Use of Dominant T-Wave to Reduce T-Wave Offset Location Uncertainty

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Abstract

Abnormalities in the electrocardiographic (ECG) T wave are associated to sudden cardiac death. Despite the QT-interval prolongation being the standard marker of cardiac risk, its reliability is limited by the T-wave offset (Toff) uncertainty provided by different automatic methods. Thus, the aim of the present study was to evaluate if the dominant T wave (DTW) can be used to reduce Toff uncertainty. Our clinical data consisted of a sinus 15-lead ECG beat randomly extracted from ECG recordings of 36 control healthy subjects (CHS) and 62 acute myocardial infarction patients (AMIP). Toff, localized measuring its distance from the preceding R peak, was independently identified in the DTW and in each single-lead T wave by means of the Zhang et al.'s method (M1) and the Daskalov et al.'s method (M2). In both populations the distributions of the temporal distances between Toff values provided by the two techniques for the DTW showed a significantly lower median value than those measured over the 15 leads (CHS: 5 ms vs. 5-18 ms, respectively; AMIP: 10 ms vs. 10-20 ms, respectively), or a comparable median value but a significantly lower variability (CHS: 5 ms vs. 3-10 ms, respectively; AMIP: 5 ms vs. 5-13 ms, respectively). Thus, the use of the DTW allowed a significant reduction of Toff uncertainty.

1. Introduction

Despite recent advances in the treatment of life-threatening ventricular arrhythmias, sudden cardiac death (SCD) remains one of the leading causes of death in developed countries [1]. Among all the possible causes of SCD there are the abnormalities in the cardiac repolarization of the heart, and thus in the electrocardiographic T wave, which are known to be associated to susceptibility to malignant ventricular arrhythmias [2-12]. At the present time, the most popular repolarization marker of cardiac risk remains the QT interval [4-6], which is measured as the time distance between the onset of the Q wave and the offset of the T wave. Despite the QT interval prolongation being the standard indicator of cardiac safety in clinical trials, its measure suffers of limited reliability, mostly as a consequence of significant variability (few tens of ms) that may affect Toff identification (and thus QT interval measure) when different automatic methods are applied (Toff inter-method variability) [13].

The aim of the present study was to evaluate if the Toff reliability may be enhanced by using the dominant T wave (DTW), a conceptual model of the cardiac repolarization introduced by van Oosterom [14-16], easily estimated using clinical multi-lead ECG. The DTW utility in enhancing Toff identification was tested by applying two different automatic methods, namely the Zhang et al.'s method [17] and the Daskalov and Christov's method [18], to ECG tracings of 36 control healthy subjects and 62 acute myocardial infarction patients. Toff localizations provided by the two techniques were eventually compared.

2. Clinical data and methods

2.1. Study populations and clinical data

Our study populations consisted of 36 control healthy subjects (CHS), who usually show regular repolarization waveforms, and 62 acute myocardial infarction patients (AMIP), who instead are typically characterized by abnormal ST segments and T waves. Each subjects underwent a 15-lead (I to III; aVl, aVr, aVf, V1 to V6, X to Z) ECG recording (www.physionet.org; sampling frequency: 1000 Hz and subsequently resampled at 200 Hz) from which a sinus beat was randomly extracted.

2.2. The dominant T wave

Using an equivalent surface source model, van Oosterom [14-16] showed that the ST-T segment shapes of all ECG leads on the thorax can be seen as a scaled version of a single waveform termed as dominant T wave (DTW), which can be defined as the time derivative of the transmembrane potential (D') during repolarization:

$$DTW(t) = -D'\left(t - \bar{d}\right) \quad (1)$$

In Eq. 1 the negative sign is inserted to force the DTW apex to have a positive polarity, t represents time and $\bar{d}$ represents the mean value of the repolarization times, respectively.

The definition of DTW provided in Eq. 1 allows its practical estimation from the real ECG recordings, since the DTW is supposed to dictate the shape of all the observed T waves. Let $T_l(t)$ be the repolarization waveform relative to lead l (l=1,2…L) expressed as function of time. It can be demonstrated [16] that the DTW can be obtained as a weighted average of $T_l(t)$ over the leads:

$$DTW(t) = \frac{1}{L}\sum_{l=1}^{L} w_l \cdot T_l(t) \quad (2)$$

where the weight of each lead (w_l) is obtained by integrating $T_l(t)$ over repolarization.

2.3. Automatic methods for T-wave offset identification

The Zhang et al.'s method (M1) [17] and the Daskalov and Christov's method (M2) [18] for automatic Toff identification were considered here. They both provide Toff localizations by measuring the time distances between Toff and the previous R peak (ms).

2.3.1. The Zhang et al method

Briefly, M1 [17] consists of the computation of an indicator A(t) through an integration operation in a 128 ms sliding window W. More specifically, the sliding window is iteratively moved from the beginning to the end of the repolarization segment of a beat, and the indicator A(t) is computed as follows:

$$A(t) = \int_{t-W}^{t} \left[s(\tau) - s(t)\right] d\tau \quad (3)$$

where t is time and s(t) is the ECG signal. Thus, A(t) represents the area in the interval [t-W, t] under the signal s(τ) and above the horizontal line crossing the point s(t). After defining two time instants as:

$$t' = \arg\max A(t) \quad (4)$$

$$t'' = \arg\min A(t) \quad (5)$$

Toff is defined as:

$$Toff_{M1} = \arg \max_{t \in \{t', t''\}} |A(t)|. \quad (6)$$

2.3.2. The Daskalov and Christov method

This technique [18], after having identified the isoelectric point S_{is}, defines two adjacent functions (W_1 and W_2), called "wings", which slide through repolarization:

$$W_1(t;\Delta T) = s(t) - s(t - \Delta T) \quad (7)$$

$$W_2(t;\Delta T) = s(t + \Delta T) - s(t). \quad (8)$$

In Eq. 7 and Eq. 8 t is time, ΔT is a time constant (ms) and s(t) is the ECG signal. The W1 and W2 functions are used to identify specific points within repolarization. At first, the T-wave peak, Tp, is identified by the minimum of the function obtained as W1(t, 40)×W2(t, 40). The point to the right of Tp in correspondence of which W1(t, 10)×W2(t, 10) becomes smaller than 3 μV represents an isoelectric point, Tis, which together with Tp , is used to define the T-wave amplitude (Tampl):

$$T_{ampl} = \left|s(T_p) - s(T_{is})\right|. \quad (9)$$

Eventually, $Toff_{M2}$ is searched in a repolarization window starting from the instant at which s(t) is equal to $0.2 \cdot T_{ampl}$ (i.e. a little earlier than T_{is}), and is identified as the instant that minimizes the angle between the segments (vectors) identified by $W_1(t, 10)$ and $W_2(t, 10)$.

2.4. Toff inter-method variability analysis

Ideally, Toff localization by M1 and M2 should be identical for any ECG beat. In real cases, however, this rarely happens because of the presence of noise, and some inter-method variability (IMV) may occur. As a consequence, a certain time-distance ($D_{M1\text{-}M2}$, ms) may separate the Toff localizations provided by the two methods:

$$D_{M1-M2} = \left|Toff_{M1} - Toff_{M2}\right| \quad (10)$$

Analysis of the Toff IMV is performed by evaluating $D_{M1\text{-}M2}$ and $D_{M1\text{-}M2}$ variability ($VarD_{M1\text{-}M2}$, ms) over a population. More specifically, after having computed the $D_{M1\text{-}M2}$ median value ($MdnD_{M1\text{-}M2}$) over a population, $VarD_{M1\text{-}M2}$ is computed as the distance of $D_{M1\text{-}M2}$ from $MdnD_{M1\text{-}M2}$:

$$VarD_{M1-M2} = \left| D_{M1-M2} - MdnD_{M1-M2} \right|. \quad (11)$$

For each subject the $D_{M1\text{-}M2}$ and $VarD_{M1\text{-}M2}$ parameters were independently computed in each single lead and in the DTW. Usefulness of the DTW in reducing the Toff IMV was evaluated by comparing $D_{M1\text{-}M2}$ and$VarD_{M1\text{-}M2}$ parameters relative to the DTW against those relative to each single lead.

2.5. Statistics

Normality of parameters distribution was performed using the Lilliefors test. Parameters characterized by not-normal distributions were described by providing the 25th, 50th and 75th percentiles, and compared using the Wilcoxon rank-sum test for equal medians. Statistical significance level was set at 0.05.

3. Results

Values of $D_{M1\text{-}M2}$ and $VarD_{M1\text{-}M2}$ parameters measured in the two populations are reported in Table 1 and Table 2, respectively. Both parameters were either comparable or significantly higher in the AMIP than in the CHS. Moreover, within each population, distributions of $D_{M1\text{-}M2}$ computed in the DTW were found to be characterized or by a significantly lower median value than those measured over the 15 leads (CHS: 5 ms in DTW and 5-18 ms in 15 leads; AMIP: 10 ms in DTW and 10-20 ms in 15 leads; Table 1), or by a comparable median value but associated to a significantly lower variability around the median in both populations (median variability values: CHS: 5 ms in DTW and 3-10 ms in 15 leads; AMIP: 5 ms in DTW and 5-13 ms in 15 leads; Table 2).

4. Discussion

This study investigated if the DTW, a common scaled version of each T wave observed in any ECG lead [14-16], can be used to reduce Toff localization uncertainty. Indeed, the existence of Toff IMV [13,19] implies that different automatic techniques may provide significantly different Toff localizations in the same T wave, as did M1 and M2 when analyzing ECG recordings from our CHS and AMIP. The different Toff localizations provided by M1 and M2 are due to a different robustness of the two techniques to the presence of noise. Since the averaging procedure involved in the computation of the DTW has the effect of reducing the level of noise affecting the T waves [20], we hypothesized the use of the DTW to improve Toff determination. The accuracy in the determination of the DTW is supposed to increase with the number of used leads. In the original experimental setting used for the DTW delineation 64 ECG leads were used [15]. Such a high number of leads, however, is not realistic in clinical practice. Thus, clinical usefulness of the DTW was evaluated when this is estimated using the maximum number of leads easily available in routine clinical ECG testing, that is 15 (I to III; aVr, aVl, aVf, V1

Table 1. $D_{M1\text{-}M2}$ measures (50th [25th, 75th] percentiles) in the CHS and AMIP.

	CHS	AMIP	
Leads	**$D_{M1\text{-}M2}$ (ms)**	**$D_{M1\text{-}M2}$ (ms)**	**P**
I	5 [5,13]	15 [5,30]	<0.01
II	10 [5,10]	15[5,45]	<0.01
III	15 [5,25]	15[5,35]	NS
aVr	15 [5,20]	20[10,25]	<0.05
aVl	13 [5,48]	15[10,25]	NS
aVf	5 [5,10]	18[5,40]	$<10^{-3}$
V1	10 [5,10]	15[5,35]	NS
V2	15 [5,25]	15[5,25]	NS
V3	15 [10,25]	13[5,25]	NS
V4	15 [8,20]	10[5,25]	NS
V5	10 [5,15]	13[5,30]	NS
V6	5 [5,10]	15[5,25]	$<10^{-3}$
X	8 [5,13]	15[5,30]	<0.01
Y	5 [0,10]	10[5,35]	<0.01
Z	18 [10,20]	20[10,25]	NS
DTW	5 [0,5]	10[5,15]	$<10^{-7}$

NS: Not statistically significant

Table 2. $VarD_{M1\text{-}M2}$ measures (50th [25th, 75th] percentiles) in the CHS and AMIP.

	CHS	AMIP	
Leads	**$D_{M1\text{-}M2}$ (ms)**	**$D_{M1\text{-}M2}$ (ms)**	**P**
I	5 [0,8]	10 [5,15]	$<10^{-3}$
II	5 [0,5]	10 [5,30]	$<10^{-4}$
III	10 [5,15]	10 [5,20]	NS
aVr	10 [5,10]	10 [5,20]	<0.05
aVl	8 [3,35]	5 [5,15]	NS
aVf	5 [0,5]	13 [8,23]	$<10^{-7}$
V1	10 [5,20]	10 [5,20]	NS
V2	10 [5,15]	10 [5,15]	NS
V3	5 [5,15]	8 [3,13]	NS
V4	5 [5,15]	5 [5,15]	NS
V5	5 [3,8]	8 [3,18]	<0.01
V6	5 [0,5]	10 [5,15]	$<10^{-3}$
X	3 [3,8]	10 [5,15]	$<10^{-4}$
Y	5 [3,5]	10 [5,25]	$<10^{-3}$
Z	8 [3,8]	10 [5,15]	<0.05
DTW	5 [0,5]	5 [5,10]	<0.01

NS: Not statistically significant

to V6, X to Z).

According to our results, as expected the single-lead Toff measures provided by the two methods are closer for regular repolarization morphologies, such those characterizing the T waves of healthy subjects, than for more complex and fragmented T waves, often characterizing diseased state, as the AMIP (Tables 1 and 2). More interesting, Toff localization from the DTW, significantly reduced IMV in terms of both D_{M1-M2} and $VarD_{M1-M2}$ thanks to the smoothing filtering effect involved in the DTW computation [20].

5. Conclusion

Toff reliability is enhanced by using the DTW estimated as a weighted average of 15 single-lead T waves. Indeed, the DTW allows a significant reduction of the Toff inter-lead variability in both healthy and pathological conditions and, consequently, appears as a useful tool for practical clinical applications.

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