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T-wave Alternans Search over 24 Hour Holter ECG Recordings based on Singular Value Decomposition*

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Abstract— **This paper proposes an efficient method to search for T-wave alternans (TWA) over 24 hour Holter ECG recordings. After appropriate pre-processing to remove baseline drift and artifact, data are segmented to 2 minute successive time intervals. For each beat in the segment, singular value decomposition is applied to derive orthogonal characteristic signals. Then two prominent orthogonal signals are used for the TWA search. A pair of alternans indices is defined for each beat as the orthogonal waveform distance between the target beat and the adjacent two beats. When alternans presents, the first index will be larger than the second index. The periodogram of the sequence of alternans indices in each segment yields a useful alternans measure named Alternans Ratio (*AR*). To show the effectiveness of the measure, the method is applied to 25 control and 24 data from patients with various cardio vascular disorders. *AR* distribution showed prominent differences among subject groups. It has been demonstrated that the measure AR is not only useful to detect the presence of TWA but the AR distribution can be used for the stratification of the TWA risk.**

Keywords— **T-Wave Alternans, Holter Electrocardiogram, Signal Detection, Biosignal Classification, Sudden Cardiac Death, Singular Value Decomposition.**

I. INTRODUCTION

Sudden Cardiac Arrest (SCA) is known to be a leading cause of death in many countries, which has been a serious global health problem. According to the report of American Heart Association[1], more than 400,000 deaths are originated from coronary heart desease (CHD) a year in the United States. Hence, the risk assessment is important to prevent these sudden cardiac deaths (SCD) since early implementation of Implantable Cardioverter- Defibrillator (ICD) is effective to prevent those fatal incidents. *T*-wave alternans (TWA) is one of the prognostic indices of SCD and documented well in the literature[2]-[4]. Recently some reports utilize Holter ECG recordings as sources of TWA detection[5],[6]. Those studies adopted a simple detection method named modified moving average analysis[7].

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Extensive validation and the development of efficient TWA detection method for Holter ECG recordings are expected to be made to disseminate simple yet reliable SCA risk assessment methods freeing us from the necessity of the lab test environment commonly used [8]. Authors proposed a novel TWA detection method[9] utilizing singular value decomposition (SVD)[10] aiming to develop robust detection method in noisy environment. The method consists of two steps, the coarse and fine TWA detections. The fine detection requires high computational power which doesn't fit to process 24 hour long term recordings effectively. In this paper, we propose alternative efficient method applicable to 24 hour data keeping the best part of the previous fine TWA detection method intact. To show the effectiveness of the proposed method, the method is applied to 51 subjects, *i.e.* 26 out patients with various cardiovascular disorders and 25 normal control subjects.

II. METHODS

A. Data acquisition and preprocessing

24 hour three lead ECGs were recorded on three subject groups. The first group consists of 11 outpatients with various cardio vascular disorders such as CHD (myocardial infarction, angina pectoris), history of life threatening arrhythmia (ventricular tachycardia, Brugada syndrome), cardio-pulmonary arrest, Cardiomyopathy (cardiac sarcoidosis, hypertrophic, cardiomyopathy, or acromegalic cardiomyopathy). This group is named group *HR* (*high risk*) since patients with these cardio vascular disorders have high risk of SCA. Another group from outpatients named *LR* (*low risk*) group, consists of 15 subjects with supraventricular tachycardia, ectopic beats, high blood pressure without arrhythmia, or diabetes with less association with SCA occurrences. 25 normal subjects are for control cases and denoted as group *NC* (normal control).

Three lead Holter ECG recordings (*Spiderview: ELA Medical, Cedex France*) were made for each subject. Data were digitized with the sampling rate at 200 Hz followed by band pass filtering (0.5-60Hz) by a FIR filter of order 1000 for artifact and baseline drift removal. Those preprocessed original digitized data were denoted as $x^{(l)}[n]$, l=1,2,3; n=1,…,N_0, where l, 1,2 or 3, denotes lead *X, Y* or Z respectively and n denotes digitized time sequence number. Two minute data are processed at a time.

B. Data segmentation and decomposition

In order to detect the alternate T-wave morphology change, we set a fixed time window, *i.e.* T-wave peak time $\pm$ 150(mS) to extract data for subsequent signal processing. Let us denote the m^{th} beat data segment from the lead l as:

$$y^{(m,l)}[n], l = 1,2,3; m = 1,...,M; n = 1,...,N. \quad \ldots(1)$$

Singular Value Decomposition (SVD) to the multiple lead data of each beat yields orthogonal signals behind the original signals. SVD is utilized and the following decomposition of segmented data has been made for each beat m(m=1,…,M):

$$Y^{(m)} = U^{(m)}\Sigma^{(m)}V^{(m)^T} \quad \ldots(2)$$

Here, $Y^{(m)}$ is $3 \times N$ matrix with raw l (l =1,2,3) being $y^{(m,l)}[n], n = 1,...,N.$ Each raw of the matrix $S^{(m)}$:

$$S^{(m)} = \Sigma^{(m)}V^{(m)^T} \quad ...(3)$$

is decomposed orthogonal signals. If we write the r-th raw of the matrix $S^{(m)}$ explicitly as

$$s_r^{(m)}[n], r = 1,2,3; m = 1,...,M; n = 1,...,N \quad \ldots(4)$$

original signals are described as:

$$y^{(m,l)}[n] = \sum_{r=1}^{3} u_{l,r}^{(m)} s_r^{(m)}[n],$$

$$m = 1,...,M; l = 1,2,3; n = 1,...,N \quad \ldots(5)$$

Two orthogonal signals with higher singular values are then utilized for alternate T-wave morphology changes. The matrix consists of those notable signals is denoted as $\widetilde{S}^{(m)}$. Fig. 1(a) and (b) show examples of extracted T-wave segments and phase plots, which we call *T*-loop, obtained from two major orthogonal signals given by $\widetilde{S}^{(m)}$. When TWA presents, the T-loops should have two different clusters for even and odd beat numbers.

C. T-wave alternans search

Beat to beat changes of orthogonal signals $\widetilde{S}^{(m)}$ are examined to search for the presence of T-wave alternans. Orthogonal signals $\widetilde{S}^{(m)}$ are partitioned first into several phases:

$$\widetilde{S}^{(m)} = \left[\widetilde{S}_1^{(m)} \middle| \cdots \middle| \widetilde{S}_p^{(m)} \middle| \cdots \middle| \widetilde{S}_P^{(m)} \right] \quad \ldots(6)$$

Starting from the first beat (m=1), m-th orthogonal signal matrix $\widetilde{S}_p^{(m)}$ is compared with adjacent signal matrix

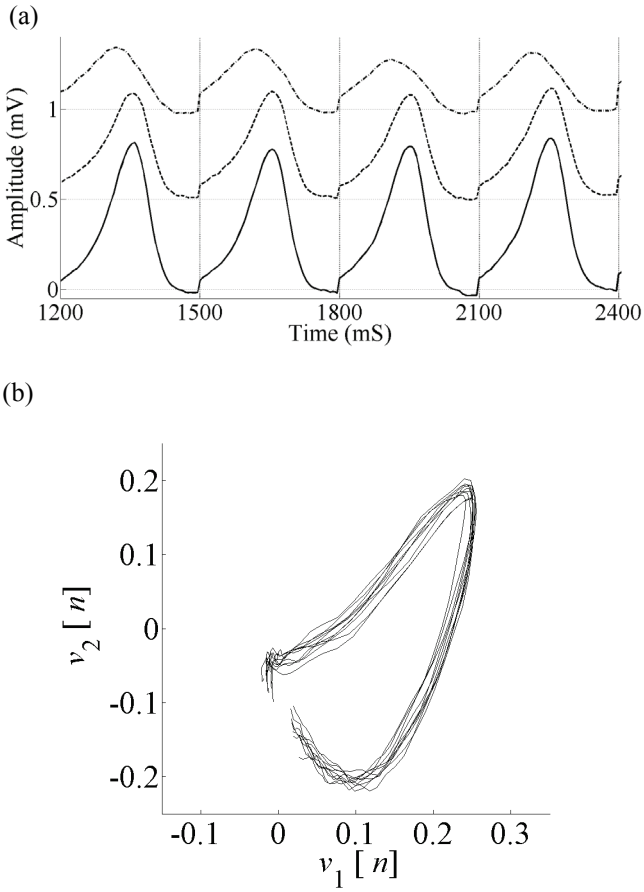

Fig. 1 Segmented *T* waves and *T*-loops
(a): Segmented T-waves from X, Y, Z (top to bottom traces);
(b): T-loops derived from four beats in Fig. 1(a)

$\widetilde{S}_p^{(m+1)}$ and $\widetilde{S}_p^{(m+2)}$. Namely, for each m, the distance pairs are calculated:

$$e_p^{(m,i)} = \frac{\left\| \widetilde{S}_p^{(m)} - \widetilde{S}_p^{(m+i)} \right\|}{\left\| \widetilde{S}_p^{(m)} \right\|}, p = 1,...,P; m = 1,...,M-2; i = 1,2 \quad \ldots (7)$$

These beat to beat signal difference pairs are then concatenated to form an error sequence E_p

$$E_p = \left\{ e_p^{(1,1)}, e_p^{(1,2)}, ..., e_p^{(m,1)}, e_p^{(m,2)}, ..., e_p^{(M-2,1)}, e_p^{(M-2,2)} \right\}$$
$$p = 1,...,P \quad \ldots(8)$$

When alternate T-wave morphology changes do present, the error sequence above will have alternate changes as well. Thus the periodogram of the error sequence is calculated and the intensity at the Nyquist frequency is examined to detect the alternate changes. In this report averaged

periogram, $P[k]$ k=0,…, M-2 over different phases is utilized for the subsequent analysis. Note that k=M-2 corresponds to the Nyquist frequency for the sequence. The index named Alternans Ratio AR is defined and utilized for the TWA search:

$$AR = \frac{P[M-2]}{\frac{1}{k_1-k_0}\sum_{k=k_0}^{k_1} P[k]}$$

The discretized frequency region [k_0 , k_1] is determined empirically where systematic errors such as respiratory changes are to be avoided. Alternans Ratios (ARs) are obtained for 24 hour Holter ECG recordings of all subjects, 13 high risk (HR) patients, 11 low risk (LR) and 25 normal control (NC) subjects. Since ARs are calculated in every two minutes, 720 ARs are obtained for each subject. The system recognizes the presence of TWA when the AR of a segment exceeds the predetermined threshold. The threshold is determined by examining statistical distribution of AR values for the control subjects as is shown in the results section below.

III. Results

An example of the alternans detection is shown in Fig. 2. Fig. 2(a) (b) show the error sequence and its periodogram. Prominent alternate changes in the error sequence and corresponding periodogram peak at the Nyquist frequency are observed. A peak observed at frequency around 0.25 (cycles/ beat) is originated the respiratory rhythm which is commonly seen. Fig. 3(a)(b) show T-wave loops and a part of original segmented T waves. T-wave loop patterns clearly separated for even (black curves) and odd (gray curves) beats. In this case, alternans is clearly visible in original T-wave segmented sequence. Note that the alternans is prominent in all leads. In order to examine the statistical nature of AR values, their distributions are compared among subject groups. TABLE 1 shows mean ± S.E. values of AR statistics. The higher the risk (HR >LR >NC) the higher the median of AR values but the differences are not statistically significant. However, 10%, 5% and 1% tile values showed significant differences between both HR vs. LR and HR vs. NC subject groups. These results are due to the fact that conditional distributions above certain critical AR value θ show notable differences among subject groups. This trend gets large as θ decreases focusing on the differences in the tail end of the distribution.

TABLE 1. AR values statistics

Subjects	N	median	10% tile	5% tile	1%tile
HR	11	1.38±0.33	15.8±3.08	25.5±4.79	81.9±37.5
LR	15	0.97±0.37	9.84±2.38	15.1±3.92	30.4±33.4
NC	25	0.92±0.21	7.72±0.84	11.3±1.12	21.2±2.28

All percentile values for HR subject groups are significantly larger ($p<0.01$) than those for different subject groups.

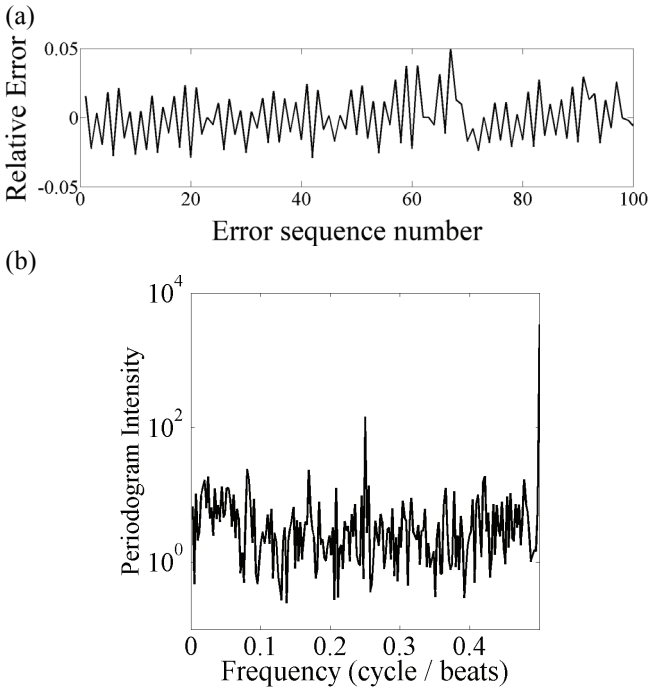

Fig. 2 An example of TWA detection
(a) Error sequence of a 2 min segment of a HR patients
(b) Periodogram of the error sequence

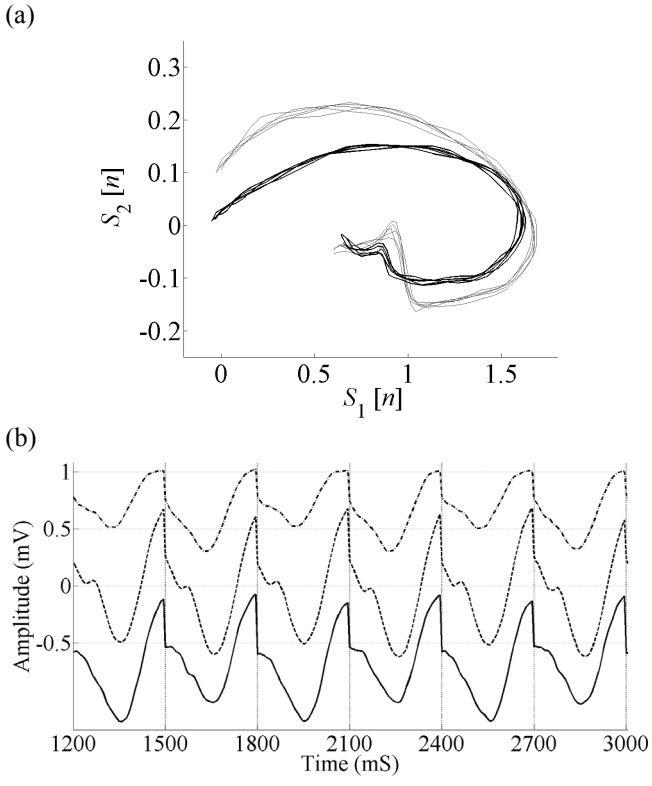

Fig. 3 An example of T-wave loop (a) and segmented original T-waves (b) in the presence of Alternans

This finding is depicted in Fig. 4. Here, average histograms for three groups are superimposed in log-log scale. It is clearly recognized that the distribution tail for HR patient group shown by the chain line is longer than those for other subject groups (LR: dashed line, NC; solid line). The tail for LR patient group is seen to be higher than that of NC subject group though the difference is not statistically significant. It is noted that the discrepancy gets large at and above AR values around 8. Maximum AR value obtained from NC subject group was 97.2. Hence, AR value 100 could be tentatively set as the threshold for apparent TWA detection. To assure the sensitivity of TWA detection, α percentile AR values mentioned above can be utilized as a TWA risk factor for the subject and denoted as $rf(\alpha)$. Fig. 5 compares the distribution of risk factors among different subject group. As is already noted in TABLE 1, the median for $rf(1)$'s, *i.e.* 1 % tile of AR values is significantly larger than those for other subject groups.

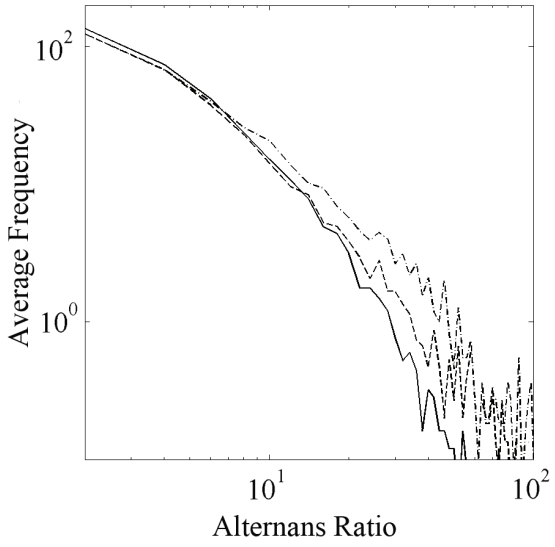

Fig. 4 Average histogram of ARs for three subject groups (The longer tail distribution the higher the SCA risk)

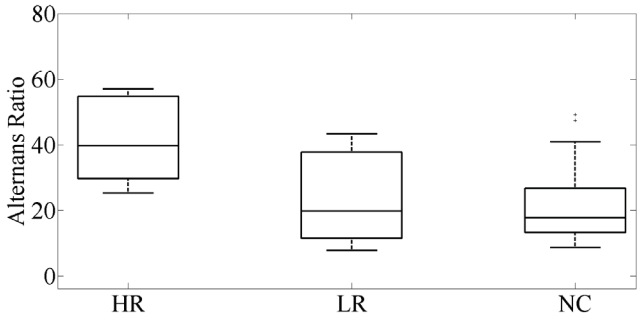

Fig. 5 Comparison of the TWA risk factor $rf(1)$ (Median for HR is significantly larger than others)

IV CONCLUDING REMARKS

An efficient TWA search method over 24 hour long term Holter ECG recordings based on singular value decomposition (SVD) has been presented. SVD extracts underlying orthogonal signals. Utilizing extracted signals with high singular values provides robust TWA detection in noisy condition which is common in Holter ECG recordings. It has been demonstrated that the proposed method successfully detect apparent TWA. In addition, proposed TWA risk factor $rf(\alpha)$ could be the prognostic index of TWA occurrence even distinct even odd beat pattern separation in T-wave loops or original T-wave sequences is not noticeable. The use of this measure will be more useful than trying exact detection of infinitesimal alternans occurences. Validation on larger data set is necessary for optimal α setting in the risk factor $rf(\alpha)$ and optimal setting of threshold θ for the TWA detection. For precise characterization of the method, difference in morphology change in each T-wave signal phase should be examined. Performances with simpler measures derived from underlying orthogonal signals such as T-loop norm, circumference or longitudinal angle have to be tested for more efficient search.

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