QRS Complex Boundaries Location for Multilead Electrocardiogram

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Abstract. In this paper a multilead methodology regarding QRS complex boundaries location is proposed and validated. It was established from a single-lead based system previously developed and attends to the spatial characteristics of the different leads, aiming to achieve a more robust delineation. It provides more robust and accurate boundaries locations than any electrocardiographic lead by itself.

Keywords: ECG wave delineation, multilead, wavelets

1 Introduction

The electrocardiogram (ECG) is the record of the cardiac electrical activity as a function of time, by means of electrodes placed on the skin. It is a noninvasive and painless procedure and an indispensable diagnostic tool for many cardiac and non cardiac conditions. By using several electrodes it is possible to access simultaneous recording directions, known as *electrocardiographic leads*, providing a spacial perspective. Each heart beat is produced by an electric wavefront that crosses the different cardiac structures; the activation/inactivation of those correspond to different waves in the ECG, known as P wave, Q, R and S waves (QRS complex) and T wave. In particular, the waves in the QRS complex reflect the activation of both ventricles. In spite of the general characteristics (as smoothness and relative polarity), the waves' morphology depends on several factors, especially on the recorded lead. ECG delineation consists on detecting peaks and boundaries (onset and end) of those waves and provides fundamental features to derive clinically useful information, namely about the duration of the phenomena and their beat-to-beat evolution. As there are not standard clear rules to locate the waves' boundaries, systematizing the delineation is a difficult task. Clinical ECG often present relevant levels of noise that mask the signal information.

This group has previously proposed an automatic single-lead (SL) delineation system (Martínez, J. P. et al (2004)), that generalizes the wavelet transform (WT) based methodology of Li, C. et al (1995). The WT provides a description of the signal in the time-scale domain, allowing the representation of its temporal features at different resolutions according to their frequency content. Thus, regarding the purpose of locating different waves with typical frequency characteristics, the WT is a suitable tool for ECG delineation.

Each lead is characterized by a lead vector giving the direction from one electrode to the other. According to the dipole hypothesis, the electrical activity of the heart can be approximated by a time-variant electrical dipole, called the *electrical heart vector* (EHV). Thus, the voltage measured at a given lead is merely the projection of the EHV into the unitary vector defined by the lead axis (Malmivuo, J. and Plonsey, R. (1995)). Nevertheless, the lead set most widely used in clinical practice is not an orthogonal system, but rather the somewhat redundant standard 12-lead system, considered to contain 8 truly independent leads describing dipolar and non dipolar components. A set of linear transformations between the 12-lead and the most used orthogonal system, the Frank leads (X, Y, Z) is given by the **Dower matrix** (Dower, G. E. (1984)). This quite old linear transformation has been object of many criticisms but no wide accepted alternative has been proposed yet.

Using a particular lead for ECG delineation determines a point of view over the cardiac phenomena, thus different latencies on the waves's onsets and ends are found in different leads. Combining adequately the information provided by multiple leads is essential for the correct location of lead-independent waves' boundaries. The SL system in Martínez, J. P. et al (2004) includes post-processing decision rules to deal with multilead records, by choosing global marks based on the single-lead derived locations. Nevertheless, in spite of the satisfactory performance, this system is not truly multilead and it requires to apply SL delineation to each one of the leads.

In this paper is proposed and validated an actually multilead (ML) methodology regarding QRS complex boundaries location. The ML approach was established from the SL system and attends to the spatial characteristics of the different available leads, aiming to achieve a more robust delineation.

2 Methods

2.1 Single-lead based delineation

The SL based delineation system is described in detail in Martínez, J. P. et al (2004) and only general features are here referred. The detection of the fiducial points is carried out across the adequate WT scales, attending to the dominant frequency components of each ECG wave. The prototype wavelet used allows to obtain a WT at scale 2^m, $w_{x,m}[n]$, proportional to the derivative of the version of the digitalized signal $x[n]$ filtered with a smoothing impulse response at scale 2^m. Thus, ECG wave peaks correspond to zero crossings in the WT and ECG maximum slopes correspond to WT's maxima and minima. The onset [end] of a wave (n_o [n_e]), occurs before [after] the first [last] maximum of $|w_{x,m}[n]|$, at sample n_f $[n_l]$. Boundaries are located by selecting the sample nearest to n_f $[n_l]$ satisfying a threshold based criteria.

To deal with multiple leads a robust post-processing decision rule over SL derived locations (SLR) is used: the SL annotations are ordered and the onset [end] of a wave is selected as the first [last] annotation whose 3 nearest neighbours lay within a δ ms interval with $\delta = 10$ ms for QRS end and $\delta = 12$ ms for QRS onset.

2.2 Multilead System

The ML delineation system proposed considers three simultaneous orthogonal leads (X,Y,Z), taking advantage of the spacial information by them represented. For a scale $2^m \big|_{m\in\{1,2,3,\ldots\}}$, a spatial WT *loop* can be defined as

$$\mathbf{w}_m[n] = [w_{x,m}[n], w_{y,m}[n], w_{z,m}[n]]^T. \tag{1}$$

The WT prototype used produces a WT loop $\mathbf{w}_m[n]$ proportional to the ECG derivative and describes the EHV evolution. Therefore, the director vector of the best straight line fit to all points in $\mathbf{w}_m[n],\ n \in W$ gives the main direction $\mathbf{u} = [u_X, u_Y, u_Z]^T$ of EHV variations in a scale 2^m for a time interval of interest W.

Considering the ECG loop $[x[n], y[n], z[n]]^T$, a *generated* lead $d[n]$ defined by axis $\mathbf{u}$ and combining the information provided by the 3 leads, can be obtained by projecting over $\mathbf{u}$ the points of the ECG loop defined on an extended interval containing one beat. Instead, the WT loop $\mathbf{w}_m[n]$ can be projected and the WT of the *derived* signal, $w_{d,m}[n]$, obtained .

The strategy proposed for ML boundary delineation using WT loops is based in a multi-step iterative search for an improved spatial lead for delineation (with *steepest* slopes). Multilead location of the QRS boundaries is performed as illustrated for QRS onset in Figure 1. Let's define $n^{(0)}_{\mathrm{QRS,o}}$ $\left[n^{(0)}_{\mathrm{QRS,e}}\right]$ as the earliest [latest] QRS onset [end] location given by the SL methods (over each orthogonal lead) and $n^{(0)}_{\mathrm{QRS,f}}$ $\left[n^{(0)}_{\mathrm{QRS,l}}\right]$ is the earliest [latest] significant maximum modulus location.

The multilead delineation strategy for QRS boundaries is described by the following algorithm, which for each beat and boundary, consists in an initialization and a variable number of iterations:

INITIALIZATION

a_0) an initial search window adequate to find the EHV's main direction in the boundary is defined respectively for QRS onset and end, as

$$Q_{[1]} = [n^{(0)}_{\mathrm{QRS,o}} - 4s_{\mathrm{CSE}}(\mathrm{QRS}_{on}),\ n^{(0)}_{\mathrm{QRS,f}}];\ \ S^{(1)} = [n^{(0)}_{\mathrm{QRS,l}}\ ,\ n^{(0)}_{\mathrm{QRS,e}} + 4s_{\mathrm{CSE}}(\mathrm{QRS}_{end})]$$

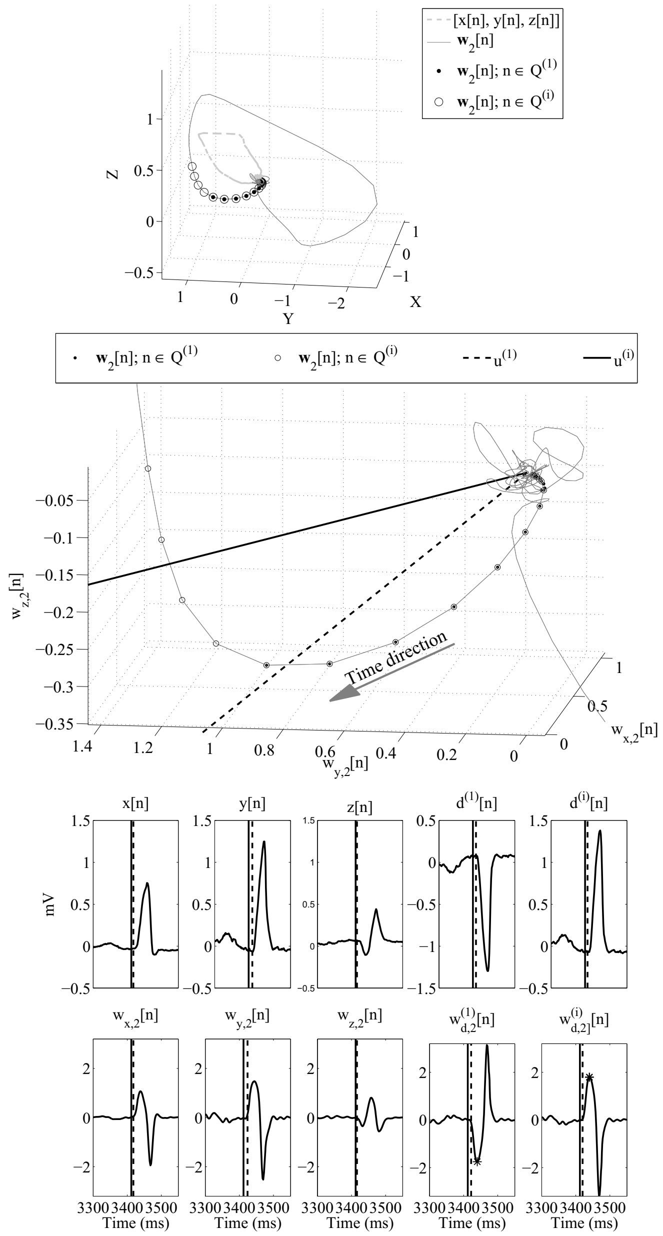

Fig. 1. Example of ML delineation (file from CSE database): initial and final steps. Upper panel: ECG and WT loops. Middle panel:WT loops and the directions of the best line fit. Lower panel: ECG in orthogonal leads, WT signals, derived ECG and WT signals, delineation mark found in the respective lead (vertical dashed lines), *median referee* marks (solid line) and first significant maximum modulus in the constructed lead (stars). ECG in mV and final step $i = 2$.

where $s_{\mathrm{CSE}}(\mathrm{QRS}_{on}) = \frac{6.5}{2} f_s$ samples $\left[s_{\mathrm{CSE}}(\mathrm{QRS}_{end}) = \frac{11.6}{2} f_s \text{ samples}\right]$ correspond to the standard deviation tolerance values provided by The CSE Working Party (1985), with f_s the sampling frequency;

b_0) the initial main direction of EHV variations $\mathbf{u}^{(1)}$ is estimated as the best line fit in total least squares (TLS) sense to $\mathbf{w}_m[n]\,|_{n \in Q^{(1)}}$ or $\mathbf{w}_m[n]\,|_{n \in S^{(1)}}$;

c_0) the loop $\mathbf{w}_m[n]\Big|_{n \in \left[n^{(0)}_{\mathrm{QRS},k-1}\, ,\, n^{(0)}_{\mathrm{QRS},k+1}\right]}$, for $n^{(0)}_{\mathrm{QRS},k}$ the median of SL derived locations for the QRS complex in the k^{th} beat, is projected over $\mathbf{u}^{(1)}$ to construct the new derived WT signal $w^{(1)}_{d,m}[n]$;

d_0) SL delineation is performed over $w^{(1)}_{d,m}[n]$ to locate $n^{(1)}_{\mathrm{QRS,o}}$ or $n^{(1)}_{\mathrm{QRS,e}}$.

ITERATION - STEP (i)

a) the search window is updated as

$$Q^{(i)} = [n^{(i-1)}_{\mathrm{QRS,o}} - 4 s_{\mathrm{CSE}}(\mathrm{QRS}_{on}),\ n^{(i-1)}_{\mathrm{QRS,f}}];\ \ S^{(i)} = [n^{(i-1)}_{\mathrm{QRS,l}}\ ,\ n^{(i-1)}_{\mathrm{QRS,e}} + 4 s_{\mathrm{CSE}}(\mathrm{QRS}_{end})]$$

where $n^{(i-1)}_{\mathrm{QRS,o}}$ $\left[n^{(i-1)}_{\mathrm{QRS,e}}\right]$ is the QRS onset [end] position found in the step $(i-1)$ and $n^{(i-1)}_{\mathrm{QRS,f}}$ $\left[n^{(i-1)}_{\mathrm{QRS,l}}\right]$ is the location of the first [last] significant maximum modulus of $w^{(i-1)}_{d,m}[n]$;

b) the main direction of EHV variations $\mathbf{u}^{(i)}$ is estimated as the TLS best line fit to $\mathbf{w}_m[n]\,|_{n \in Q^{(i)}}$ or $\mathbf{w}_m[n]\,|_{n \in S^{(i)}}$;

c) the new derived WT signal $w_{d,m,[g]}[n]$ is constructed by projecting $\mathbf{w}_m[n]\Big|_{n \in \left[n^{(0)}_{\mathrm{QRS},k-1}\, ,\, n^{(0)}_{\mathrm{QRS},k+1}\right]}$

d) IF $n^{(i)}_{\mathrm{QRS,f}}$ $\left[n^{(i)}_{\mathrm{QRS,l}}\right]$ has the same polarity than $n^{(i-1)}_{\mathrm{QRS,f}}$ $\left[n^{(i-1)}_{\mathrm{QRS,l}}\right]$, equal or lower amplitude and QRS complex morphology includes a Q [S] wave (the lead constructed at step (i) is not better for QRS onset [end] location than the constructed in the step $(i-1)$)

OR no significant maximum of $w^{(i)}_{d,m}[n]$ was found (the lead is not adequate for boundary location)

THEN $n^{(i-1)}_{\mathrm{QRS,o}}$ $\left[n^{(i-1)}_{\mathrm{QRS,e}}\right]$ is adopted as ML mark; STOP;

ELSE SL delineation of the boundary is performed over $w^{(i)}_{d,m}[n]$ to find $n^{(i)}_{\mathrm{QRS,o}}$ $\left[n^{(i)}_{\mathrm{QRS,e}}\right]$ updated marks;

e) IF the same location is achieved for 3 (possible nonconsecutive) iterations

THEN $n^{(i)}_{\mathrm{QRS,o}}$ $\left[n^{(i)}_{\mathrm{QRS,e}}\right]$ is adopted as ML mark; STOP;

ELSE REPEAT from a).

It must be remarked that the choice of *basing the lead direction* in the WT loop, instead of taking directly the ECG loop is relevant, as it allows to avoid the high frequency noise contamination and thus produces a more accurate selection.

3 Results and discussion

The evaluation of the automatic delineation strategies was performed over real files from the CSE multilead measurement database (CSEDB, Willems, J. L. et al (1987), 42 short signals in 15 leads at 500 Hz) which include referee marks for 32 QRS onsets and 26 QRS ends. The delineation error (ε) was taken as the *automatically detected boundary minus the respective referee mark* and the mean (m_ε) and standard deviation (s_ε) of ε were evaluated across files; the mean $\left(m_{|\varepsilon|}\right)$ and standard deviation $\left(s_{|\varepsilon|}\right)$ of the absolute error $|\varepsilon|$ were also calculated. Additionally, the above mentioned parameters were calculated after the exclusion of the 5% most *extreme cases* in each tail.

Different orthogonal lead systems were considered:
lead set F - defined by recorded orthogonal Frank leads (X,Y,Z);
lead set M - defined by leads *V5*, *aVF* and *V2*, a subset of 3 mutually orthogonal leads out of the standard 12-lead system;
lead set D - defined by the synthesised orthogonal leads from the standard 12-lead system, by using the coefficients provided by the *Dower Matrix*;
lead set PC1 - defined by the first 3 principal components calculated from the whole 12-lead signal;
lead set PC2 - defined by the first 3 principal components calculated from the 8 truly independent leads and based in the segment of interest QRS onset to T wave end according to SL delineation over lead II.

For the sake of comparison, SL was applied to each available lead and the post processing rules (SLR) described in Subsection 2.1 were applied over 12 or 15 leads. Results are presented in Figure 2 and 3.

It was found that a relative low number of extreme cases was causing a large fraction of the global error. The exclusion of the 10% more extreme measurements in each approach allowed a generalised improvement in the errors dispersion, with bias increase in some cases. In particular ML over lead sets F, PC1 and PC2 after the exclusion of the most extreme files performs closely as well as the best SL based delineation. Nevertheless still far from the error dispersion obtained using SLR over the 12 leads or all the 15 leads together. It should be remarked that the ML proposed method requires the WT calculation of 3 leads, with delineation procedures involving a variable number of signals. Thus, even considering fitting and projecting features, the ML strategy is likely to be more efficient than applying SL to 12 or 15 leads, as the number of iterations needed is not very high. Thus, the results presented denote a clear improvement in terms of computational complexity with comparable performance. The lead sets PC1 or PC2 are good alternatives to Dower matrix, since ML performs better over those than over D.

The bias found can be due to the referee annotation protocol itself. Referees were required to look for the earliest onset and latest end signs of the waves, in order to detect the whole electric activation/inactivation phenomena reflected in the QRS complex. This rule is risky, especially in automatic strategies, as it likely to be affected by outliers resulting from noise contami-

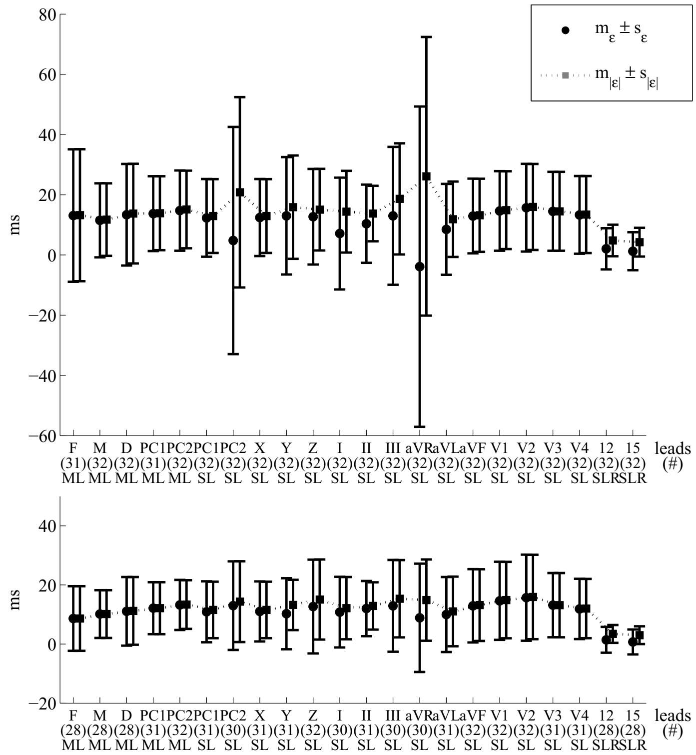

Fig. 2. Delineation results for QRS onset: upper panel corresponds to results in all true positive detections (# denotes the number of detections out of 32 reference marks provided), lower panel corresponds to results in after excluding 10% extreme cases in each approach (# denotes the number of beats considered).

nation. Furthermore, these early activation / late inactivation signs can reflect local properties not related to the whole myocardium. Thus, a more global rule, as the one proposed in this work, is better suited for global myocardium activation/inactivation in applications like evaluation drug cardiotoxicity or others where the effect of interest comes from the global myocardium.

In this work we focused on the problem of QRS boundaries location, that is, the delineation of the higher frequency component of the ECG. The boundaries of the waves P and T, which reflect lower components of the signal, can be also located by similar, although adapted, strategies.

4 Conclusions

A novel ML WT based automatic system for ECG boundaries delineation was here proposed and evaluated with respect to the QRS boundaries. The results pointed out that both SL and ML methodologies are adequate for ECG

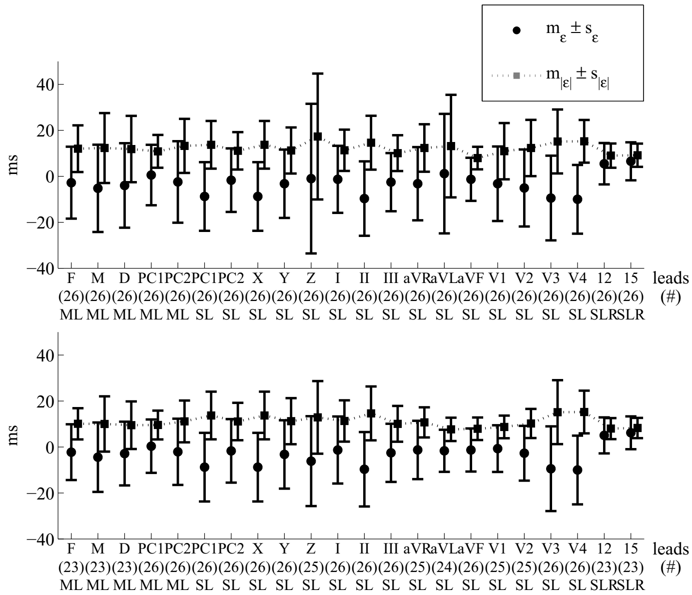

Fig. 3. Delineation results for QRS end: upper panel corresponds to results in all true positive detections (# denotes the number of detections out of 26 reference marks provided), lower panel corresponds to results in after excluding 10% extreme cases in each approach (# denotes the number of beats considered).

waves delineation. ML provided more robust and more accurate boundaries locations than any electrocardiographic lead by itself. ML over lead set PC1 or PC2 performs better than lead set D on QRS onset, being a good alternative to Dower matrix when Frank leads are not available.

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