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Use of the dominant T wave to enhance reliability of T-wave offset identification☆,☆☆,★

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Abstract T-wave offset (Toff) identification may be jeopardized by the presence of a significant inter-method (IMV) and inter-lead (ILV) Toff variability. Thus, the aim of the present study was to investigate if the dominant T wave (DTW) may be used to enhance Toff-identification reliability. DTWs and 15-lead ECG T waves of 46 control healthy subjects (CHS) and 103 acute myocardial infarction patients (AMIP) were analyzed for Toff identification using Zhang et al.'s (M1) and Daskalov and Christov's (M2) methods. Results indicate that IMV is significantly reduced when identifying Toff from the DTW rather than from single ECG leads in both populations (CHS: 5 ms vs. 5–15 ms; AMIP: 10 ms vs. 10–20 ms). Moreover, when analyzing ILV, Toff was found to be equivalent (correlation = 0.71–0.98; $P < 10^{-14}$) to the median Toff among leads, but required only one identification instead of 15. Thus, the DTW can be used to enhance Toff-identification reliability.

Keywords: T-wave offset; Dominant T wave; Inter-method variability; Inter-lead variability

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. At the present time, patients are selected for clinical evaluation and treatment of ventricular arrhythmias only after they have experienced and survived a major cardiac event. Thus, from a public health viewpoint, identification and treatment of such high-risk subjects before the occurrence of a cardiac event are expected to have a great impact on the problem of SCD.

Among all the possible causes of SCD there are the abnormalities in the cardiac repolarization of the heart which are known to be associated to susceptibility to malignant ventricular arrhythmias [1–6]. A simple and economic way to diagnose most cardiac abnormalities is to perform an electrocardiogram (ECG) to evaluate indexes of risk based on the ST segment and T wave, which correspond to the repolarization phase of the ventricles. At the present time, the most popular repolarization marker of risk remains the QT interval [2,3], which is measured as the time distance between the onset of the Q wave and the offset of the T wave, thus representing the total duration of the contraction and subsequent relaxation of the ventricles. Despite the QT interval prolongation being the standard indicator of cardiac safety in clinical trials, its measure suffers of limited reliability because of the difficulty in the delineation of the T-wave offset timing (Toff) in clinical settings. Indeed noise, artifacts and repolarization morphology and duration changes affecting clinical ECG recordings make Toff hardly identifiable so that a significant variability (few tens of ms) may affect Toff identification (and thus QT interval measure) when different automatic methods are applied (Toff inter-method variability) [7,8] and/or when measures are obtained

Abbreviations: AMIP, acute myocardial infarction patients; CHS, control healthy subjects; DTW, dominant T wave; ECG, electrocardiogram; ILV, inter-lead variability; IMV, inter-method variability; M1, Zhang et al.'s method; M2, Daskalov and Christov's method; SCD, sudden cardiac death; Toff, T-wave offset.

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★ Ethical Approval: Physionet organization warrantees that all PhysioBank data have been fully deidentified (anonymized), and may be used without further institutional review board approval.

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from different leads (Toff inter-lead variability or Toff dispersion) [1,9–13].

There is currently a lack of standardization of methods for measuring the QT interval. Based on custom, the most commonly used lead for QT measurements is lead II [8,9]. Nevertheless, a reliable QT measurement should not rely on a single ECG lead but rather on global repolarization waveforms obtained from all available leads, since these show the advantage of a reduced level of noise and allow a better separation of the T wave from any physiologic low-amplitude U wave [9,12,14]. The aim of the present study was to evaluate if the dominant T wave (DTW), a global repolarization waveform introduced by van Oosterom and obtained as a weighted average of the T waves over the leads [15–17], can be clinically used to enhance reliability of the QT measurements by enhancing accuracy in the Toff identification. The DTW utility in enhancing Toff identification was tested by applying two different automatic methods (Zhang et al.'s method [18] and Daskalov and Christov's method [19]) to ECG tracings of 46 control healthy subjects and 103 acute myocardial infarction patients.

Clinical data and methods

Study populations and clinical data

Our study populations consisted of 46 control healthy subjects (CHS), who usually show regular repolarization waveforms, and 103 acute myocardial infarction patients (AMIP), who instead are typically characterized by abnormal ST segments and T waves. The basic clinical parameters of our study populations are reported in Table 1. Each subjects underwent a 15-lead (I to III; aVr, aVl, aVf, V1 to V6, X to Z) ECG recording (www.physionet.org; originally sampled at 1000 Hz and subsequently resampled at 200 Hz) from which a sinus beat was randomly extracted. Toff was first independently identified in each single lead of the extracted beat, and subsequently in the DTW constructed using the 15 available leads (see below).

The dominant T wave

Using an equivalent surface source model, van Oosterom [15–17] 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. In clinical applications the DTW can be estimated from multiple-lead ECG recordings, since it 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 [17] that the DTW can be obtained as a weighted average of $T_l(t)$ over the leads:

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

where the weight of each lead (w_l) is obtained by integrating $T_l(t)$ over repolarization. An example of a DTW of a healthy subject is displayed in Fig. 1.

Table 1
Clinical parameters relative to the control healthy subjects (CHS) and the acute myocardial infarction patients (AMIP).

	CHS (N = 46)	AMIP (N = 103)
Age (year)	46 ± 14	58 ± 11*
Gender (male)	38 (83%)	84 (82%)
Hypertension	0 (0%)	29 (28%)§
Obesity	0 (0%)	8 (8%)
Diabetes	0 (0%)	12 (12%)§
Other pathologies	0 (0%)	55 (53%)*
Heart rate (bpm)	69 ± 11	81 ± 15*

§ $P < 10^{-3}$ when comparing against the CH subjects.
* $P < 10^{-5}$ when comparing against the CH subjects.

Automatic methods for T-wave offset identification

Zhang et al.'s method (M1) [18] and Daskalov and Christov's method (M2) [19] for automatic Toff identification were considered here. They both provide Toff localizations ($Toff_{M1}$ and $Toff_{M2}$, respectively) by measuring the time distances between Toff and the previous R peak (ms). The Matlab implementation of the M1 algorithm was directly provided by the authors (downloadable at http://www.irisa.fr/sosso/zhang/biomedical/), whereas the M2 algorithm was implemented in Matlab by ourselves. Some details of the two automatic T-wave offset identification methods can be found in the Appendix.

Analysis of the Toff inter-method variability (IMV)

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 repolarization variability and noise. As a consequence, a certain time–distance (D_{M1-M2}, ms) may separate the Toff localizations provided by the two methods:

$$D_{M1-M2} = |Toff_{M1} - Toff_{M2}|. \quad (2)$$

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

$$VarD_{M1-M2} = |D_{M1-M2} - MdnD_{M1-M2}|. \quad (3)$$

For each subject the D_{M1-M2} and $VarD_{M1-M2}$ 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-M2} and $VarD_{M1-M2}$ parameters relative to the DTW against those relative to each single lead.

Analysis of the Toff inter-lead variability (ILV)

The Toff ILV, also called Toff dispersion, consists of different Toff identifications provided by a method through the leads. The Toff distribution over the leads was described here by means of its median (MdnToff) value and by its range of variability (RangeToff), defined as the maximum