Change in angular velocity at the end of the QRS loop aids the electrocardiographic detection of acute inferior myocardial infarction

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Abstract

We developed a new method for determining the QRS end, based on angular velocity (AV) changes around the QRS loop, and compared the method's performance to that of more established methods for determining QRS end in both healthy subjects and patients with acute myocardial infarction (AMI). Specifically, using Frank leads reconstructed from standard 12-lead ECGs, we determined AV in the direction of change raised to the 4th power, d(t). We found that the d(t)-determined AV transition (AVTr) nearly coincided with manually determined QRS end in healthy subjects, and in 27 patients with anterior AMI. However, in 31 patients with inferior AMI, AVTr typically preceded that of QRS end determined by the established methods, and by more than 10 ms in 32% of cases. While this "AVTr precedence" coincided with diagnostic ST elevation in only a minority of patients with recent inferior AMI, the use of AVTr precedence as a complement to more established methods for QRS end determination increased the sensitivity for detecting inferior AMIs from 23% to 42% without notably compromising specificity in healthy subjects (N=1050)

1. Introduction

Precise determination of the QRS complex and its borders is important not only for detection of large conduction delays such as in bundle branch blocks, but also for tracking slowly progressive conduction abnormalities [1]. As summarized by Martinez et al [2], different delineation approaches have been described, based mainly on the amplitude of single or multiple lead signals. It was shown that the spatial orientation of the ECG vector in normal men changes very rapidly during transition from the late QRS into the early ST segment, but considerably more slowly thereafter [3,4].

Hence, we speculated that an exploration of potentially rapid changes in the ECG vector angle backward from the early ST segment into the late QRS might characterize QRS end with improved precision. For this purpose we studied the behavior of d(t), the angular velocity of derived VCG vector in the direction of change (AV), raised to the 4th power, in standard 12-lead ECG recordings contained within four previously published and de-identified databases. These included files from patients with either acute inferior or acute anterior MI, files from generally healthy patients or test subjects, and files from patients with RBBB but without known infarction or ischemia. Our specific hypothesis was that changes in the spatial orientation of the VCG vector might especially aid delineation of QRS borders and the J point in the context of acute inferior MI.

2. Methods

2.1. Study population

Database 1 consisted of ECGs collected from healthy, asymptomatic individuals during serial (monthly or yearly) encounters (N=134) at NASA's Johnson Space Center, Houston, TX [5,6]. It was used to initially test the reliability and reproducibility of the proposed QRS end (J point and/or ST onset point) determination against those of more established methods, and also the relative specificity of the methods..

Database 2, the PTB Diagnostic ECG Database, available on Physionet.org [7,8], consisted of patients within that database who had AMI. It was used to compare the diagnostic sensitivity of the proposed AV method of QRS end determination against that of other automated J-point determination methods. We excluded patients with previous MI and used only those ECG recordings obtained less than 2 days after the AMI event. The reduced population consisted of 27 patients with anterior AMI, and 31 patients with inferior AMI, each with one recording.

Database 3 contained 12-lead ECGs from an unselected group of 1050 subjects from outpatient clinics in Slovenia or at NASA Houston, without previous history of cardiovascular disease, from which we excluded those with RBBB. It was used to test the specificity of the proposed QRS end method.

Finally, Database 4 consisted of ECGs from group of 45 patients with RBBB but without any known MI or

ischemia. This database was used to study the behavior of the proposed QRS end determination in patients with slow conduction abnormalities.

2.2. ECG signal processing

In each subject, a high-fidelity ECG system with a frequency response to 300 Hz and a sampling rate of 1 kHz with at least 12 bit resolution was used to acquire a 12-lead surface ECG at least 3 min in length. Signals from the conventional 12-lead ECG were analyzed automatically using customized software [5,6,9]. The QRS end was determined from the template signals, obtained by signal averaging over the time window of 30 s to obtain up to 60 QRS and T complexes.

Although each ECG record within the PTB ECG Database contains both conventional 12 lead ECGs and Frank 3-lead ECGs, only the conventional ECG was used in our analysis. Frank lead signals (Vx, Vy and Vz) were derived from the conventional 12-lead ECG by using the Frank-lead reconstruction technique of Kors et al. [10] after clamping (setting to zero) the baseline immediately preceding the QRS complex from each lead signal [4].

2.3. Rate of change of ECG vector angle

Our proposed new method for the QRS end detection is based on angular velocity changes of the derived VCG vector, $\Delta\alpha(t)/\Delta t$ (unit: radians/s), obtained as time change of the normalized vector in the direction of change. With two normalized vectors, $\mathbf{u_1}(t+\Delta t/2)$ and $\mathbf{u_2}(t-\Delta t/2)$, involved in the estimation of AV, the cosine of the angle $\Delta\alpha$ (t) between them is the dot product of their. Thus, $\cos(\Delta\alpha(t)) = u_1(t)*\mathbf{u_2}(t)$. In the application for estimating the local velocity along the projected vector loops, the angle α is small, say $\Delta\alpha$, and we may use the series expansion $\cos(\Delta\alpha\ (t)) = 1- \Delta\alpha 2(t)/2$. Hence,

$$\Delta\alpha(t)\ /\Delta t = \mathrm{sqrt}(2*(1- \mathbf{u_1}(t)* \mathbf{u_2}(t)))\ /\Delta t. \qquad [1]$$

To increase the sensitivity of this function for faster changes, and minimize fluctuations due to noise, we raised [1] to the 4th power to obtain d(t), and considered only values $\Delta\alpha(t)/\Delta t > 2$ (otherwise d(t) = 0),

$$d(t) = (\Delta\alpha(t)/\Delta t)^4 = 4/\ \Delta t^4*(1- \mathbf{u_1}(t)*\mathbf{u_2}\ (t)\ )^2. \qquad [2]$$

Although this method does not require any information on vector amplitude, the determination of the vector orientation becomes uncertain at low vector magnitude. As this might occur in case of clamping the original ECG signal to zero just before the QRS complex, the method is not applicable for detection of the QRS onset.

2.4. Methods for detection of QRS end and of onset and amplitude of ST segment

a. **Manual J Point (JP) method**. We adhered to the concept that the J point is the first point of inflection on the upstroke of the S wave [11]. QRS complexes were inspected by an experienced ECG reader. If two inflection points were recognized in one lead, the earliest was considered as the J point, denoting the end of the QRS complex, and the other as the ST segment onset (see method b). J points from all leads were inspected by using a special software program that enabled visualization of all leads simultaneously. The last one among them having a neighbor J point in any other lead closer than 10 ms was identified as the global J point, at the time instant t_{JM}, with M denoting manual.

b. **Manual ST method**. QRS complexes were inspected similarly as in the manual JP method to find the second inflection point if it existed in the particular lead, and obtain the ST segment onset location at t_{ST}.

c. **Automated JP method**. QRS complexes were inspected by the software program following the criteria of the manual JP method to obtain the automated JP location at t_{JA} (A for automated).

d. **Automated mean ECG method**. The J point at the time instant t_{mECG} was identified from the mECG(t) curve, with mECG(t) being the mean of the absolute value of potentials computed at time instant t over all ECG leads involved. It was considered to be coincident with a local minimum at the end of the QRS complex or the inflection point in the absence of local minimum.

e. **Automated angular velocity (AV) method**. The derived Frank lead signals provided instantaneous normalized ECG vectors that enabled determination of d(t) signal according to eq. [2] with $\Delta t/2$ = 2 ms. To provide the QRS end at the time instant t_{AV}, d(t) was inspected backward in time from the time instant t_{JA}+100 ms until d(t) rose rapidly, exceeding the empirically determined threshold value at $\Delta\alpha(t)/\Delta t$ = 2 degrees/ms.

A method-specific QRS duration was obtained for each method above by subtracting the *global* QRS onset, t_{QRS0}, which was obtained by using the mean ECG method. Specifically, $\Delta QRS_{JM} = t_{JM} - t_{QRS0}$ was determined with the manual JP method; $\Delta QRS_{ST} = t_{ST} - t_{QRS0}$ with the manual ST method; $\Delta QRS_{JA} = t_{JA} - t_{QRS0}$ with the automated JP method; $\Delta QRS_{mECG} = t_{mECG} - t_{QRS0}$ with the automated mean ECG method; and $\Delta QRS_{AV} = t_{AV} - t_{QRS0}$ with the new (automated) AV method.

For the new (AV) method, we also calculated the **AV transition precedence (ΔAV)**, i.e. the difference in the QRS end location obtained via the automated JP vs. the AV method, $\Delta AV = t_{JA} - t_{AV}$. Here, ΔAV is positive when t_{AV} occurs earlier than t_{JA}. In order to eliminate the uncertainty of determination of both t_{JA} and t_{AV}, ΔAV was considered positive when exceeding 10 ms.

For all ECGs within Databases 2 and 3, **ST segment amplitude** was determined in the lower limb leads (II, III and aVF) as the mean amplitude of the 50 ms long segment after t_{JA} from the isoelectric point 20 ms before the onset of the QRS. A representative lower lead segment amplitude (ST_{LL}) was then defined as that lead

amongst II, III and aVF that had the highest positive amplitude. A positive ST_{LL} was present when ST_{LL} had ST amplitude above 0.1 mV.

2.5. Statistical analysis

Two types of analysis were used, intraclass correlations (ICCs) based on analysis of variance (ANOVA), and Bland and Altman tests [12,13]. ICCs(1,1) were first used to test the reproducibility of QRS end location from two different measurements using the same method, this ICC(1,1) providing an estimate of intra-method reliability [12]. ICC was also used to test reliability of determination of the QRS end location obtained by two different methods, ICC(3,1), providing an estimate of the inter-method reliability [13]. Both should approach unity for measures with good diagnostic capability. The Bland-Altman method was used to estimate the bias between two corresponding methods [13].

3. Results

In healthy subjects, when observing the d(t) signal in the retrograde direction from the ST segment back into the QRS complex, the signal is initially close to zero, but then rises rapidly when passing the conventionally determined J point at t_{JA} in the QRS complex (Figure 1). The sharp transition of the d(t) signal may contribute to its relatively precise determination of the J point location.

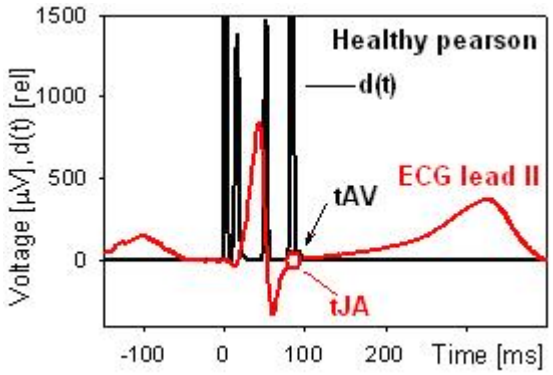

Figure 1. d(t) signal (solid black line) and ECG signal in a healthy person with t_{AV} (black open circle) and t_{JA} nearly coinciding (red open circle).

Regarding J point location reproducibility in healthy subjects as ascertained through QRS duration, ΔQRS_{AV} by the AV method was nearly as reproducible as that of ΔQRS_{JM} by the manual JP method ((ICC(1,1) of 0.912 and 0.949, respectively). (Table 1). Comparison of different ΔQRS provided the relative location of t_{AV}. On average, t_{AV} was located ~5 ms after t_{JM} and ~4 ms before t_{ST} (ΔQRS_{JM} = 90.2; ΔQRS_{ST} = 99.1; ΔQRS_{AV} = 95.4 ms, respectively, Table 1). The automated mean ECG and JP methods yielded intermediate mean values for QRS duration (ΔQRS_{JA} = 92.0, ΔQRS_{mECG} = 90.3 ms). ΔQRS values were in accordance with bias of the Bland and Altman test; t_{AV} lagged behind t_{JM} by 4.85 ms and preceded t_{ST} by -4.16 ms.

Although in the anterior AMI group, the d(t) signal also demonstrated a sharp rise backward from t_{JA} into the QRS complex, the d(t) signal behaved quite differently in many (but not all) cases with inferior AMI, with a pronounced attenuation or disappearance of d(t) when observing it in a retrograde fashion from the ST segment into the QRS complex, which in turn moved the AV-determined QRS end ahead in time, resulting in positive ΔAV (Figure 2).

Table 1. Intra-method reliability and reproducibility of ΔQRS, based on two serial measurements

ΔQRS	ICC(1,1)	Mean	Bias	SDdif
ΔQRS_{JM}	0.949	90.2	0.43	2.94
ΔQRS_{ST}	0.887	99.1	0.83	3.97
ΔQRS_{JA}	0.875	92.0	1.05	3.69
ΔQRS_{mECG}	0.857	90.3	1.31	4.07
ΔQRS_{AV}	0.912	95.4	0.69	3.69

ICC(1,1), intraclass correlation coefficient in relative units; Mean (mean QRS interval), Bias, and SDdif (standard deviation of differences between two measurements) are all in ms; total number of healthy subject recordings = 134 (67 pairs).

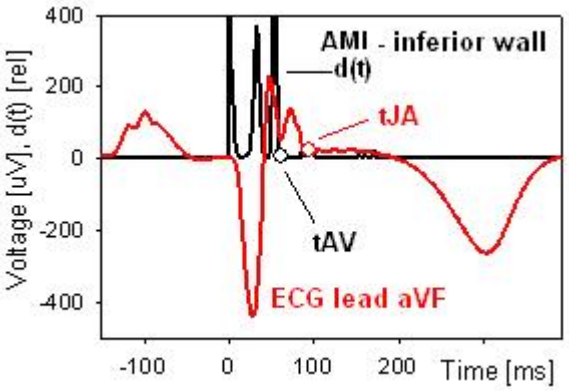

Figure 2. d(t) signal (black, solid line) and ECG signal (red, dashed line) in a patient with infero-posterior AMI, day 1. Here, t_{AV} (black circle) precedes t_{JA} (red circle).

When studying behavior of the d(t) signal with respect to the automated J point determination using ΔAV, we therefore found differences between anterior and inferior AMI (Table 2). The rate of appearance of positive ΔAV in the inferior AMI subgroup was 32.3%, whereas it was very low in both the anterior AMI subgroup (3.7%) and in the healthy group (4.3%). However, positive ΔAV was also high in patients with RBBB, occurring in 13 of the 45 patients (30.2%) with RBBB in Database 4.

When comparing the appearance of positive ST_{LL} with positive ΔAV in the inferior AMI subgroup, positive

ΔAV did not always coincide with positive ST_{LL}. Positive ΔAV appeared in 10 of the 31 inferior AMI patients, positive ST_{LL} in 7 of the 31, and positive ΔAV *or* positive ST_{LL} in 13 of the 31 patients (Table 3). The use of positive ΔAV in conjunction with ST_{LL} thus increased sensitivity for detecting recent inferior AMI from 23% (7/31) to 42% (13/31). At the same time, positive ΔAV was found in less than 5% of apparently healthy subjects.

Table 2. Behavior of ΔAV and lower limb lead ST segment amplitude (ST_{LL}) in different study groups

Disease	N	ΔAV+	%	ST_{LL}+	ΔAV+ or ST_{LL}+
Healthy	1050	46	4.3	3	9
Ant. AMI	27	1	2.0	0	1
Inf. AMI	31	10	32.3	7	13
RBBB	45	13	30.2	N/A	N/A

Ant., anterior; Inf. inferior; AMI, acute myocardial infarction; RBBB, right bundle branch block; ΔAV+, number of cases wherein the J point by the AV method preceded that by the automated JP method by at least 10 ms; ST_{LL}+: number of cases wherein ST_{LL} amplitude > 0.1 mV; N/A, not applicable.

Table 3. Sensitivity and specificity of prediction of inferior AMI vs. healthy

	Inf. AMI		Healthy			
Criterion	TP	FN	TN	FP	Sens	Spec
AV+	10	21	1004	46	32.3	95.6
ST_{LL}+	7	24	1047	3	22.6	99.7
AV+or ST_{LL}+	13	18	1041	9	41.9	99.1

Inf AMI, AV+ and ST_{LL}+ per legend of Table 2; TP, true positive; FN, false negative; TN, true negative; FP, false positive; Sens, Spec, sensitivity and specificity in %.

4. Discussion and Conclusions

We demonstrated a new angular velocity method of QRS delineation that improves, compared to current automated methods, the reproducibility of automated J point determinations in healthy subjects. Moreover the same new method, when used in conjunction with ST_{LL} and the more established methods to derive ΔAV, also improves (from 23% to 42% in this study) the sensitivity of detection of recent inferior AMI without substantively affecting specificity, i.e., the ability to correctly make "no AMI" calls in healthy subjects. Because when used alone, the more established methods are currently less sensitive for detecting inferior than anterior wall AMIs, implementation of the new method in conjunction with the more established methods may eventually further improve accuracy of inferior wall AMI detection.

One limitation of the new method is that it might be susceptible to noise. To diminish it, we used template signals for derivation, and also introduced a threshold value that makes the method slightly more robust. However the ideal threshold value should be more systematically explored in future studies. Another limitation is that other solutions will likely be required when conditions such as RBBB are also present.

In conclusion, in patients with inferior AMI, the QRS end location defined by the newly described method often precedes that defined by more established methods. While notably earlier QRS end calls (>10 ms) by the new method coincided with diagnostic ST elevation in less than 50% of studied inferior AMI cases, the delineation of QRS end by the new method allowed for more sensitive detection of recent inferior AMIs without notably compromising specificity in healthy subjects.

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