Calculating Stable Reference Potentials for Measuring ECG Wave Amplitudes Across a Range of Heart Rates

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Abstract

The UP segment is the normal isoelectric reference level for ECG wave amplitude measurements but becomes obscured at high heart rates. The aim was to identify alternative reference levels suitable for use across a wide range of heart rates. 12-lead ECGs were recorded from 10 healthy subjects before and immediately following exercise. Amplitudes of the UP segment, Q wave, end of T wave (T_{end}) and zero voltage level, all relative to PQ level were measured from V3. The performances of beat waveform averaging (AvgBeat) and mathematical averaging of separate beat measurements (AvgVal) on reducing the influence of noise and measurement errors were compared.

Due to merging of P and U waves at high heart rates, the UP segment amplitude was measureable in only approximately 71% when the heart rate was over 120 b/min. Both the UP segment amplitude and T_{end} amplitude tended to be overestimated at high heart rates. The standard deviations (SDs) were 0.02, 0.005, 0.021 and 0.016 mV for UP segment, Q wave, end of T wave (T_{end}) and zero voltage levels over the range of heart rates when using AvgVal. The SDs of amplitudes measured by AvgBeat and AvgVal methods were significantly lower than those measured from single beats ($p < 0.05$) for almost all features. Generally, these two methods achieved comparable performance on reducing measurement variability.

1. Introduction

When examining the amplitude characteristics of ECG features following exercise, such as the T wave and U wave, a reliable isoelectric reference over a range of heart rates is necessary.

The amplitude of the segment after the end of the U wave and the onset of following P wave (UP segment) is often used as an ECG reference in normal situations, as action potential propagation would normally have expected to have stopped during this segment. However, the encroachment of the P wave and the U wave can lead to unmeasurable or overestimated UP segment reference levels at high heart rates [1].

The PQ segment (from the end of the P wave to the onset of Q wave) is a commonly used reference in practice because it is measurable in a wide range of heart rates. However, an often neglected limitation is that this segment contains potentials due to atrial repolarisation [2]. Conversely, potentials due to atrial repolarisation are relatively small, being about three times lower than that of the P wave [2].

Other ECG features which are available and easy to detect for all heart rates include the Q wave, end of T wave (T_{end}) and also the ECG zero voltage level, which might serve as alternative reference levels. However, relevant investigations are limited.

In addition, to reduce the influencing of noise and measurement errors, beat averaging and mathematic averaging of values measured from several consecutive beats have been commonly used [3, 4]. Kelsey and Guethlein showed that those two methods could provide comparable reliable results when measuring amplitude of features from impedance cardiogram (ICG) [4]. However, to our knowledge, the performances of these techniques on the ECG following exercise have not been compared.

Therefore with the overall aim of identifying methods to calculate stable reference potentials for ECG wave amplitude measurements across a range of heart rates this study had two objectives: firstly, to quantify the stability of reference potentials measured from the above mentioned features, and secondly, to assess different methods of calculating the potentials to reduce measurement variability.

2. Methodology

2.1. Data collection

Standard 12-lead ECG traces were recorded from 10 healthy subjects without any diagnosed heart disease (5 men, age 33 ± 11 years, mean ± SD). The bandwidth of the recording system was 0.05-100 Hz and the sample rate was 500 Hz.

Prior to exercise, a 30-second ECG was obtained on each resting subject in the supine position. Then, the subject was exercised on a treadmill under the Balke II protocol until the target heart rate of 0.8 * (220 - age) was achieved. A 360-second ECG was obtained with the subject in a supine position immediately following exercise.

2.2. Feature extraction

Lead V3 was analyzed after filtering by a bidirectional filter (passband 0.5 – 35 Hz) to remove respiratory and muscle artifact. The PQ segment amplitude was determined by the average value of the 16 ms interval with the smallest sum squared deviation before the R wave, and was used as the reference level for the following features.

- **UP segment reference level:**
  The UP segment amplitude was determined by the average value of the 16 ms interval centered at the point with minimum amplitude between the U wave and following P wave.
- **Q wave reference level:**
  The Q wave was defined as the first point with slope change in sign when searching backward from R wave.
- **T wave end reference level:**
  Tend amplitude was determined by the minimum within a window of 130 ms following the peak of T wave.
- **ECG zero voltage level.**

The amplitudes of these reference levels were measured with respect to PQ segment amplitude.

2.3. Amplitude calculation methods

All amplitudes were obtained by three methods as follows:

- **MidBeat (single beat) method:**
  Amplitude measured from the single middle beat of 5 consecutive beats;
- **AvgVal method:**
  Amplitude determined by mathematical averaging the values measured from 5 consecutive beats;
- **AvgBeat method:**
  Amplitude measured from the average waveform generated from 5 consecutive beats.

The process was fully automated but were visually confirmed and corrected manually if necessary. For the MidBeat method, UP segments were examined on an alternative beat in the set of 5 if it was not measurable on the middle beat. For the AvgVal method, only measurable UP segments in the 5 beats were used for average value calculation.

2.4. Statistical analysis

The whole range of heart rate following exercise, from over 120 to 70 b/min, was divided into 7 recovery bands (>= 120, 110 - 120, 100 - 110, 90 - 100, 80 - 90, 70 - 80 b/min). Another band was used for data examined at resting (baseline band). The means and standard deviations (SDs) of amplitudes of all features obtained on individual subjects were calculated for each recovery band with respect to the baseline band.

The SDs of reference levels obtained on each subject by using different amplitude calculation methods were computed. The mean value of SDs, which reflected the overall variability, was calculated for each method. ANOVA test was used to examine the effect of different calculation methods on the measurement variability, and Post-Hoc Multiple Comparisons were implemented to compare the difference among the three methods.

3. Results

3.1. Examples

Figure 1 illustrates an ECG signal during the early stage of recovery, when the heart rates were over 120 b/min. As can be seen, both UP segment and T_{end} were affected by the encroachment of U wave into the P wave or T wave. On the first beat, UP segment was not measurable and tended to be overestimated on the other three beats. However, the PQ segment and Q wave were detectable on all beats.

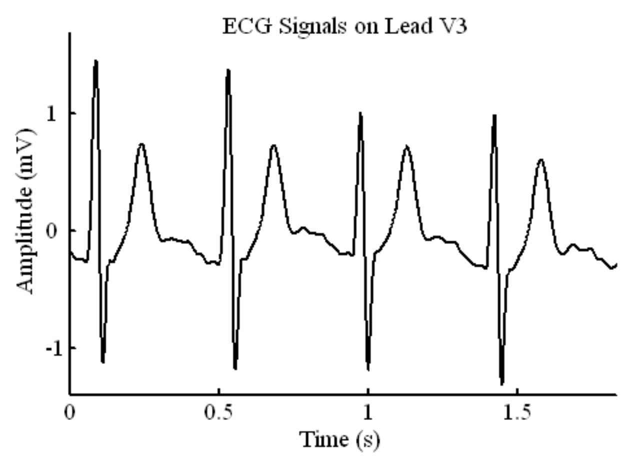

Figure 1. Example of an ECG signal with a high heart rate on lead V3. Merging of U wave, T wave and P wave can be seen. PQ and Q wave reference levels remain distinct and easily measureable.

3.2. Amplitude changes with heart rate

The means and SDs of amplitude of the UP segment, Q wave, T_{end} and zero voltage level within the baseline band obtained on individual subjects are given in Table 1. Q wave had the smallest mean value among all features (-0.01 mV). Zeros voltage level had both largest mean and SD (0.1 ± 0.05 mV). The three methods got the same results for all reference levels at baseline.

Table 1. Mean and SDs of amplitude of the features at the baseline band (Unit: mV).

Reference Levels	MidBeat Method	AvgVal Method	AvgBeat Method
Zero voltage	0.1 ± 0.05	0.1 ± 0.05	0.1 ± 0.05
UP segment	0.02 ± 0.01	0.02 ± 0.01	0.02 ± 0.01
Q wave	-0.01 ± 0.02	-0.01±0.02	-0.01 ± 0.02
Tend	0.03 ± 0.03	0.03 ± 0.03	0.03 ± 0.03

The overall means and SDs of changes relative to baseline amplitudes of the UP segment, Q wave, T_{end} and zero voltage level obtained within each heart rate band are illustrated in Figure 2. For all the features, the SDs of measured amplitudes were higher in the bands with high heart rates than those with low heart rates.

The UP segment was measurable only in approximately 71% of beats when the heart rate was over 120 b/min. The mean value of UP segment level decreased from 0.112 to 0.006 mV with respect to the baseline during recovery. The SDs also decreased with the decreasing heart rate during recovery.

The Q wave level had the smallest values among all the features in most bands with the maximum of -0.002 mV in the band of HR >= 120. In addition, the variance of Q wave levels across a wide range of heart rate was relatively low (less than 0.004 mV).

Both T_{end} and zero voltage levels had high SDs in most heart rate bands.

3.3. Variability of amplitudes measured by different methods

The SDs of reference levels measured across the whole recovery stage are shown in Figure 3.

ANOVA test results showed that the reference levels were significantly affected by using different methods ($p < 0.001$) for all other features except the UP segment ($p = 0.154$).

Reference levels obtained by the MidBeat method had the highest mean value of SDs in all cases. According to the results of Post-Hoc Multiple Comparison, the variability from the MidBeat method was significantly higher than those of the other two methods ($p<0.05$) when examining reference levels at Q wave, T_{end} and zero voltage level. AvgVal method was superior to the AvgBeat method only when examining the Q wave amplitude ($p<0.05$). Otherwise, they achieved comparable performances on reducing measurement variability in other cases.

Again, the Q wave amplitude had the lowest variability among all features. The mean value of SDs of Q wave amplitude was only 0.005 mV when using the AvgVal method, which was followed by that of the zero voltage level (0.016 mV).

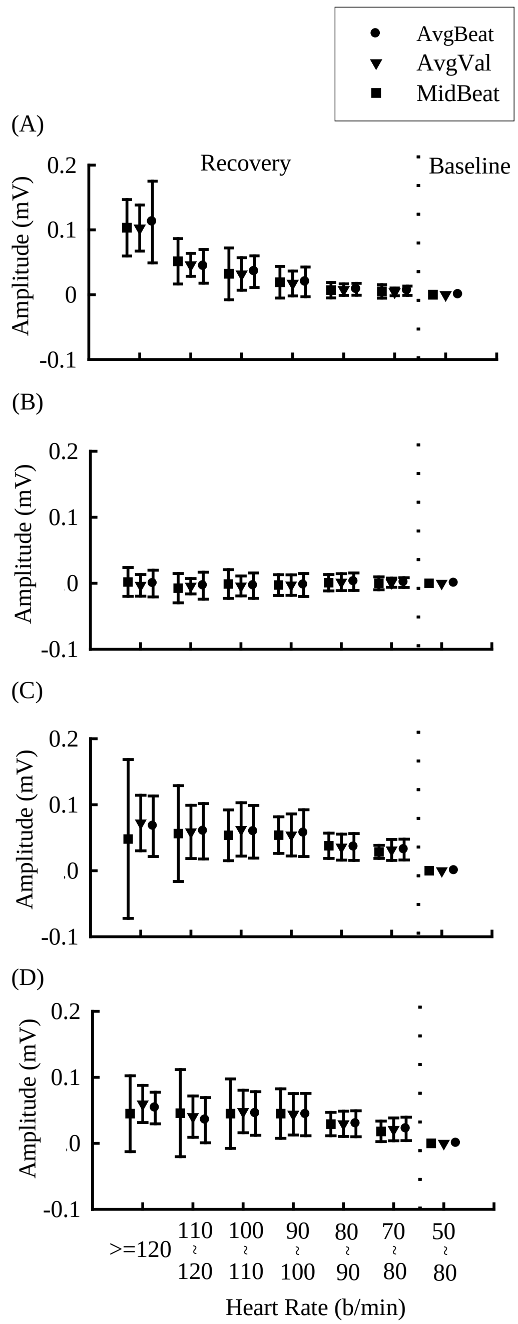

Figure 2. Overall means and SDs of changes relative to baseline amplitude of (A) UP segment, (B) Q wave and (C) T_{end} and (D) zero voltage reference in different heart rate bands.

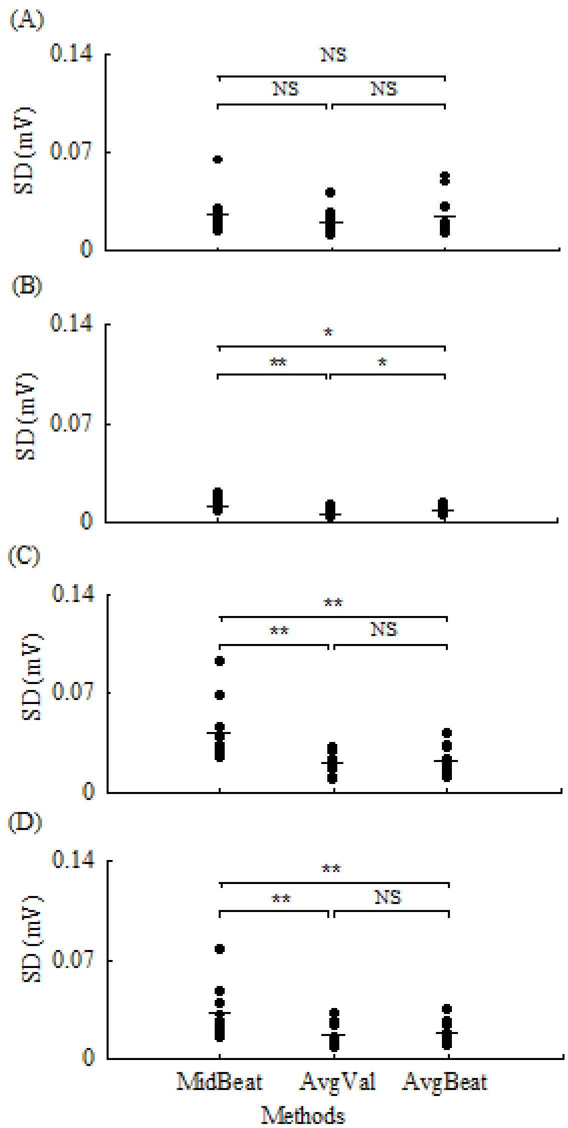

Figure 3. The SDs of amplitude of (A) UP segment, (B) Q wave, (C) T_{end} and (D) zero voltage level obtained on individuals during the recovery by different calculation methods. The mean value of SDs for each method is marked by the horizontal solid line ('*' and '**' denoted significant differences at the level of $p < 0.05$ and $p < 0.001$ respectively.).

4. Discussion

The amplitudes of the UP segment, Q wave, T_{end} and zero voltage level were examined with respect to PQ segment in a range of heart rate following exercise.

As expected, although the amplitude of UP segment was considered as the most ideal isoelectric reference at low heart rate, it tended to be not measurable or overestimated at high heart rate because of the encroachment of U wave into P wave on lead V3. The T_{end} was also influenced by high heart rates, which makes both of UP segment and T_{end} unsuitable to be considered as amplitude measurement references. Zero voltage level might be the most intuitive reference on ECG. However, it had the high variability even at low heart rate because of the influence of the respiratory and muscle artifacts, which cannot be removed by linear filter. However, the Q wave, as a feature quite close to PQ segment, least variability across a range of heart rates. The observations might be because the Q waves on lead V3 were usually small, so the amplitude is close to and changes in the same way as PQ segment.

According to Figure 2 and Figure 3, the amplitudes measured from a single beat always had high variability especially at high heart rate. Therefore, methods to reduce noise and measurement errors would be recommended for amplitude measurement on ECGs following exercise. The mathematical averaging method was found to be superior to the beat waveform averaging method for Q wave levels measurement. This might be because the beat waveform averaging always suffers from artificial distortion caused by intra-beat variance [5]. The large beat-to-beat variance at the early stage of recovery may produce significant influence when detecting features with small amplitude. Otherwise, these two methods achieved comparable performances on reducing measurement variability.

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