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COHERENT AVERAGING IN THE PRESENCE OF NOISE

ايجاد المتوسط المتلازم فى وجود الضوضاء

By

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الخلاصة ـ يحتاج تعيين وتقدير نموذج قياسى لشكل النبضات فى الاشارات الموجية التى يصاحبها نسبة عالية من الضوضاء الى ايجاد متوسط عدد من النبضات . وفى كثير من التطبيقات لا تتكرر هذه النبضات دوريا وانما باختلافات عشوائية فى لحظة حدوثها لذلك يكون دوريا عمل نوع من التزامن للنبضات حتى يعطى حساب المتوسط تقديرا مناسبا للشكل القياسى للنبضة والطريقة الشائعة لذلك تعتمد على تحديد نقطة مميزة فى كل نبضة (القيمة العظمى منها) مثلا وحساب متوسط النبضات بعد عمل ازاحة مناسبة لكل منها حتى تنطبق هذه النقطة فى جميع النبضات . والبحث الحالى يعرض طريقة بديلة تقوم على اختيار نموذج لهذه النبضة وتحسين وتجديد هذا النموذج باستمرار على أساس دراسة معامل الترابط المتبادل بينه وبين النبضات المتعاقبة . ويعرض البحث نتائج تطبيق هاتين الطريقتين على اشارتين لرسم القلب : الأولى تسجيل حقيقى لاشارة رسم القلب ، والثانية اشارة محاكية لرسم القلب وقد أظهرت النتائج أن الطريقة المقترحة تعطى تقديرا أحسن للشكل القياسى للاشارة حيث تؤثر الضوضاء على شكل النموذج حول النقطة المميزة فى الطريقة الأولى فضلا عن عدم حساسية النتائج باختيار النموذج الأولى للنبض .

ABSTRACT- Detection and estimation under poor signal-to-noise (SNR) conditions may require the averaging of an ensemble of time-locked signals. However, when there is a variation in signal delay, it is necessary to adjust the alignment of the different signals in the ensemble in order for averaging to produce an undistorted estimate of the signal waveform. Two techniques for alignment are considered; the fiducial point alignment and the template updating technique. The two techniques are applied to simulated and true ECG signals. It is shown that the morphology of the estimated averaged waveform using the fiducial point alignment is affected by the SNR and that the template updating technique is more convenient for such a purpose.

I- INTRODUCTION

In the analysis of biological signals especially those which have a repetative nature, we are often faced with a situtation in which we require to determine a standard form for the signal to be used for classification purposes. As an example we refer to the electrocardiogram (ECG) where the waveform is periodic and a representative beat can be determined. One of the referenced and frequently used signal processing techniques for this purpose is coherent averaging. It is widely accepted that under the conditions of noise stationarity, physiological invariability and uncorrelation between signal and noise, the signal is filtered from background noise, and the SNR can be increased by a factor of nearly $N^{1/2}$ where N is the number of averaged waveforms [1]. However, coherent averaging requires the determination of a time reference that is phase locked with the periodic component of the signal. It has been established that variability in this time reference namely time jitter, results in a low-pass filtering effect on the averaged signal and if in addition to the jitter there is a significant amount of noise, a difficult alignment problem arises [2]-[4].

A number of methods were developed for the estimation of a time reference, amongst these, two methods have been widely used; the alignment of a fiducial point in all the ensemble (e.g. R-peaks in the ECG beats) [5] and the template matching technique (matched filter) [6].

In the present work, the template matching technique is improved by updating the template iteratively. The performance of this updating technique is compared with that of the fiducial point method. The comparison is firstly made for simulated signals to exclude physiological variability in real ECG signals and to make a quantitative analysis of the noise in the original and averaged signals. The two techniques are then applied to the real ECG signal and comparison is also performed.

II - COHERENT AVERAGE DETERMINATION

a- TRUE AND SIMULATED ECG.

Two signals have been considered; a true ECG signal recorded using a philips ECG monitoring system type XV1503 and an idealized simulated model of the ECG.

The ECG signal in Fig.1.a has been recorded from a normal subject. The subject was lying down and breathing quietly. Twenty QRS complexes have been recorded at a bandwidth of 1-100 Hz and digitized using a 12-bit A/D converter. A sampling rate of 200 Hz have been found to be most satisfactory. The signal have been low-pass filtered to remove the artifact due to interference from the mains.

In the idealized model of the ECG, the QRS complex is approximated by one period of a symmetric cosine wave. It is assumed that the ECG is composed of a number of such beats.

An ensemble of 200 discrete cosine sequences each of length 128 time units have been generated. Each sequence is given a random delay (phase shift) with uniform distribution of 32 units wide and centered at time unit 64. Gaussian noise whose whiteness is certified by a Kolmogorov - Smirnov goodness - of - fit test [7] has been generated numerically and added to each sequence such that:

$$SNR = A/\sigma$$

where A is the peak amplitude of the cosine wave and σ is the standard deviation of the noise. The resulting signals are shown in Fig.2 for SNR = 8 .

b - THE FIDUCIAL POINT METHOD

The alignment of the fiducial point in the ensemble of beats is achieved by an automatic identification of the maximum point of each signal length (this corresponds to the R - peak in case of the true ECG). These are used as synchronization points.

Once all the sequences are properly aligned, averaging can be computed by the following equation:

$$Y_i = \frac{1}{k} \sum_{j=1}^{k} Y_{ij}$$

where Y_i represents the signal average amplitude measured at sample i, (i = 1,2,...,128) and Y_{ij} indicates the signal amplitude measured at sample i of signal length number j where (j = 1,2, ...,k) and k is the number of signal lengths to be averaged.

The averaging procedure needs an equal number of sample values within each signal length (i.e. N = 128) . The alignment procedure results in a shifting of all the signal length either sides. However, as the signal is periodic, each signal length has been spun on its time - base so that the reference point is treated as occurring in the midpoint (time unit 64).

In case of the real ECG and due to heart rate variations, the number of samples N_j within the jth beat, say, may be different from any other beat. Therefore, elimination of a number of samples which lie within the inactive region (namely, the T - P interval) is necessary . This procedure is based on the fact that small variations in the heart - rate only affect the segment between the T- wave and the P- wave [5]. Evidently, the spinning procedure is not adequate for the true ECG. An alternative efficient algorithm can be obtained as follows :

Let M_j (j = 1,2,...,k) represent the peak location, and let K be the number of R peaks. Define N by the equation:

$$N = \min (N_j) \quad J = 1,2,...,k$$

where N_j is the number of sample points in beat j.* Then averaging can be expressed as follows:

$$Y_i = \frac{1}{k} \sum_{j=1}^{k} Y(M_j + i - 1)$$

where Y_i represents the average ECG at sample i (i = 1,2,...,N/2).

The second half of the average ECG complex can be obtained as:

$$Y_L = \frac{1}{k} \sum_{j=2}^{k} Y(M_j + L - N)$$

where L = N/2,.....,N.

In this manner, elimination of a number of samples within the inactive region is automatically achieved without having to align the individual heartbeats.

c - TEMPLATE UPDATING TECHNIQUE

The template matching technique assumes that certain recurrent pattern is present in the signal. Some reference pattern or template is chosen and compared with individual beats usually by some means of cross-correlation. The simplest way involves the use of the cross-correlation coefficient which measures the degree of similarily between two waveforms.

Cross - correlation between the template and each successive beat of the ensemble is performed in the time domain using the equation:

$$r = \sum_{i=1}^{N} \frac{(X_i - \bar{X})(Y_i - \bar{Y})}{S_x \; S_y}$$

where X_i are the sampled values of the template and Y_i the samples from an individual beat, $\bar{X}$ and $\bar{Y}$ are the sample means of X_i and Y_i, respectively, and S_x and S_y are their respective standard deviations.
Instants of maximum correlation within each waveform are considered as trigger times and some N successive waveforms were then averaged according to their respective trigger time.

The choice of a suitable template is of considerable importance. The performance of coherent averaging can be affected by the morphology of the template and its level of noise[6]. To avoid this difficulty, the following "updating" procedure is suggested. An initial template, not necessarily accurate, is chosen. The first waveform (beat) may serve for this choice. The cross -correlation of this tempelate with the successive beats is performed as above. However, once the trigger instant within a beat (point of maximum correlation) has been determined, the template is replaced by the average of the current and preceding beats aligned to the trigger instant.

In this way, the template is iteratively updated. This procedure has the advantage that it reduces the degradation caused by the molding effect. This effect is discussed by Lippens et al., 1989 [6], a noisy template impedes the SNR improvement during the averaging procedure.

Different SNR's are used to compare the performance of both techniques. The programs are written in Fortran 77 and computations were performed on an Xenix computer.

III - RESULTS

Fig.3.a. shows the coherent averaged waveform for the simulated signal obtained using the fiducial point technique for an ensemble of 200 signals. As can be shown, The signal-

* In the choice of N_j, it has been assumed that a beat starts at the middle of the inactive region.

averaging procedure has reduced the noise to some extent. However, the noise level is still high around the fiducial point (time reference). A sharp peak is observed at the fiducial point. To highlight this phenomenon, the averaging procedure has been repeated using a smoothed version of the same signal so as to reduce the noise. The smoothing has been carried out using a Hanning digital filter [8·] However, the resultant average signal still exhibits a similar sharp peak (Fig.3.b); the noise in the averaged signal seems to be reinforced around the fiducial point, although the SNR has been increased by the smoothing procedure. The magnitude of the sharp peak has been investigated and it has been found thatit increases as the number of averaged beats increases (Fig. 3.c).

Fig.3.d shows the SNR of the averaged signal obtained by the fiducial point method as a function of the number of averaged beats. Evidentty, the SNR improvement does not follow the $N^{1/2}$ law; the SNR does not improve with increasing the number of averaged signals beyond a certain value. This is presumably due to the noise around the fiducial point.

The results for the template updating technique are shown in Fig. 4.a. Although the resultant signal is, to some extent, similar to the one obtained by the fiducial point method, the sharp peak has been disappeared and a flat peak has been obtained. Contrary to the fiducial point results, the signal - to - noise ratio improves continuously with increasing the number of averaged waveforms as shown in Fig. 4.b.

Similar results have been obtained for different SNR's. However, for higher SNR values (above about 30), the results of the two techniques are almost similar.

It is interesting to investigate the effect of choosing a distorted initial template. Therefore, a notch has been made in the initial template (Figs .5.a and 5.b). Fortunately, the resultant averaged signal does not seem to be affected by the notch (Fig.5.c), which shows that the method is not sensitive to improper choice of the initial template.

Figs 1.b and 1.c. show the averaged real ECG beat obtained by the two techniques. It can be noted that the magnitude of the R - peak is greater in case of the fiducial point method, which confirms that the template updating technique gives better SNR improvement.

IV - DISCUSSION

The present results show that the proposed template updating technique is a powerful and efficient technique for obtaining a representative standard pattern for an ensemble of signals, even in low SNR conditions. The coherent - average pattern obtained from the fiducial point technique reduces the noise in the whole signal length but fail to do this in the neighbourhoodof the fiducial point, especially when the chosen fiducial point is a maximum or minimum. The alignment of points of maxima (or minima) in successive waveforms results in a sharp peak (or. trough) as the noise is always added positively. This results in a significant alteration of the morphology of the desired representative pattern, especially under poor SNR conditions. The patte n obtained in this way is evidently not reliable for comparative or diagnosis purposes in such applications as ECG analysis, for instance.The application of the averaging techiques to simulated signals has enabled us to evaluate the SNR of the averaged pattern for different SNR values. as the original signal shape is known in its ideal form. This is not possible with real signals like, for instance, the ECG, which is subject to high variability and noise from different sources (respiration, muscles, recording electrodes, ...etc). Moreover, the shape of the QRS complex itself does not help to discover the artificial sharp - peak resulting from the averaging process; the QRS by its nature is peaked at the R - point.

Although, the choice of a "good" inital template to start the updating process may be useful, it is not necessary as the updating will itself improve the template recurrently Making a good initial estimate is difficult if the SNR is low and especially when the signal and noise have similar spectral densities. The template updating technique aligns each waveform (e.g. QRS complex) to a reference template by maximizing the temporal coicidence of several points on both waves. This gives a high degree of accuracy for alignment and automatically improves the template morphology to be highly correlated with the successive waveforms in the ensemble.

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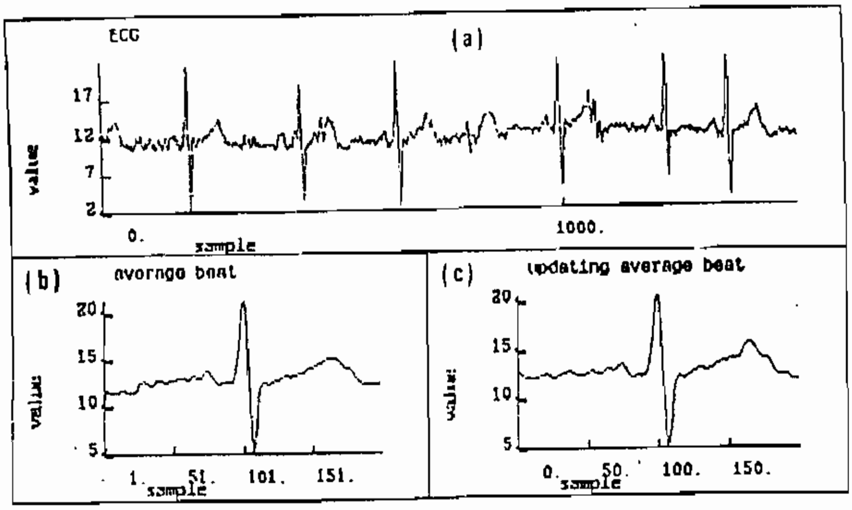

Fig.1 Recorded ECG signal (a) raw data (b) fiducial point average beat (c) template updating average beat

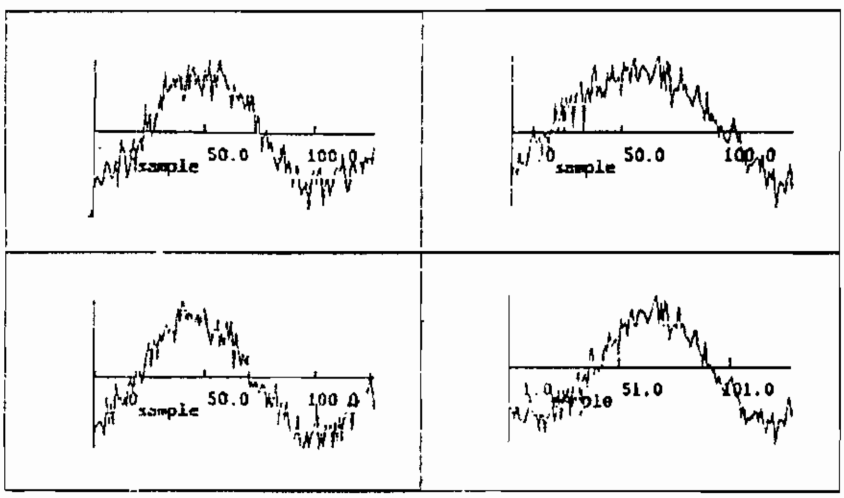

Fig.2 Examples of simulated data

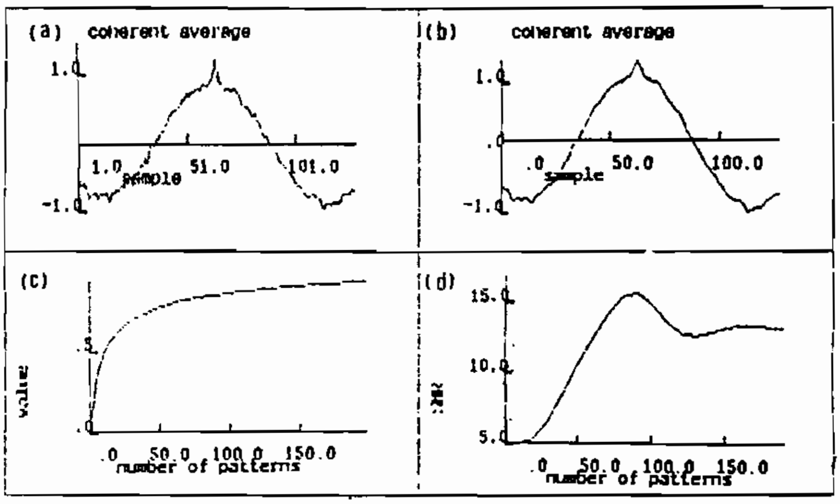

Fig.3 Fiducial point averaging of simulated data

(a) average patten (raw data) (b) average pattern (smoothed data)

(c) sharp peak magnitude versus number of averaged patterns

(d) effect of the number of averaged patterns on SNR

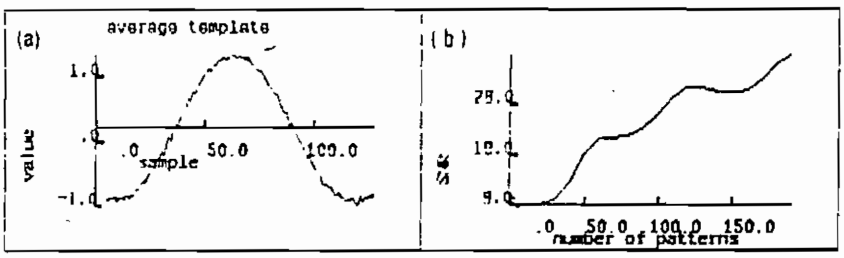

Fig.4 Template updating averaging of simulated data.

(a) average pattern (b) effect of the number of averaged patterns on SNR

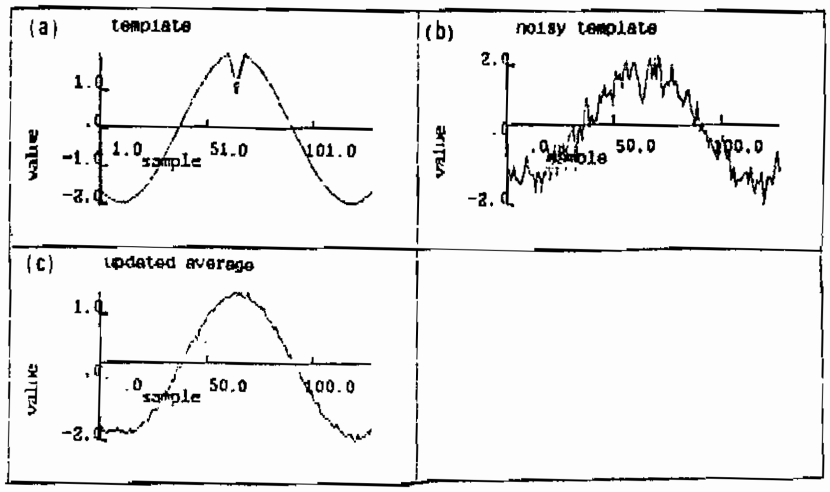

Fig.5 Averaging using a distorted template

(a) notched template (b) notched template with noise

(c) the average pattern obtained by updating technique using template (b)