Repolarization Alternans Detection Using the KL Transform and the Beatquency Spectrum

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Abstract

Electrical alternans at the repolarization phase of the cardiac cycle have been reported to be related with increased risk for ventricular arrhythmias (VA). In this work we present and study a method for detecting ST-T complex alternans based on the Karhunen-Loève (KL) transform and a beatquency transform (Fourier transform of KL series with beat order as temporal reference). The ratio of the power in the band around 0.5 cycles/beat respect to the total power is then used as indicator of the period 2 alternans presence. Similarly is done for period 4 alternans. To study the performance of this detection system we have generated a simulated alternating ECG with added noise (moving artifacts, EMG and baseline wander noise). The results for SNR around 15 dB at ST-T complex (normal value at ECG signals) give a sensitivity and specificity for period 2 alternans detection over 95%. This method applied to the entire European ST-T database gives 25 alternating episodes, 56% corresponding to ischemic episodes, showing that 5.3% of the ischemic episodes include alternans episodes.

1. Introduction

Electrical alternans affecting the repolarization phase of the cardiac cycle have been reported[1] to be related with patients at increased risk for ventricular arrhythmias (VA). These alternans are reflected at the ST-T complex of the surface ECG signal. In Figure 1 it is plotted an ECG from record e0105 of the European ST-T Database[2] with visible alternans on the ST-T complex. In other cases there are reported alternans not visible by single visual inspection but indicating relevant clinical information. Automatic and early detection of these alternans can add a new non-invasive index for prevention of cardiac vulnerability to VA. Previous works[3] detect the alternans performing a FFT over the corresponding aligned samples of consecutive beats. This technique requires a large amount of calculations for non independent sampled values. Other works[4] perform a "complex demodulation" on similar kind of series (area instead of amplitude) to detect the alternans over the ECG. This method allows to identify single frequency alternans but is not suited for several overlapped alternans with different periodicities.

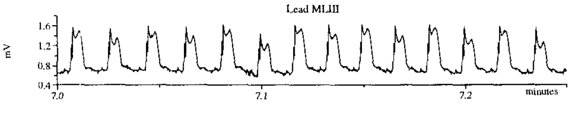

Figure 1: *Excerpt of ECG from record e0105 (lead MLIII) of the European ST-T Database containing visible ST-T complex alternans.*

In this work we present and study a method for detecting ST-T complex alternans based on the Karhunen-Loève (KL) transform and a beatquency transform (Fourier transform of $kl(\mathrm{k})$ series with the $\mathrm{k}th$ beat order as temporal reference). The method requires low number of FFT calculations since we study the KL coefficients of the ST-T complex that is the representation that recovers the maximum information in the minimum number of coefficients. The *kl* series contain equivalent information than exhaustive amplitude series but with much lower series number[5]. In addition the KL domain is where the signal and noise are more separated, and it makes the KL technique the best suited to be minimally noise affected.

An alternating behavior of the ST-T complex is reflected as an alternating value at *kl* series. The *kl* series become referred by the beat order instead of by a time reference. Alternans of period 2 beats will be reflected as a period 2 alternation of the *kl* series and then at the beatquency spectrum will appear a peak at the 0.5 cycles/beat (cb). The ratio of the power in the band around 0.5 cb respect to the total power will be then an indicator of the alternans presence or absence. To study the performance of this detection system we have generated a simulated ECG signal adding controlled alternans and noise (moving artifacts, EMG and baseline wander noise). This method has also been applied to the entire European ST-T database giving 25 alternating episodes of period 2; from which 56% correspond to ischemic episodes, and showing that 5.3% of the ischemic episodes include a period 2 alternans episode.

2. Methods

The proposed method for alternans detection requires:

2.1 QRS detection to position every beat. This QRS detector also includes an alignment step to assure equal ST-T complex delineation at every beat and avoid to generate artifactual alternans.

2.2 Baseline wander suppression to attenuate ST-T vari-

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

ations non-repolarization related, like respiration related. This is performed by a cubic spline interpolation.

2.3 KL transformation on the ST-T complex[5]. The KLT is a rotational signal-dependent transformation of a pattern vector (ST-T(n)) into a *feature vector* kl_i, the components of which are the coefficients of the KLT. The first few components (4 kl coefficients) of the feature vector represent almost all of the signal energy (90%), and the remaining components need not even be computed[5]. The low-order basis functions of the transformation are those functions that are best able to represent an arbitrary pattern vector; the next function is the (orthogonal) function best able to represent the residual error obtained from fitting the first function, etc. From this analysis we have different kl_i values for each kth ST-T complex generating then the $kl_i(k)$ series used by the alternans detection method. In Figure 2 we present the $kl_i(k)$ from the ECG record of Figure 1. Note how at the time (around minute 6 and 7) where the ischemia and alternans appear the kl series present a clear oscillating behavior.

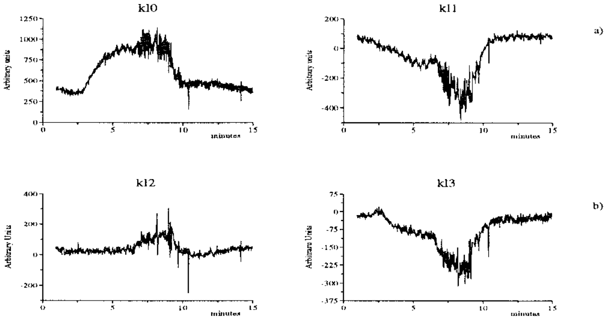

Figure 2: *a) kl series from ECG record in Figure 1. a)* $kl_0(k)$ *(left) and* $kl_1(k)$ *(right). b)* $kl_2(k)$ *(left) and* $kl_3(k)$ *(right). Note an oscillation of the kl values around minute 7 belonging to an alternating behavior of ST-T complex in the acute phase of an ischemic episode (elevation/depression of* kl_i *values from minute 3 to 10).*

2.4 Beat spectrum estimation of the $kl_i(k)$ series. It is calculated the Power Spectral Density (PSD) of the $kl_i(k)$ series by the FFT during fixed periods of time. The width of these periods of time defines the precision of the alternans location in time. Consecutive periods are selected having 50 % overlap with previous period to avoid short alternating events to be split in two different analyzing periods. In Figure 3 it appears the ECG from previous figures and the spectrum of kl_0 series. It appears clear peaks at 0.5 cb and at 0.25 cb evidentiating period 2 and 4 alternans overlapped on the same ECG record.

2.5 Power band estimation in those bands where we are looking for their corresponding alternans. In this study we concentrate in period 2 and 4 alternans corresponding to 0.5 and 0.25 cb respectively. The Energy is computed in the bands from 0.496 cb to 0.504 cb (E_2) for period 2 alternans, and from 0.246 cb to 0.254 cb (E_4) for period 4 alternans. The width of the bands is that corresponding to the width of the spectrum of an ideal alternans lasting 5 minutes (sinc funtion). The band energy values E_2 and E_4 are normalized with respect to the total band energy from 0.125 cb to 0.875 cb (E_T). Then we define the relative values

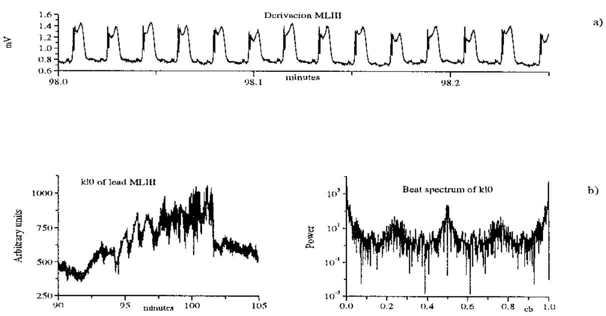

Figure 3: *a) Excerpt of ECG from record e0105, b) Corresponding* kl_0 *series (left) and its beat spectrum (right).*

$$RE_2 = \frac{E_2}{E_T} \qquad RE_4 = \frac{E_4}{E_T} \tag{1}$$

that are the ones used to detect the alternans when they reach some threshold value (TH). The E_T does not include the total band to avoid large DC artifact due to gradual ischemical variation (commonly associated with alternans. Fig. 2) that could generate a large peak around 0 cb and then distort the RE_i index.

2.6 Alternans detection based on the $RE_{2,4}$ values and a threshold value to decide the presence of alternans. The minimum value of this threshold is the ratio between bands (TH=0.008/0.75=0.0106) However the election of this TH value is not desirable since the noise will generate a large number of false positives detections. A larger threshold is then desirable and the greater the value the greater the specificity and lower the sensibility, so a compromise is required. From the simulations results we will fix the threshold values.

Since we have several kl series and several leads for each record we consider two criteria to detect alternans. Criterion 1 considers independently each lead and the resulting alternans are associated to each lead. When the RE factor crosses the threshold in more than half the number of kl series analyzed, the alternans is considered to appear. Criterion 2 considers all leads together and then when the RE factor crosses the threshold in more that half the kl series analyzed (considering all leads) the alternans is detected. In Figure 4 is plotted the beat spectrum of record e0105 (kl_0) for the different 5 minutes (half width overlapped) periods analyzed in a 15 minutes ECG recording. The Figure 5 shows the alternating periods detected on this lead with a threshold value of 0.04. Note how the period 2 alternans are detected at the second, third and fourth windows and the period 4 at the first and last window of 5 minutes length. These detections are evident from visual inspection of spectra in Figure 4.

3. Detector validation

To test the performance of this detector we need a controlled alternating ECG. This is not the case in real ECG records where we do not have a priori information about the alternans content. We generate artificial ECG records formed by a patron beat concatenated itself to generate the ECG recording. In fact the beat patron comes from averaging of 10 consecutive normal beats of a real ECG record. The alternating behavior is generated by adding to the ST-T complex a signal with the shape of Figure 6. This addition is performed every two beats for period 2 alternans and on all beats with a period four weighting factor for period 4 alternans. Also the alternans are generated directly on the ST-T complex or after introducing a gradual ischemia elevation on ST-T complex to recover the common observation that alternans comes frequently at ischemic episodes. We consider 7 different patrons of ST-T complexes, with three different types of noise (baseline wander, moving artifact and EMG) in different signal to noise ratios (SNR). Also different types of alternans are considered (different alternating μV step value of the ST segment amplitude, Fig. 6). The total record duration was 17:30 minutes. The alternans were added only from minute 5:00 to minute 12:30 and the analyzing window was of 5 minutes resulting in 6 analyzing windows in each record. This construction generates three kind of windows: windows with no alternans, others with alternans in half of the window and others with alternans during the entire window. The same number of window (WN/3) of each type are in the experiment, 1/3 of the total window number (WN). The alternans detections in this experiment can be classified in three groups: *False Positives (FP)* that belongs to detections made at the windows where was not added alternans, *True Median Positive (TMP)* that belongs to the true detections obtained at the windows with alternans in half their size, and *True Entire Positive (TEP)* obtained at the windows with alternans in the entire size. To study the results of the detections we define the following magnitudes:

- Sensitivity to median window $SENM = \frac{TMP}{WN/3} \cdot 100$
- Specificity to median window $SPM = \frac{TMP}{TMP+FP} \cdot 100$
- Sensitivity to entire window $SENE = \frac{TEP}{WN/3} \cdot 100$
- Specificity to entire window $SPE = \frac{TEP}{TEP+FP} \cdot 100$
- Sensitivity to any window $SEN = \frac{TMP+TEP}{2WN/3} \cdot 100$
- Specificity to any window $SP = \frac{(TMP+TEP)/2}{(TMP+TEP)/2+FP} \cdot 100$

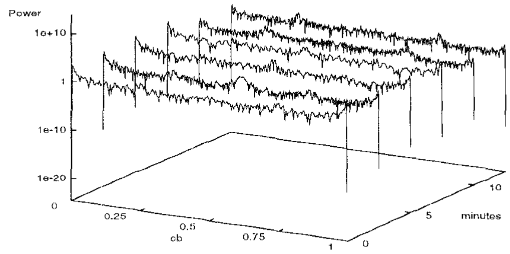

Figure 4: *Spectra from consecutive 5 minutes windows (half overlaped) from the kl_0 of record e0105. Note how peaks are marked at 0.5 and 0.25 cb related to alternating episodes.*

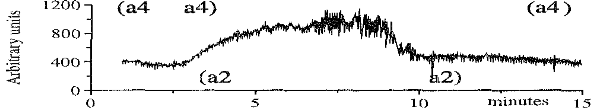

Figure 5: *Alternating periods detected with a threshold value of TH=0.04 and considering four kl series.*

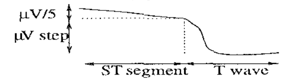

Figure 6: *Shape of the added signal to simulate the alternans.*

In the value of SP a factor 2 has been included. This SP value can change as a function of the ratio between alternating windows and non alternating at the experiment. In the proposed experiment there are twice alternating windows than non alternating so, to normalize to an experiment with equal windows of the different types, it is included the factor 2. In the cases of SPM and SPE there are already equal windows of each type and does not need normalization.

In table 1 we present the results for criterion 1 (independent leads) for the 7 ECG patrons, with 3 types of ischemia (no ischemia, linear ST-T growing ischemia and sine like growing ischemia), and 3 types of noise ($WN = 7 \cdot 3 \cdot 3 \cdot 6 = 378$), a $SNR \simeq 15$ dB at the ST-T complex, an alternating step at the ST segment of 60 μV with period 2 and four *kl* series. Different threshold values are considered showing that TH=0.04 is a reasonable option for this case. In table 2 are the results for TH=0.04 and others SNR. We see that for SNR values down 10 dB the performance decreases largely. Of course if the alternating step is larger the performance remains acceptable for lower SNR values.

Independent leads, SNR=15						
TH	SENM	SPM	SENE	SPE	SEN	SP
0.070	74.6	100.0	90.5	100.0	**82.5**	**100.0**
0.057	76.2	100.0	90.5	100.0	**83.3**	**100.0**
0.040	81.0	91.9	90.5	92.7	**85.7**	**92.3**
0.032	81.0	87.2	90.5	88.4	**85.7**	**87.8**
0.020	88.1	71.2	95.2	72.7	**91.7**	**72.0**
0.010	97.6	59.4	100.0	60.0	**98.8**	**59.7**

Table 1: *Sensitivity and specificity for period two alternans, different threshold values, 60 μV alternating step and criterion 1.*

Similar analysis can be done for period 4 and for the criterion 2 considering all leads together. In table 3 are the results for the global detector, period 2, two leads, a TH=0.04 and four *kl* series (two from each lead). We can note how the performance is better considering both leads together than in an isolated way, being the number of *kl* series considered in each case the same. As conclusion the results are highly dependent on many factors, but for SNR=10 dB or higher and TH around 0.04 the proposed methods get sensitivity and specificity acceptable for clinical use (> 74%). These values decrease as the alternans value decreases. In table 4 are the results for an alternating step of 40 μV where it is clear that the performance decrease in terms of SEN and SP.

Independent leads, TH=0.04						
SNR	SENM	SPM	SENE	SPE	SEN	SP
20	98.4	98.4	97.6	98.4	**98.0**	**98.4**
15	81.0	91.9	90.5	92.7	**85.7**	**92.3**
10	48.4	95.3	73.8	96.9	**61.1**	**96.2**
5	14.3	75.0	23.8	83.3	**19.0**	**80.0**

Table 2: *Sensitivity and specificity for period two alternans and different SNR values. 60 μV alternating step and threshold at TH=0.04 with criterion 1.*

Global leads, TH=0.04						
SNR	SENM	SPM	SENE	SPE	SEN	SP
20	100.0	100.0	100.0	100.0	**100.0**	**100.0**
15	88.9	100.0	100.0	100.0	**94.4**	**100.0**
10	64.8	100.0	83.3	100.0	**74.1**	**100.0**
5	27.8	83.3	38.9	87.5	**33.3**	**85.7**

Table 3: *Sensitivity and specificity for period two alternans and different SNR values. 60 μV alternating step and threshold at TH=0.04 with criterion 2.*

Global leads, 40 μV step, TH=0.04						
SNR	SENM	SPM	SENE	SPE	SEN	SP
20	100.0	100.0	100.0	100.0	**100.0**	**100.0**
15	83.3	100.0	100.0	100.0	**91.7**	**100.0**
10	51.9	100.0	66.7	100.0	**59.3**	**100**
5	11.1	66.7	9.3	62.5	**10.2**	**64.7**

Table 4: *Sensitivity and specificity for period two alternans and different SNR values. 40 μV alternating step and threshold at TH=0.04 with criterion 2.*

4. Results on the ST-T database

Applying the alternans detector to the entire ST-T database we can observe the alternating periods. Also, since at the database the ischemic episodes are annotated, it can be analyzed the number of alternans associated to a ischemic episode or not associated to ischemia. To study the result we define:

- I. total number of ischemic episodes at the database
- S/A: Percentage of alternans on ischemic episodes respect to the total alternans episodes
- S/I: Percentage of alternans on ischemic episodes respect to the total number of ischemic episodes

Table 5 summarizes the results in case a threshold value TH=0.056 is used. Consecutive alternating windows are considered as an unique alternans episode.For 5 minutes observation window we have 5.3% of ischemic episodes containing period 2 alternans and 1.9% containing period 4 alternans. By other hand 56.0% of the period 2 (p2) alternans detected are associated to a ischemic episode whereas only 12.8% of period 4 (p4) are associated to ischemia. If the observation window increases (7:30 minutes) the alternans need to maintain during longer period to be detected and then the number of detected alternans decreases, being those detected more highly related to ischemia, 76.9%, indicating that stable alternans are highly related to ischemic processes. By the contrary a decrease at the observation window (2:30 minutes) detect more transient alternans that are less related to ischemia (29.9%) as a result either of rear alternating episodes or a lower specificity due to the small observation size.

TH= 0.057							
		Window 2:30		Window 5:00		Window 7:30	
Per.	I	S/A	S/I	S/A	S/I	S/A	S/I
2	262	29.9	9.9	56.0	5.3	76.9	3.8
4	262	11.6	5.7	12.8	1.9	19.2	1.9

Table 5: *Results of alternans detected at the European ST-T database. There are the results for two alternanting periods (2 and 4) and for several observation window size (2:30, 5:00 and 7:30 minutes).*

5. Conclusions

It has been developed an alternans detector based on the KL transform. The detector has been proved to give robust alternans estimation for SNR over 15 dB (normal values at Holter recordings) and alternans representing around 60 μV variations at ST-T complex. The sensitivity and specificity is over 95% depending of noise and alternans level. The detailed analysis of the European ST-T database has shown that about 5% of ischemic episodes present alternans associated with them and also more than 50% of the alternans present at the recordings are associated with the ischemic episodes. This corroborates previous clinical works that highly relate the alternans phenomena with the ischemia. This detector can be used as a new index when analyzing Holter ECG recording to prevent ventricular arrythmias.

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