Amplitude Differences Least Squares Method Applied to Temporal Cardiac Beat Alignment

R O Correa¹, E Laciari¹ and M E Valentinuzzi¹,²
¹ Gabinete de Tecnología Médica, Facultad de Ingeniería, Universidad Nacional de San Juan, Argentina
² Instituto Superior de Investigaciones Biológicas, UNT-CONICET, Tucumán, Argentina

E-mail: rcorrea@gateme.unsj.edu.ar; laciari@gateme.unsj.edu.ar; maxvalentinuzzi@arnet.com.ar

Abstract. High resolution averaged ECG is an important diagnostic technique in post-infarcted and/or chagasic patients with high risk of ventricular tachycardia (VT). It calls for precise determination of the synchronism point (fiducial point) in each beat to be averaged. Cross-correlation (CC) between each detected beat and a reference beat is, by and large, the standard alignment procedure. However, the fiducial point determination is not precise in records contaminated with high levels of noise. Herein, we propose an alignment procedure based on the least squares calculation of the amplitude differences (LSAD) between the ECG samples and a reference or template beat. Both techniques, CC and LSAD, were tested in high resolution ECG’s corrupted with white noise and 50 Hz line interference of varying amplitudes (RMS range: 0–100 μV). Results point out that LSDA produced a lower alignment error in all contaminated records while in those blurred by power line interference better results were found only within the 0–40 μV range. It is concluded that the proposed method represents a valid alignment alternative.

1. Introduction
During the last 3 or 4 decades, several studies have demonstrated the existence of ventricular late potentials (VLP’s) in post-infarcted patients with high risk of ventricular tachycardia [1] and in chronic chagasic patients showing severe myocardial damage [2-3]. Those late potentials usually have very low amplitude (in the order of μV’s) and high frequency content (between 40 and 250 Hz), localized at the final portion of the QRS complex and initial section of the ST segment [4]. Their detection is of interest and averaging is the most frequent technique to extract them. The basic hypothesis states that the late potential repeats itself in each subsequent beat and that random noise does not correlate with the signal. However, averaging requires precise synchronization of the beats because alignment errors lead to a low-pass filter effect on the averaged signal [5], which limits seriously further detection of VLP’s.

According to the standard document [4] for the análisis of VLP’s, the alignment error (measured with an artificial QRS) must be smaller than 1ms; several methods have been proposed to meet the latter requirement [6-9] and the fiducial point appears always as the crucial element.
Cross correlation (CC) is the most frequently used alignment method; with it, the correlation between each detected beat and a reference one is calculated. It works fine when the noise level does not go beyond 20μV RMS. However, the fiducial point it gives is not good enough when noise increases leading to poorer alignment [5].

In a previous paper, we proposed an alignment method based on minimizing the distances between each beat samples and the samples of a reference beat [10]. Herein, the alignment errors obtained with a procedure based on the least squares calculation of the amplitude differences (LSAD) are compared against the standard cross correlation technique (CC), using a set of high resolution ECG’s contaminated either with white noise or with power line interference of different amplitudes.

2. Methods

The fundamental objective of any alignment method is finding the fiducial or synchronism point on each beat to be averaged. Each previously detected beat \( y(k) \) is compared with a reference beat \( x(k) \), within a temporal window where the steepest QRS changes of both beats must be included [5].

There are two ways for selection of the reference beat: one relies on the visual choice of a beat with normal morphology and low noise level and another takes a previous version of an average beat. The latter allows an experimented user to easily pick out from the record string an adequate beat. This is why we preferred here the second technique. Thereafter, each beat was aligned with the reference.

2.1. Cross Correlation Method

It is the most frequently used in VLP detection [5] and is recognized as such by the standard document [4]. Alignment is reached by calculating the normalized cross correlation (NCC) function \( \rho_{xy} \) between the reference beat and each detected beat, always within a temporal window including the most abrupt QRS complex changes of both beats. The method has two stages: a) reference beat selection, which is a preliminary version of the averaged beat, and b) alignment of each detected beat with the reference. The NCC function is defined as [5],

\[
\rho_{xy}(l) = \frac{\sum_{k=1}^{N} x(k)y(k - l)}{\left[ \sum_{k=1}^{N} x^2(k) \right]^{\frac{1}{2}} \left[ \sum_{k=1}^{N} y^2(k) \right]^{\frac{1}{2}}}
\]

where \( x(k) \) and \( y(k) \) are, respectively, values of the reference and the detected beats at the \( k \)-th temporal sample; \( l \) stands for the delay between both beats while \( N \) represents the number of samples within the window. We chose herein a 200ms window containing 200 samples at a sampling frequency of 1kHz. The function \( \rho_{xy} \) is obtained shifting the detected beat one sample at a time.

Figure 1 shows the alignment between the reference or template beat \( x(k) \) (upper trace) and two detected beats \( y_1(k) \) (middle trace in red), with 60ms delay, and \( y_2(k) \) (middle trace in green), 30ms ahead. The lower traces of Figure 1 display the two CC functions. Notice that the maxima for \( \rho_{xy}(l) \) fall at \( l = -60\)ms and \( l = 30\)ms, respectively. Hence, the \( \rho_{xy}(l) \) maxima correctly estimate whatever delay there is between both beats.
Figure 1. Cross Correlation Method (CCM). The upper trace represents the reference or template beat \( x(k) \); the middle traces stand for, respectively, a 60ms delayed \( y_1(k) \) beat (in red) and a \( y_2(k) \) 30ms ahead beat (in green). The lower traces display both CC functions.

Thus, the fiducial point is defined as the maximum of \( \rho_{xy}(l) \); ideally such maximum equals 1 because the CC function is normalized. However, in practice, \( \max(\rho_{xy}) \) < 1 due to the ever present of noise in spite of its previous filtering.

2.2. Least Squares of the Amplitude Differences (LSAD) Method

Alignment is carried out minimizing a functional \( J(l) \), which is the summation of the squared distances between the instantaneous beat value \( x(k) \) and its corresponding shifted beat version \( y(k \pm l) \), i.e.,

\[
J(l) = \min_l \sum_{k=1}^{N} [x(k) - y(k \pm l)]^2
\]  

(2)

where,
- \( l \): shift in integer number of the beat to be aligned
- \( N \): number of samples in each beat
- \( x(k)-y(k \pm l) \): instantaneous amplitude differences between \( x(k) \) and \( y(k) \) for a \( l \) shift

Numerical evaluation to minimize equation (2), based on the LSAD method, leads to the optimum \( J \) by means of an iterative algorithm. Figure 2 summarizes the procedure as a flow diagram. The reference beat \( x(k) \) is obtained as a preliminary average version of 100 non-aligned beats; thereafter, functionals \( J \) are determined for each beat \( y(k) \) and for all shifts \( l \), saving those that give the least \( J \) (optimum \( l \)). At this point, the algorithm proceeds by correcting the marked QRS using the saved \( l \). The first alignment cycle is so concluded. After that, the average is recalculated realigning the beats, but now using the estimation of the average; such latter step provides recursivity.
A previous paper from our group [10] found empirically that the maximum number of iterations for an adequate alignment is $N_{iter} = 4$; more iterations do not significantly improve the results.

2.3. Procedure
To evaluate both methods, a set of 20 simulated High Resolution ECG records (sampling frequency = 1000 Hz; number of bits = 16), each composed of 100 beats, with the following characteristics was prepared:

1º. Each record was constructed by repeating the morphology of real beats obtained from healthy subjects and from chagasic patients showing ventricular tachycardia.1

2º. The position of each inserted beat was interfered with random error to simulate the error produced by the QRS detector. The real temporal positions where beats were inserted were kept in a special file (marks’ file) for further validation.

3º. Each record was contaminated, too, with white noise and with power line interference at different levels.

Performances of both methods, CC and LSAD, were evaluated with the standard deviations $\sigma$ produced by the alignment errors of all beats. Alignment errors, in turn, came from the difference between the inserted temporal position for each beat and the fiducial point given by either method.

1 Real ECG’s were extracted from the Universidad Simón Bolívar’s Data Base, in Venezuela.
3. Results

The $\sigma$ values obtained for both methods, corrupted either with white noise or with power line interference, are displayed numerically in TABLE I and graphically in Figure 3.

**Table 1.** Mean value of $\sigma$ for LSAD and CC methods for simulated HRECG records corrupted with white noise and line interference of different RMS levels

| RMS Noise Level (µV) | White Noise | Line Interference |
|---------------------|-------------|-------------------|
|                     | LSAD $\sigma$ [ms] | CC $\sigma$ [ms] | LSAD $\sigma$ [ms] | MCC $\sigma$ [ms] |
| 0                   | 0.000       | 0.122             | 0.000               | 0.122             |
| 10                  | 0.000       | 0.206             | 0.004               | 0.172             |
| 20                  | 0.000       | 0.249             | 0.024               | 0.220             |
| 30                  | 0.006       | 0.322             | 0.077               | 0.238             |
| 40                  | 0.025       | 0.353             | 0.240               | 0.314             |
| 50                  | 0.075       | 0.478             | 0.580               | 0.445             |
| 60                  | 0.156       | 0.516             | 1.250               | 0.609             |
| 70                  | 0.236       | 0.537             | 1.578               | 0.683             |
| 80                  | 0.313       | 0.612             | 2.329               | 0.870             |
| 90                  | 0.404       | 0.680             | 3.091               | 0.985             |
| 100                 | 0.463       | 0.738             | 3.593               | 1.187             |

Figure 4 shows the HRECG estimations averaged over each of the four LSAD iterations. For the first iteration, a notorious low-pass filter effect is evident due to the initial error in the fiducial points with which the preliminary reference beat was obtained. For the three next iterations, the beat gains details and amplitude, especially after alignment. Significant differences cannot be seen between the 2nd, 3rd and the 4th estimation; however, magnifying certain zones (Zoom A, for example), the 4th estimation appears with slightly higher amplitude. All studied records undoubtedly demonstrated that iterations beyond the fourth did not bring any significant improvement in the averaged beat.

Figure 3. Mean value of $\sigma$ for both alignment methods compared in this report applied to HRECG, contaminated with, (a) white noise and, (b) power line interference.
Figure 4. Average HRECG estimations for four LSAD iterations. Observe the differences between each and the low pass filter effect.

Finally, Figure 5 illustrates the behavior of $\sigma$ as the noise level increases, for each iteration of LSAD, from top to bottom, clearly showing the improvement with the number of iterations.

Figure 5. The performance parameter sigma as a function of the noise level and for each LSAD iteration.

4. Discussion and Conclusions

The development of new digital techniques to acquire ECG records of high resolution (HRECG’s) drives the search for fresher and more efficient alignment methods, especially with stronger robustness against noise than the older and traditional cross-correlation (CC). This paper has described an alignment procedure based on minimization of the squared amplitude differences between a reference beat and each detected beat. The fiducial or synchronism point was correctly estimated leading to alignment errors smaller than the standard requirement ($\sigma < 1$ms) in records contaminated with white noise lower than 100 $\mu$V RMS or with power line interference smaller than 50 $\mu$V RMS. It should be underlined that, in HRECG’s with the latter kind of interference, the alignment errors were larger than those obtained with white noise.

After comparison against the traditional CC, it is seen that the proposed LSAD gives off $\sigma$ values notable smaller than the former for all HRECG’s corrupted with white noise. Nonetheless, when the
interference comes from the power line, both methods behave differently even though \( \sigma \) for LSAD appears as slightly smaller than for CC (up to 40 \( \mu \)V). When noise is higher than 40 \( \mu \)V, however, the standard CC produced better results than our proposed least squares.

Moreover, the algorithm recursivity for the beat alignment produced a considerable decrease in the standard deviation of the alignment error, \( \sigma \), in all records contaminated with white noise. However, it should be pointed out that the algorithm recursivity did not lead to a significant fall in records corrupted by line interference due to the estimation of the averaged beat used in the iteration process is affected by this type of noise, in such a way that their RMS level doesn't decrease enough, then when alignment the beats this small component of noise it blocks the correct alignment.

In conclusion: The proposed method permits a better estimate of the averaged HRECG, especially when records are corrupted by white noise.

Acknowledgments
This work was partially supported by grants from Universidad Nacional de San Juan (cod. 21/I575). All authors are supported by Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET) of Argentina. This paper was communicated to the XVI Congreso Argentino de Bioingeniería, San Juan Argentina, September 26-28 2007.

References
[1] M. Borggrefe, T. Fetsch, A. Martinez-Rubio, M. Makijarvi and G. Breithardt 1997 “Prediction of arrhythmia risk based on signal-averaged ECG in postinfarction patients,” Pacing. Clin. Electrophysiol. 20 2566-2576.
[2] L. Dopico, J. Nadal, A. Infantosi 2000 “Analysis of late potentials in the high-resolution electrocardiogram of patients with Chagas’ disease using weighted coherent average,” Revista Brasileira de Engenharia Biomédica. 16 49-59.
[3] E. Laciar, R. Jané, D. H. Brooks 2006 “Evaluation of Myocardial Damage in Chagasic Patients from the Signal-Averaged and Beat-to Beat Analysis of the High Resolution Electrocardiogram,” Computers in Cardiology. 33 25-28.
[4] G. Breithardt, M.E. Cain, N. El-Sherif, N.C. Flowers, V. Hombach, M. Janse, M. Simson, and G. Steinbeck 1991 “Standards for analysis of ventricular late potentials using high-resolution or signal-averaged electrocardiology,” Circulation. 83 1481-1488.
[5] P. Lander and E.J. Berbari 1992 “Principles and signal processing techniques of the high-resolution electrocardiogram,” Prog. Cardiovasc. Dis. 35 169-188.
[6] S. Abboud and D. Sadeh 1984 “The use of cross-correlation function for the alignment of ECG waveforms and rejection of extrasystoles,” Comput. Biomed. Res. 17 258-266.
[7] R. Jané, H. Rix, P. Caminal, and P. Laguna 1991 “Alignment methods for averaging of high-resolution cardiac signals: A comparative study of performance,” IEEE Trans. Biomed. Eng. 38 571-579.
[8] O. J. Escalona, R. H. Mitchell, D. E. Balderson, and D. W. G. Harron 1993 “Fast and reliable QRS alignment technique for high-frequency analysis of signal-averaged ECG,” Med. Biol. Eng. Comp. 31 S137–S146.
[9] E. Laciar, R. Jané, and D. H. Brooks 2003 “Improved Alignment Method for Noisy High-Resolution ECG and Holter Records Using Multiscale Cross-Correlation,” IEEE Trans. Bioine. Eng. 50 344-353.
[10] R. Correa, E. Laciar 2007 “Método de alineamiento de latidos cardiacos basado en la técnica minimización del cuadrado de las distancias,” XII Reunión de Trabajo en Procesamiento de la Información y Control (RPIC), submitted.