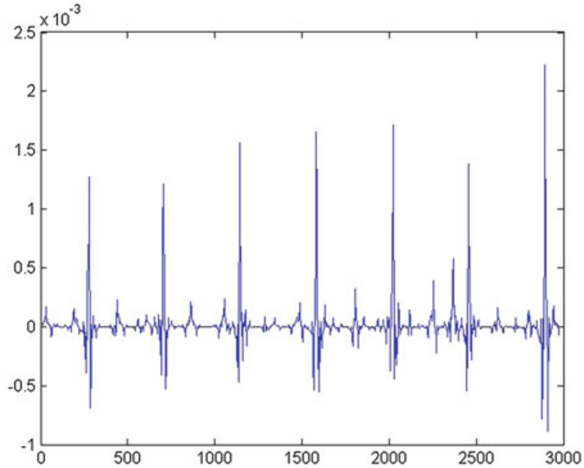


Fig. 11 Reconstructed signal after denoising and compression using the CDF2.2 MW, with a threshold of 400 * *q*

Considering as useful for diagnosis, a MCG signal with clearly defined components, the CDF1.3 MW is the most suited biorthogonal MW for compression. We also notice a better denoising performance than in case of orthogonal wavelets.

The compression ratios and SNR_+ obtained are displayed in Table 1.

Analyzing the results, we notice an average CR of 15.05 and an average SNR_+ of 2.27. Considering the most appropriate MWs for compression as a compromise between output SNR and CR and analyzing the experimental data, we may conclude that it belongs to the CDF1.3 MW. Compared to the average CR of 4.59 [7] obtained for the orthogonal wavelets, we conclude that the CR is enhanced when using biorthogonal wavelets.

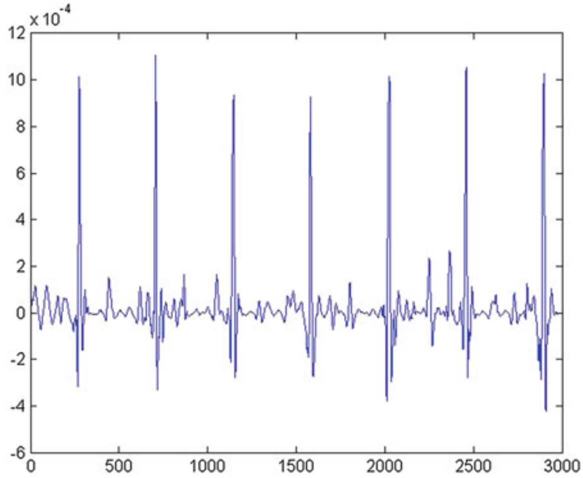


Fig. 12 Reconstructed signal after denoising and compression using the CDF2.6 MW, with a threshold of 400 * q

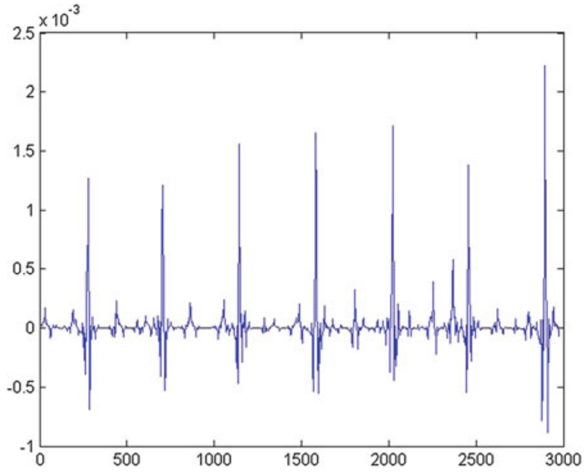


Fig. 13 Reconstructed signal after denoising and compression using the Vil4 MW, with a threshold of 400 * q

Table 1 Results of the performed simulations using biorthogonal MWs

Biorthogonal MW	CR	SNR_+
CDF1.3	*19.78*	*2.95*
CDF2.2	12.25	1.56
CDF2.4	12.19	2.55
CDF2.6	12.42	2.60
CDF2.8	12.19	2.52
Vil1	20.40	2.51
Vil2	23.74	1.81
Vil3	14.47	3.36
Vil4	12.25	1.56
Desl	10.89	1.28

4 Discussion and Conclusions

Magnetocardiograms are a passive technology suited for fetal recordings, providing the opportunity of a timely diagnosis. The implementation of a novel medical technique involves an important prior step of optimizing the design and performances of the proposed system.

The main aim of the paper is to propose optimal software algorithms which should allow the construction of a remote-automated MCG system, offering medical services to a larger community. Therefore, previously proposed algorithms have been enhanced and further developed in order to propose a more competitive MCG monitoring system.

We have tested wavelet-based algorithms for several steps of the processing of acquired magnetocardiograms: baseline drift correction, denoising, and compression. The MCG system was developed at IPHT, Jena, the MCGs presented in the paper being recorded under stress conditions, using an unshielded environment.

Previously performed tests on MCGs showed poor denoising and compression performances for orthogonal MWs, therefore the next step was to test another class of MWs, in order to check whether improvements can be obtained.

The performances of the algorithms were tested using biorthogonal wavelets belonging to the CDF, Villasenor, and Deslauriers family of MWs. The baseline drift correction algorithm is less influenced by the decomposition and reconstruction filters' length of the biorthogonal wavelets, a fact which proves the stability of the algorithm.

The denoising and compression performances are influenced in a higher degree by the appropriate choice of the MW. Biorthogonal wavelets prove to be more suited for denoising purposes. The initial threshold value used for orthogonal wavelets had to be increased in order to obtain accurate results. The most suited MW biorthogonal family for compression and denoising belong to the CDF MWs. We obtained an average CR of 15.05, being a CR three times greater than the one obtained for orthogonal wavelets. Considering as most appropriate signals for diagnosis, the signals which are clearly defined, we may consider the CDF1.3 MW as appropriate.

Future research directions should envisage the further development of a denoising method based on biorthogonal wavelets, so as to suit better the characteristics of MCGs signals recorded under stress conditions. Also, the performances of the algorithms should be tested using a shift-invariant wavelet transform, like the hyperanalytic wavelet packets transform.

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