

A NEW ALIGNMENT METHOD BASED ON THE WAVELET MULTI-SCALE CROSS-CORRELATION FOR NOISY HIGH RESOLUTION ECG RECORDS

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Abstract- The coherent signal averaging process requires an accurate estimation of the fiducial point in all beats to be averaged. The temporal cross-correlation between the detected beat and a template beat is the typical alignment method used with high-resolution ECG (HRECG) records. However, this technique does not produce a precise fiducial mark in records with high noise levels. In this study, we propose a new alignment method based on the multi-scale cross-correlation between the wavelet transforms of the template and the detected beat, respectively. The wavelet and temporal methods were tested for several simulated records corrupted with white noise and electromyographic (EMG) noise of different RMS levels. The results indicate that wavelet alignment method produces a lower trigger jitter than the temporal method in all tests. We conclude that the proposed alignment method can be used in records with high noise levels, like those found in Holter HRECG systems.

Keywords - Alignment method, fiducial point, high-resolution ECG signals, wavelet transform

I. INTRODUCTION

Coherent signal averaging is the classical method to improve the signal-to-noise ratio of cardiac micropotentials hidden in the background noise of high-resolution ECG (HRECG) records. It is based on the hypothesis that the signal of interest repeats itself with every beat and that the noise is random and uncorrelated with the signal. The resultant averaged signal is used to detect abnormal cardiac micropotentials, like ventricular late potentials (VLP), which are widely used to identify individuals at risk of ventricular tachycardia and sudden cardiac death [1].

For the averaging process, a precise synchronization of heartbeats is essential for the correct estimation of VLP. The existence of trigger jitter in the synchronization process causes a low-pass filtering effect in the averaged signal [2], which seriously limits the subsequent detection of the micropotentials. According to the standard [3], the trigger jitter, measured with an artificial QRS complex, should be less than 1 msec and ideally less than 0.5 msec. For this reason, several alignment techniques have been proposed to search for a precise fiducial point in HRECG records [4], [5], [6], [7]. A complete comparative study of the performance of the different alignment methods was presented in [8].

The alignment technique most widely used for HRECG records is the temporal cross-correlation method, where each incoming beat is matched to a pre-selected or averaged template beat. This technique works well when the noise level of the HRECG record does not exceed 20 μ V RMS. However, for higher noise levels, like those found in Holter

HRECG systems, the temporal cross-correlation does not produce a precise fiducial mark [9]. Consequently the trigger jitter increases in these situations.

In this paper, we propose a new alignment method based on the multi-scale cross-correlation between the wavelet transform (WT) of each detected beat and the WT of a pre-selected template beat. The proposed method appears to work better than the temporal cross-correlation method in records with high noise levels. In this work, the algorithm is compared with the traditional method for several simulated records corrupted with stationary white noise and real EMG noise of different RMS levels.

II. METHODOLOGY

A. Temporal Cross-Correlation Method

In this method, each previously detected incoming beat is compared against a template beat in a temporal window that includes at least the most rapidly changing part (upstroke and downstroke) of the QRS complex of both beats [3]. The template beat is usually chosen visually, by selecting a typical QRS morphology. The method consists of the computation of a cross-correlation coefficient sequence $r_{xy}(l)$ between the template beat and the time shifted detected beats in the temporal window. The cross-correlation coefficient sequence is defined as [10],

$$r_{xy}(l) = \frac{\sum_{k=1}^N x(k)y(k-l)}{\sqrt{\sum_{k=1}^N x(k)} \sqrt{\sum_{k=1}^N y(k)}} \quad (1)$$

where $x(k)$ and $y(k)$ are the values of the template and the detected beat respectively at the k -th sampling instant; l is the lag between the beat y , with respect to the template x ; and N is the total number of samples includes in the template, which should include at least 40 ms of the morphology of the QRS complex. The correlation coefficient is computed at each sampling instant lag over a sweep range, shifting the incoming beat one sample point at time.

Figure 1 illustrates the cross-correlation process between a template beat (Fig. 1a) and an incoming beat (Fig. 1b). The cross-correlation coefficient (Fig. 1c) is maximum when the incoming beat and the template are perfectly aligned. The vertical dashed line represent the position of the fiducial point.

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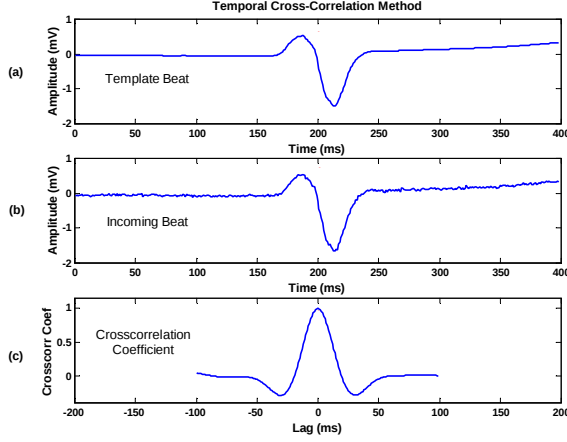


Fig. 1. Temporal cross-correlation method. (a) Template beat, (b) Incoming detected beat, and (c) Crosscorrelation coefficient. Vertical dashed line correspond to the position of the best alignment

Consequently, the fiducial point is defined as the position of the maximum of r_{xy} , which is ideally equal to 1. In practice, $\max(r_{xy}) < 1$ due to noise. Figure 2 illustrates the cross-correlation coefficient between a noisy beat and the template beat for different RMS levels of white noise. It can be seen that $\max(r_{xy})$ decreases as noise level increases. Likewise, it can be observed that the cross-correlation function shows many local maxima when the noise level increases. This makes correct localization of the fiducial point difficult in high noise level records. Therefore, the trigger jitter increases when the noise level of the record increases.

B. Wavelet Multi-Scale Cross-Correlation Method

In order to overcome the difficulties of the temporal cross-correlation method, we propose a new alignment based on the multi-scale cross-correlation between the wavelet transform (WT) of the noisy incoming beat and the WT of the template beat.

The wavelet transform (WT) of a signal $x(t)$ is defined as

$$WT_x(b, a) = \frac{1}{\sqrt{|a|}} \int_{-\infty}^{+\infty} x(t) y^* \left(\frac{t-b}{a} \right) dt \quad (2)$$

where the $y(t)$ is the basic wavelet, and b and a ($b, a \in \mathbb{R}$, and $a \neq 0$) are the translation and dilation parameters, respectively. When $a=2^j$ ($j=1,2,\dots$), the WT is called dyadic WT.

The basic wavelet used in this work was the quadratic spline Mallat wavelet [11] with compact support and one vanishing moment. The Fourier transform of this $y(t)$ is

$$\Psi(e^{jw}) = jw \left(\frac{\sin \frac{w}{4}}{\frac{w}{4}} \right)^4 \quad (3)$$

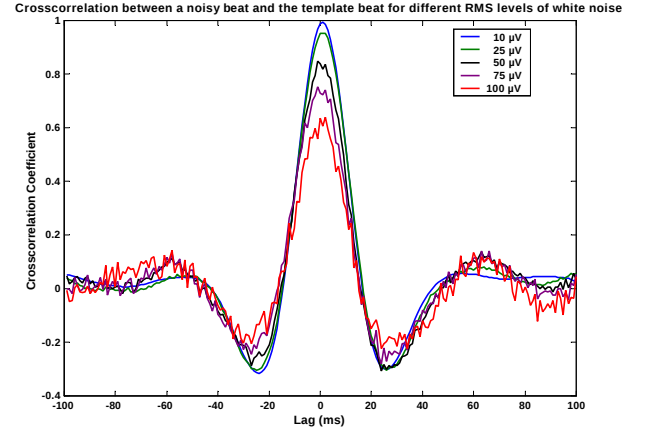


Fig. 2. Cross-correlation coefficient between a noisy beat and the template beat for different RMS levels of white noise.

This wavelet transform can be implemented using the Mallat algorithm [11] as a filter bank without decimators, as it is illustrated in Figure 3. In this way, the discrete signal $x[n]$ is decomposed in a set of detail signals $d_{x,i}[n]$ and a set of approximation signals $a_{x,i}[n]$. The low-pass filter $h[n]$ and the high-pass filter $g[n]$ have linear phase and give a signal decomposition that is shift-invariant across the different analysis scales. Due to these characteristics, this wavelet function has been previously used for the detection of characteristic points in ECG [12] and for the detection of the QRS complex [13]. In previous work, we have used this wavelet in order to estimate the QRS duration in healthy people and in patients with high risk of ventricular tachycardia, both in signal-averaged records and beat-to-beat records [14],[15]. Unlike previous work, in this method we use the approximation signals $a_{x,i}[n]$ with $i=2,3,4$ instead of the detail signals $d_{x,i}[n]$, because the bandwidth of the former corresponds approximately with the frequency range containing the main portion of energy of the QRS complex to be aligned.

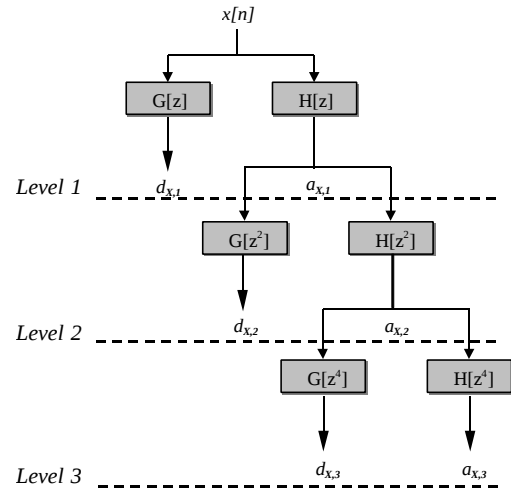


Fig. 3. Filter bank approach of Mallat wavelet transform.

The proposed method computes the wavelet approximation signals $a_{x,i}(k)$ of the template beat and $a_{y,i}(k)$ of the incoming beats. Afterwards, we calculate separately for each scale i the wavelet cross-correlation coefficient $P_{xy,i}$ as

$$P_{xy,i}(l) = \frac{\sum_{k=1}^N a_{x,i}(k) a_{y,i}(k-l)}{\sqrt{\sum_{k=1}^N a_{x,i}^2(k)} \sqrt{\sum_{k=1}^N a_{y,i}^2(k)}} \quad (4)$$

Then we localize the alignment point at each scale as the position of the maximum of $P_{xy,i}$. Finally, we compute the fiducial point as the median value of the position of $\max(P_{xy,i})$ for $i=2,3,4$. The selection of this parameter allows a robust detection of the fiducial point in records with a high noise level.

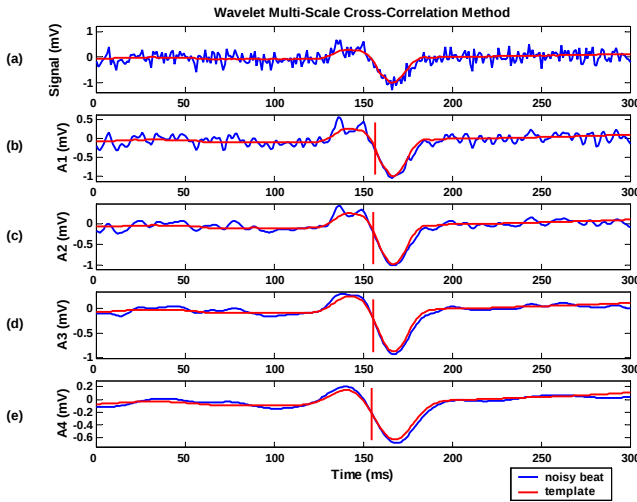


Fig. 4. Wavelet multi-scale cross-correlation method. (a) Template and incoming detected beats, (b-e) Approximation signals a_1 to a_4 . Vertical dashed line correspond to the best alignment in each scale.

Figure 4 illustrates the wavelet alignment method. The template beat and a noisy beat are represented in Fig. 4a, and its approximation signals a_1 - a_4 in Fig. 4b-4e, respectively. We observe that in the scales 3 and 4 the noise is well filtered and the QRS complex morphology is preserved. The vertical dashed line represents the position of the best alignment for each scale.

III. RESULTS

The two alignment methods were evaluated by applying them to a collection of 10 simulated high resolution ECG (HRECG) records of 300 beats each. These signals were corrupted separately with stationary white noise and real EMG noise of different noise levels, ranging from 0 to 100 μV RMS in 5 μV step. Each record was constructed repeating in time a real beat extracted from a real HRECG record

sampled at 1000 Hz. Five pathological and five normal QRS complexes with different morphologies were selected in order to construct the simulated records. The white noise used in the simulation was random, stationary, Gaussian, with zero mean and a standard deviation dependent on the noise level selected. The electromyographic noise was obtained from a real EMG record available from the MIT-BIH database and its amplitude was adjusted to obtain the noise level required.

The performance of the alignment methods was evaluated by the standard deviation σ of the alignment error, which is inversely related with the cutoff frequency of an equivalent lowpass filter of the averaged signal [8].

Noise level (μV)	White noise		EMG noise	
	σ Temp (ms)	σ Wav (ms)	σ Temp (ms)	σ Wav (ms)
0	0.000	0.000	0.000	0.000
10	0.000	0.000	0.000	0.000
20	0.067	0.013	0.094	0.004
30	0.331	0.124	0.341	0.082
40	0.590	0.257	0.589	0.227
50	0.821	0.347	0.883	0.379
60	1.056	0.468	1.232	0.548
70	1.326	0.559	1.660	0.740
80	1.587	0.660	2.283	0.998
90	1.915	0.783	3.576	1.382
100	2.200	0.931	5.805	1.915

The mean value of σ for all morphologies tested is presented in Table 1 and in Figure 5 for a range of noise levels of white and EMG noise for both temporal and wavelet cross-correlation methods. It can be observed that the wavelet method presents a lower alignment error compared with temporal method for all levels of white or EMG noise. This improvement is particularly noticeable for high noise levels.

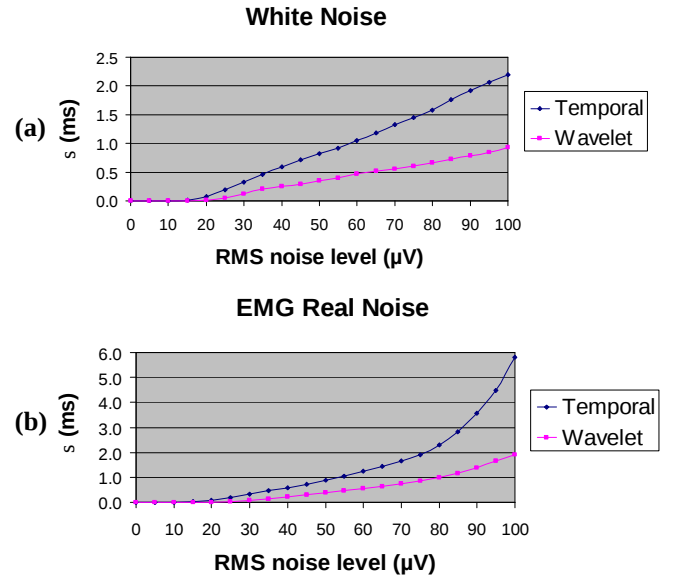


Fig. 5. Mean value of performance parameter σ for temporal and wavelet alignment methods for records corrupted with white noise and real EMG noise at different RMS noise levels.

IV. DISCUSSION

The results indicate that the standard temporal cross-correlation method works correctly for normal noise levels (2-20 μV) of HRECG records with the patient completely at rest. However, for higher levels noise (20-100 μV) as were found in ambulatory Holter signal-averaged systems [16], the standard method introduces an important alignment error. According to our results, the temporal method does not satisfy the maximum allowed value of trigger jitter of 1 msec, when the noise level increases over 50 μV .

The trigger jitter of the proposed wavelet alignment method is under the threshold for most of the simulated records corrupted with white noise and for those corrupted with a EMG noise up to 80 μV . The reason that EMG noise causes more difficulty than white noise for both methods is probably due to its non-stationary characteristics, which tends to corrupt some beats much more than others.

We have also observed that the alignment error not only depends on noise level but also on the particular QRS morphology and the peak-to-peak amplitude of the QRS complex.

V. CONCLUSION

The use of recent digital Holter signal-averaged systems motivates the development of alignment methods that are more robust than the traditional temporal cross-correlation method, due to the higher noise level of the records.

In this study, we have presented a new alignment method based on the multi-scale cross-correlation between the wavelet transform of a template beat and the detected beats. The method estimates correctly the fiducial point in records with low noise levels and produces a low alignment error in records with high levels of white or EMG noise.

We concluded that the presented method is a promising alignment technique for records with high noise levels. Further investigations should be carried out to examine the performance of this method in real Holter high-resolution records.

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REFERENCES

- [1] M. Borggrefe, T. Fetsch, A. Martinez-Rubio, M. Makijarvi and G. Breithardt, "Prediction of arrhythmia risk based on signal-averaged ECG in postinfarction patients," *Pacing Clin. Electrophysiol.*, vol. 20, no. 10, part 2, pp. 2566-2576, October 1997.
- [2] O. Rompelman and H.H. Ros, "Coherent averaging technique: A tutorial review. Part 1: Noise reduction and the equivalent filter. Part 2: Trigger jitter, overlapping responses and non-periodic stimulation," *J. Biomed. Eng.*, vol. 8, pp. 24-35, January 1986.
- [3] G. Breithardt, M.E. Cain, N. El-Sherif, N.C. Flowers, V. Hombach, M. Janse, M.B. Simson, and G. Steinbeck, "Standards for analysis of ventricular late potentials using high-resolution or signal-averaged electrocardiology," *Circulation*, vol. 83, pp. 1481-1488, April 1991.
- [4] S. Abboud, D. Sadeh, "The use of cross-correlation function for the alignment of ECG waveforms and rejection of extrasystoles," *Comput. Biomed. Res.*, vol. 17, no. 3, pp. 258-266, June 1994.
- [5] V. Barbaro, P. Bartolini, and M. Fierli, "New algorithm for the detection of the ECG fiducial point in the averaging technique," *Med. Biol. Eng. Comp.*, vol. 29, pp. 129-135, March 1991.
- [6] P. Laguna, R. Jané, and P. Caminal, "A time delay estimator based on the signal integral: Theoretical performance and testing on ECG signals," *IEEE Trans. Signal Processing*, vol. 42, no. 11, pp. 3224-3229, 1994.
- [7] P. Laguna, B. Simón, L. Sörnmo, "Improvement in high-resolution ECG analysis by interpolation before time alignment," *IEEE Computers in Cardiology*, vol. 24, pp. 617-620, 1997.
- [8] R. Jané, H. Rix, P. Caminal, and P. Laguna, "Alignment methods for averaging of high-resolution cardiac signals: A comparative study of performance," *IEEE Trans. Biomed. Eng.*, vol. 38, no. 6, pp. 571-579, June 1991.
- [9] P. Lander, J.S. Steinberg, J.T. Bigger, and E.J. Berbari, "Signal averaging of ventricular potentials using Holter Recordings," *IEEE Computers in Cardiology*, pp. 377-380, 1989.
- [10] P. Lander and E.J. Berbari, "Principles and signal processing techniques of the high-resolution electrocardiogram," *Prog. Cardiovasc. Dis.*, vol. 35, no. 3, pp. 169-188, Nov/Dec 1992.
- [11] S. Mallat and S. Zhong, "Characterization of signals from multiscale edges," *IEEE Trans. Pattern Anal. Machine Intell.*, vol. 14, pp. 710-732, July 1992.
- [12] C. Li, C. Zheng, and C. Tai, "Detection of ECG characteristic points using wavelet transforms," *IEEE Trans. Biomed. Eng.*, vol. 42, no. 1, pp. 21-28, January 1995.
- [13] S. Kadambe, R. Murray, and G. Boudreaux-Bartels, "Wavelet transform-based QRS complex detector," *IEEE Trans. Biomed. Eng.*, vol. 46, no. 7, pp. 838-848, July 1999.
- [14] E. Laciár, R. Jané, and D.H. Brooks, "Analysis of QRS duration in Chagasic patients with ventricular tachycardia in time and wavelet domains," *Proc. XXVII Int. Cong. Electrocardiol.*, June 2000 (in press).
- [15] E. Laciár, R. Jané, and D.H. Brooks, "Beat-to-beat analysis of QRS duration in time and wavelet domains," *IEEE Computers in Cardiology*, vol. 27, pp. 719-722, 2000.
- [16] H.L. Kennedy, N.S. Bavishi, T.A. Buckingham, "Ambulatory Holter electrocardiography signal-averaging: a current perspective", *Am. Heart J.*, vol. 124, no. 5, pp. 1339-1346, November 1992.