Improvement in High-Resolution ECG Analysis by Interpolation Before Time Alignment

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Abstract

In this work we study the use of interpolation prior to time alignment and averaging in the analysis of high resolution ECGs. The resolution of time alignment is limited by the sampling interval and interpolation makes the alignment error reduced. Five alignment methods were used in combination with white noise and 50/60 Hz interference. The results were quantified in terms of power of the deviation signal, the deviation of the misalignment error and the energy of the error signal. A considerable decrease of the deviation signal power was noted when the sampling rate was increased from 1 kHz to 4 kHz. Modest improvements were only obtained when the sampling rate was further increased, making 4 kHz suitable sampling rate for high frequency studies. In actual and simulated ECG records it was found that the filtered QRS duration index increased only 4 ms whereas $RMS40$ and $LAS40$ remained unchanged.

1. Introduction

Averaging of time-aligned beats is a wide-spread technique used to improve the signal-to-noise ratio (SNR) of high resolution ECG signals. It makes use of the repetitive nature of signals and of the lack of correlation between noise and the ECG. This technique is applied to study ventricular late potentials (VLP), useful to identify patients at risk of ventricular tachycardia from those who had suffered myocardial infarction [1], and to study His-Purkinje activity[2]. Time alignment is also important when morphological beat-to-beat QRS variability is studied e.g. in patients with signs of infarction and ischemia [3]. In VCG loop analysis it is also necessary to use time-alignment techniques[4].

Averaging requires that all analysed beats are aligned in time. Misalignment introduces an undesirable low-pass effect in the averaged signal which may obscure the presence of VLP. This phenomenon can be of critical importance in VLP analysis where the interesting frequencies are found between 50 and 300 Hz [1]. The accuracy of high-frequency ECG analysis is then limited by the presence of noise, time alignment precision and signal nonstationarity. The sampling rate is usually selected according to the expected frequency content of the ECG. However, the sampling rate also limits the alignment precision to a value proportional to the sampling period. We propose an interpolation procedure prior to alignment which reduce the alignment error.

There are several techniques to align ECG signals. Here we consider five methods for which the performance is compared on simulated and measured ECG signals corrupted with white and 50/60 Hz noise. Results were obtained with and without interpolation prior to alignment. The simulation was done with a QRS-like signal to which noise was added. The performance was measured by the power of the ensemble deviation signal, the deviation of the misalignment error and the energy of the error signal. Also, the effect on the classical indexes to quantify VLP were studied with and without interpolation.

2. Methods

2.1 Interpolation

Interpolation is the operation which is used for increasing the sampling rate, F_s, of a sampled signal [5]. The resulting decrease in the sampling interval is the basis of our work. The limitation of the alignment methods given by F_s will be reduced by a factor which is proportional to the increased sampling rate. The interpolation consists of a non-linear operation, in which zero-valued samples are inserted between the samples of the original signal, followed by a linear lowpass filtering which produces the interpolated values of the new samples. The interpolator performance depends on the design of the lowpass filter. In this work, the window method is used for design of FIR filters [5].

2.2 Alignment

Different alignment techniques have been used in the literature for ECG signal averaging. It is well-known that the matched filter is optimal for stationary, white noise (the impulse response of this filter is a time-reversed replica of the analyzed signal). However, other techniques have been used because of the difficulty to estimate the optimum impulse response or because it has been reported that others methods have superior performance in certain noise enviroments. We have considered five different techniques: **1**-Maximum of the *correlation* between a reference beat and every signal beat in the ensemble. This method is based on the matched filter, for which the impulse response is taken as a noisy realization. The time sample where the correlation is maximal is considered as the alignment point. **2**-Woody alignment

*This work was supported by grant TIC94-0608-C02-02, from CICYT, and PIT06/93 from CONAI". Spain

(WA) [6]. This technique improves the correlation technique by introducing an iterative procedure in which the alignment is reperformed when a new averaged beat is computed (the averaged beat is used as the impulse response). The iterations are repeated until no significant changes in alignment is observed. **3**-Normalized integrals *(NI)* [7]. This method estimates the delay between two signals by means of their normalized integral difference. In noiseless conditions, this method produces an unbiased estimate, which for 50/60 Hz noise has been found to have performance which is comparable to, or even better, than the previous methods. **4**-Sliding windows *(SW)* [8]. This method is proposed due to the special morphology of the QRS signal (two well marked, opposite sign slopes). **5**-threshold crossing *(TC)* [9]. This is a very fast and simple method which has been included due to its simplicity.

3. Signal Estimation

In order to characterize the interpolation effect we construct a simulated QRS-like signal (Fig. 3) sampled at 250 Hz. This QRS is repeated in time simulating a ECG record of 100 beats with a QRS width of 100 ms and free of noise. The ith beat in the ensemble is resampled with a random delay τ_i which has a uniform distribution in $(0,T_s)$ where T_s is the sampling period. If $qrs(t)$ is the original beat before sampling, the ith beat after sampling is given by $qrs_i(k) = qrs(kT_s + \tau_i)$. In this way we mimic the real situation where beat occurrence is unsynchronized with the sampling. The resulting signals define the ensemble to be used for averaging. The signals are then interpolated with factors ranging from 1 to 10, i.e. F_s ranges from 250 Hz to 2500 Hz.

3.1 Noise free signals

In this first case we will average the ensemble of QRS complexes without noise such that the estimation error is only due to misalignment. The averaging has been done for the five different alignment methods. Figure 1a shows the power P_{dp} of the deviation signal $(dp(k))$ as a function of F_s, where

$$dp(k) = \sqrt{\frac{\sum_{i=1}^{N}(qrs_i(k) - \hat{qrs}(k))^2}{N}} \quad ; \quad \hat{qrs}(k) = \frac{\sum_{i=1}^{N} qrs_i(k)}{N} \qquad (1)$$

In Fig. 1b, the standard deviation of the alignment error, σ_a, is shown. This can be computed since we know the exact alignment point. Finally, Fig. 1c shows the energy of the difference, E_e, between the original signal $qrs(k)$ and the estimated $\hat{qrs}(k)$. As expected, the three performance indexes decrease with increased F_s. The indexes P_{dp}, and σ_a decreases. The evolution of E_e is less illustrative since $qrs(k)$ is essentially low frequency and therefore the alignment error translates into poor high-frequency estimation. However, the improvement will be more evident in cases with VLP. This can be shown in Fig. 2 where the ideal signal that introduces a sine-like simulated VLP of 100 μV amplitude and 200 Hz is shown in Fig. 2a, and the evolution of E_e as a function of F_s is shown in Fig. 2b. The WA method is the one that produces the lowest E_e, however, the improvement with interpolation is less noticeable than for the other indexes. The lowest σ_a is obtained by WA method, together with correla-

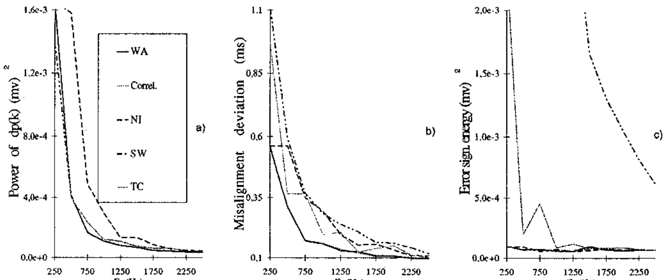

Figure 1: *Results on the QRS-like simulated signal at different sampling rates, F_s: a) power of the averaging deviation signal, P_{dp}, b) misalignment deviation, σ_a, and c) energy of the error signal, E_e.*

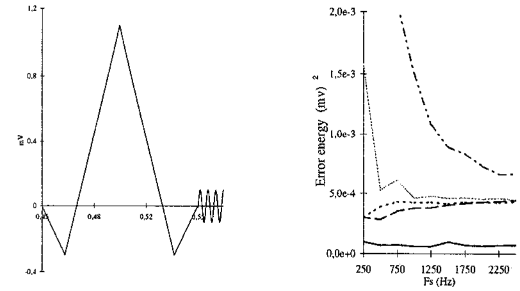

Figure 2: *As in Fig. 1 but with sine-like VLP added to the QRS.*

tion, being the more robust in the noise free cases. In Fig. 3 the original signal and the reconstructed signal are shown for several interpolation factors. Also the deviation signal $dp(k)$ is presented for each case.

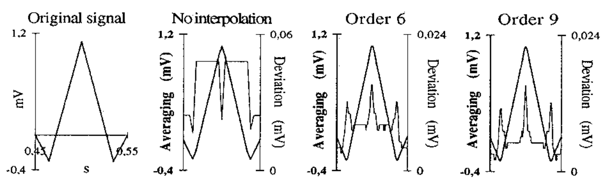

Figure 3: *Original and reconstructed signals after averaging with different interpolation orders, together with their deviation signals. The scale of the left axis refers to reconstructed signal and that of the right axis refers to the deviation signals.*

3.2 White noise contamination

Figure 4 presents the results corresponding to Sec. 3.1 but with white noise added to the beat ensemble (SNR=10 dB). The Woody alignment and correlation remain the methods that yield the best results. The improvement in the σ_a is also observed (around 0.5 ms), however, the absolute value of the misalignment is higher due to the noise which increases the error associated with any method. The WA produces again the lowest P_{dp} which becomes even more evident for lower SNRs. The NI method gives a surprisingly linear increase of the σ_a for increasing F_s. This phenomenon was already predicted in [7], where it is was shown that for the same SNR the σ_a increased with the number of samples in $qrs(k)$, as happened now when interpolating by a factor higher that

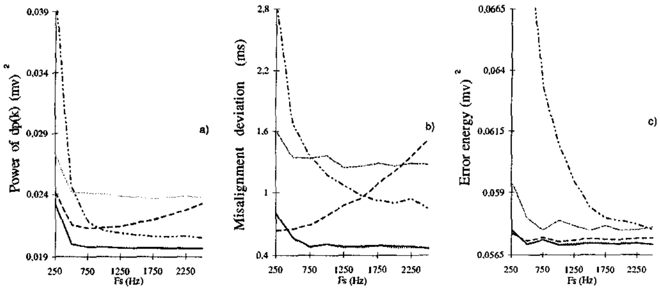

Figure 4: *Same analysis as in Fig. 1 but with white noise added (SNR=10dB).*

one.

3.3 50 Hz noise contamination

We now consider the same original signal but corrupted with 50 Hz noise (SNR=0 dB). The realizations have been generated in such a way that the phase of the 50 Hz varies randomly from the QRS maximum in order to reflect that the phase of the mains interference is uncoupled to heart. The results are presented in Fig. 5. The best method in

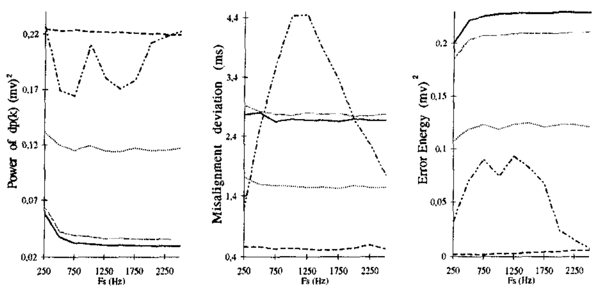

Figure 5: *Same analysis as in Fig. 1 but with added white noise (SNR=0dB).*

terms of σ_a is NI. The reason is that the correlation and WA methods try to align the 50 Hz contaminating signal rather than the QRS, whereas the NI treated all the signals in a global way and do not suffer from this problem. This effect is more pronounced for a decreasing SNR (we select here 0 dB for graphic clarity), at SNR=10 dB the NI method is only slightly better than WA and the differences in performance increase when the SNR decreases. Figure 6 shows five 50 Hz noisy QRSs aligned with WA, and the same five aligned with NI. It can be noted that WA has aligned the 50 Hz signal whereas NI has aligned QRS-like signals.

In Fig. 5a we can also note that P_{dp} is much bigger for the NI method than for the others. This apparent contradiction can be explained with a detailed analysis of the $dp(t)$ signal. We will denote $s(t) = qrs(t)$ the deterministic signal, and the noise (in this case other deterministic signal of 50 Hz) $r(t)$. First, we consider that the signal $s(t)$ is perfectly aligned in the ensemble. The noise will be the 50 Hz sine misaligned with respect to the $s(t)$ synchronization point. If the misalignment τ_i is small compared with the $r(t)$ signal variations we can do a Taylor approximation of the delayed noise signal $r(t-\tau_i) = r(t) - r'(t)\cdot\tau_i$. Including this in the squared deviation signal we have

$$\begin{aligned} dp^2(t) &= E\left[(s(t) + r(t-\tau_i) - E[s(t) + r(t-\tau_i)])^2\right] \\ &= r'^2(t)E[\tau_i^2] = r'^2(t)\sigma^2 \qquad (2) \end{aligned}$$

where σ^2 is the misalignment deviation of τ. P_{dp} can then be expressed as : $P_{dp} = \sigma^2 \int_{-\infty}^{\infty}(2\pi f)^2 R(f)df$. This shows that P_{dp} does not only depend on the noise signal misalignment but also of the noise frequency characteristics. Larger noise frequency components produce higher P_{dp}. This is in agreement with the idea that a fast changing signal (high frequency) implies a large variation value for short time shifts, and much lower for slow changing signals and same shift. The NI method aligns the QRS-like signal, and then the noise ($r(t)$) is the 50 Hz, by the contrary WA aligns the 50 Hz and the QRS-like signal acts as $r(t)$. The QRS signal has its main frequency content much lower than the 50 Hz signal, and so their contribution to P_{dp} is lower than in the case of NI alignment. This explains the apparent contradiction between Fig. 5a and b, and corroborates that the NI method is better suited to align ECG primarily corrupted by 50/60 Hz noise.

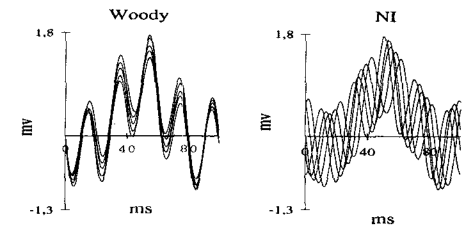

Figure 6: *Sample of 5 aligned beats by WA and NI methods.*

3.4 ECG signals

We now apply the interpolation-based averaging to a set of ECG signals. Since the true signal is unknown we can only estimate P_{dp} to evaluate the results. We study 19 high resolution ECG signals (X,Y,Z leads) sampled originally at 1 kHz, and with a SNR lower than 10 dB. In Fig. 7, the evolution of P_{dp} is shown for five records when estimated the average with interpolation factors from 1 to 5 and realigned with WA method. The intrinsic variability of the signal in the ensemble and the noise made a P_{dp} higher that in the noise free simulation but still lower than at the 10 dB white noise simulation. Also, we can note the decrease in P_{dp} with the interpolation factor as occurs at the simulation. We have studied the values of F_s from which further decrease in P_{dp} is less than 20% from the next lower sampling rate. With this criteria, and in the processed signals, we obtain a mean $F_s \simeq 3500Hz$ with a deviation of $\simeq$ 500 Hz. Since this is always a particular case and the limit of 20% is arbitrary we conclude that up to 4 kHz some improvement can be achieved.

4. Ventricular late potential study

In this section we analyze the influence of interpolation in the VLP indexes obtained from high resolution ECGs. We have made the study in simulated as well as in actual signals. The simulation was done with a triangular QRS-like signal, adding a sine VLP-like contribution at the end of the QRS

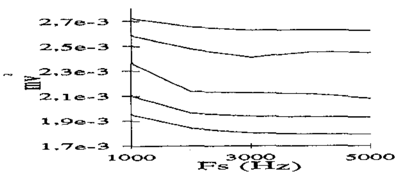

Figure 7: *Power of the deviation signal as function of the interpolated sampling rate in the averaging of 5 actual records.*

and noise with different SNRs. We compute the $QRSd$ and $RMS40$ for 100 trial and for 1 kHz sampling rate and interpolated to 4 kHz. No remarkable differences were obtained for VLP with frequencies of 40, 60 or 80 Hz (amplitude of 10 μV) and SNR of 10, 15, 20 or 30 dB. Only with VLP of 100 Hz we obtain a minor increase of 1% in $QRSd$ and $RMS40$. In the actual signal study we use the same orthogonal recordings than in previous case sampled at 1 kHz. We compute the $QRSd$, $RMS40$ and $LAS40$ indexes for the 35 records obtaining the results of table 1 We can see how we obtain an

	F_s=1000 Hz	F_s = 4000 Hz
$\overline{QRSd} \pm \sigma$ (ms)	76 ± 26.5	79.4 ± 29.6
$\overline{RMS40} \pm \sigma$ (μV)	64.1 ± 39.8	65 ± 40
$\overline{LAS40} \pm \sigma$ (ms)	22.6 ± 19.8	23.7 ± 20.4

Table 1: *VLP results on 35 actual ECG records with and without interpolation.*

increase 3.4 ms in the mean value of the $QRSd$ and how the $RMS40$ and $LAS40$ basically do not change. The $RMS40$ and $LAS40$ indexes remained with the same mean values as a possible result of two conflicting effects: an improved high-frequency signal estimation (which increases $RMS40$) and the delayed end of the 40 ms interval where the $RMS40$ is estimated that decreases its value. The minor increase in $QRSd$ can be due to the enhanced estimation of the high frequency activity. Figure 8 shows for one recording the vector magnitude (VM) obtained with high-pass filtering with a bi-directional 4-poles Butterwoth[1] with and without interpolation. The interpolation has enhanced estimation of the high frequency components of VLP (amplitude of 38.75μV respect to 39.0 μV), and $QRSd$ increased from 105 to 110 ms.

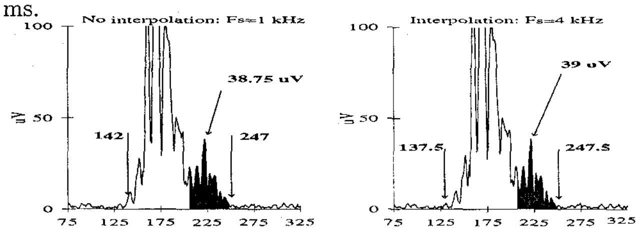

Figure 8: *Vector magnitude for one record with and without interpolation.*

5. Conclusions

The use of interpolation prior to time alignment has been shown to improve the synchronization and estimation in averaging. In white noise, Woody alignment method produced the best performance. In 50/60 Hz noise, both WA and NI yielded similar results at high SNRs (>10dB) while NI performed better at lower SNRs. It was shown that the deviation signal power not only depends of the misalignment but also of the frequency distrubution of signal componets. This aspect that should be considered when studying beat-to-beat variability with the deviation signal power, since this will depend of the dynamics of signal, the misalignment and the spectrum of the analyzing signal. The decrease in the power of the deviation signal with the interpolation was evident either in the simulated case as in the actual ECG signals considered. This decrease was noted remarkable up to a sampling rate of 4 kHz and less noticeable when increased further; this sampling rate is therefore recommended for alignment in studies of high-frequency ECG analysis. In 35 of these records the conventional indexes of late potential analysis ($QRSd$, $RMS40$ and $LAS40$) were computed. It was found that $QRSd$ increased by around 4 ms when F_s was increased by interpolation from 1 to 4 kHz. This result can be explained by the reduced low-pass effect due to improved alignment. The integral $RMS40$ and $LAS40$ indexes remained with the same mean values as a possible result of two conflicting effects: an improved high-frequency signal estimation (which increases $RMS40$) and the delayed end of the 40 ms interval where the $RMS40$ is estimated that decreases its value.

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