A Method of Efficient Cardiac Risk Assessment based on the T-wave Morphology Changes in Holter ECG Recordings

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Abstract. This paper proposes a method of efficient assessment of the cardiac risk based on the long term Holter ECG recordings. In order to process a vast amount of clinical data a simplified yet effective method to characterize T-wave morphology changes has been proposed. The method prevents from using procedure with high computational power such as orthogonal signal decomposition or repetitive use of Discrete Fourier Transform. To eliminate artifact, the beat to beat adaptive artifact detection and rectification methods have been introduced. T-wave alternans, T-wave variability and related indices are suggested to be utilized for the integrated cardiac risk assessment. Illustrative examples have been shown to demonstrate the effectiveness of the method.

Keywords: Holter ECG, sudden cardiac arrest, risk assessment, T-wave alternans, biosignal processing

1. Introduction

The risk assessment of the sudden cardiac arrest (SCA) has been one of the most important issues in the field of health care since SCA is one of the major causes of death worldwide. In the U.S. for example, over 300,000 SCA incidents are reported [1]. Several indices based on ECG recordings for the risk assessment are well known[2]. Recently, indices derived from 24-hour long term Holter ECG recordings attract considerable attention of research community [3]-[5]. Authors have been proposing new indices named T-wave alternans ratio percentile (ARP) and QT-RR co-variability extracted from Holter ECG record[6]. This paper focuses on the use of T-wave morphology changes for the risk assessment and introduces an efficient method to cope with the need to process vast amount of clinical data. An adaptive correlation method is introduced for both artifact rectification and T-wave characterization without using methods with extensive computational power. The paper also briefly discusses the future research direction under the vision of “Computational Electrocardiology (CECG),” where the ECG data were acquired, stored and processed continuously based on wearable sensors and the cloud information processing systems[7].

2. Methods

We briefly review the SCA risk index named alternans ratio percentile (ARP), which we proposed[6], as a mean to detect the presence of alternans in 24 hour Holter ECG recordings. Then a new alternative method for the efficient clinical data analysis will be introduced.

2.1. Alternans Ratio Percentile

T-wave alternans ratio (TWA) has been recognized as an effective measure of SCA risk assessment. The index has been typically measured in the clinical test environment with elevated heart rate[2]. It is desirable if the TWA is evaluated from the Holter ECG recordings in the natural living environment. Although some software has been provided for the Holter ECG evaluation, the large amount of noise contamination makes it difficult to obtain reliable consistent measures.

Instead of performing manual inspection of derived indices, we propose to utilize alternans ratio percentile (ARP) as a measure of SCD risk assessment. The method has been described in [6] in detail. Here is a brief summary of the proposed index. T-wave alternans ratio (AR) has been obtained for all
one-minute successive segments of ECG data for 24 hours. T waves have been extracted beat to beat and the singular value decomposition has been applied to extract orthogonal signals behind the T-wave signals. Then, adjacent and one after adjacent vector distances of two orthogonal signals are measured and the distance sequence thus obtained has been analyzed. The T-wave aveform alteration has been detected by the alternans ratio (AR) which is the ratio of the DFT power of the sequence at the Nyquist frequency and the average DFT amplitudes at adjacent frequencies. DFT has been applied to all one-minute segmented data. In such a way we obtain 1,440 AR values for 24 hours. For such large number of segments, there is a good random chance to yield the segment with high AR value. For example, random chance of alternate changes for successive 10 beats is 0.001 which may yield a high AR value. These incidents may happen a few times in average for the normal subjects without any SCD risk. To avoid such random chance cases, θ percentile values of Total ARs in a day is suggested to use for the SCD risk index. We named it the alternans ratio percentile (ARP). The value of θ has to be determined empirically.

Figure 1. An example of extracted T-waves for a one-minute segment

2.2. Simplified ARP estimation

In order to estimate the ARP of vast amount of clinical data, the method described in the previous section is too time consuming especially orthogonal signal decomposition takes a lot of time. DFT/FFT calculations for all one-minute data segments are also time consuming. In this section, a simplified method of ARP estimation has been described.

T-wave amplitude estimation

The IIR Bandpass filtering is applied to the original ECG data to reduce the effect of baseline drift. Empirically, we have been adopted 12th order Butterworth band pass filter (0.5-60Hz). The filter removes the drift fairly well, but apparent drift still remains after the filtering. Further increase in the cut off frequency of high pass part of the filter deteriorate the T-wave morphology. To concur this problem, we introduced the following adaptive method of amplitude estimation with baseband correction. T-wave peak time plus minus 150 mS has been extracted for each of successive one-minute ECG segments. Fig. 1 shows a typical example of extracted T-wave’s for an one-minute segment. Two types of alternans at the first part of the segment and apparent artifact are visually seen at the end. To perform the reasonable estimate of T-wave amplitude, the average waveform using all T-waves in the segment has been obtained (Fig. 2).

Figure 2. Averaged T-wave
Now to remove the artifact, correlation coefficients between the averaged T-wave and bias corrected T-wave are estimated. Fig. 3 shows the result for the data shown in Fig. 1. The T-wave with the correlation coefficients less than 80% is assumed to be artifact and if the ratio of artifact is less than 80%, average T-wave is replaced by the artifact. Otherwise the whole segment is excluded from the further analysis. When the artifact is replaced by the average T-wave, the process is repeated until all correlation coefficient values exceed 0.8. The least square curve fit of average T-wave and each T-waves in the segment is utilized to estimate both the drift bias and T-wave amplitude.

**Figure 3.** Correlation coefficients between average and individual T-waves

**ARP estimation**
Discrete Fourier Transform (DFT) power has been calculated from the T-wave amplitude series thus obtained. Then the alternans ratio, that is the ratio of the power at the Nyquist frequency and the average power at surrounding frequencies, have been estimated for all segments. ARP is finally estimated as the $\theta$ percentile values of all ARs. This ARP estimation needs a lot of computational power since it requires the DFT of all segments, i.e. DFT calculation of 1,440 times. For simplified measure, the relative amplitude difference between even and odd beats will be utilized. The amplitude sequence can also be used to estimating T-wave amplitude variability (TAV).

3. Results
The ARP is applied to 26 outpatients with SCD risk and 25 control subjects. The outpatients are further divided into two groups, that is high risk patient group with life threatening incidents or severe arrhythmia and low risk patient group with high blood pressure without arrhythmia or supraventricular tachycardia. The results showed 5 percentile of AR values is most effective to differentiate the high risk group and the rest. $p$-values are less than $0.07 \times 10^{-7}$ to differentiate high risk from low risk patients. Fig 4 shows the typical examples of ordered ARs for a patient with high SCA risk with the history of severe heart attack (Solid line) and for a control normal subject (dotted line). The differences are apparent and this figure suggests that the ARP can be a stable measure of the presence of T-wave alternans.

**Figure 4.** Ordered Alternans Ratio for 24 hours
The simplified method presented here performs equally well to estimate the alternans ratio. Fig. 5 shows the relative amplitude series obtained by the method described in the previous section for the sample data shown in Fig. 1 where the apparent amplitude alternation is observed. This alteration is also visually seen mainly in the first part of Fig. 1.

![Figure 5](image)

*Figure 5. An example of amplitude series with apparent T-wave alternans*

DFT power of the amplitude series is calculated and shown in Fig. 6 where excess power at Nyquist frequency is observed.

![Figure 6](image)

*Figure 6. DFT power of the amplitude sequence with T-wave alternans*

As a simplified measure of detecting the presence of T-wave alternans, the $p$-value of statistical test to see the median or mean difference between odd and even T-wave amplitude can be used. Fig. 7 shows the box plot of T-wave amplitude for even and odd beats. The difference in median is significant with $p$ value equals to 0.004. Inverted logarithm $p$ could be a suitable measure of the presence of T-wave alternans.

![Figure 7](image)

*Figure 7. T-wave amplitude difference between even and odd*
4. Discussion and Conclusion

An efficient method of SCD risk assessment for processing vast amount of 24 hour Holter clinical data has been proposed. Instead of methods utilizing heavy computational power such as orthogonal signal decomposition or repetitive use of DFT/FFT, the proposed method utilizes fairly simple signal processing methods yet aiming at preserving the accuracy of SCD risk assessment. The comparison of the method with high computational load is shown in Fig 8. Although some commercially available software implements methods to derive the indices for SCD risk assessment, they remain as an experimental stage. Clinicians need to make considerable amount of eye inspections to eliminate artifacts to get a meaningful result[8]. The automatic artifact detection and processing method proposed in this paper will be utilized for reducing the load of clinicians’ eye inspection. This paper focuses on the evaluation of T-wave alternans. However, the method could be applied to derive other indices such as T-wave amplitude variability (TAV). Recently, the heart rate variabilities, short term or long term including the diurnal changes are studied for SCA risk assessment[3]-[6]. Integration of all these measures both derived from ECG waveforms and beat occurrence timing data should be pursued to establish reliable and efficient means to assess the SCA risk assessment. In the latest issue of the journal of methods of information in medicine For-Discussion-Section[7], the future vision of ECG study has been discussed under the symbolic notion of Computational Electrocardiography (CECG). In this vision the continuous multichannel ECG data are acquired by wearable sensors and stored/processed online to make the timely feedback for the health care practice. The SCD risk assessment will be one of the most important development goals for CECG practice. Integration of the risk assessment indices derived from Holter 24 hour or even longer continuous ECG recordings for the timely health care advice is the ultimate goal of the study. To develop such systems, the introduction of a standardized ECG data format will be useful to establish the common foundation of the system development. The integrated file format of ISHINE[9] or MFER[10] and beat annotation format adopted by Rochester University Telemetric and Holter ECG warehouse named THEW file format[11] will be one of promising candidates for such standardization.

References

Figure 8. Schematic Diagram to Extract T-wave Related SCA Risk Indices