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The impact of baseline wander removal techniques on the ST segment in simulated ischemic 12-lead ECGs

Abstract: Baseline wander removal is one important part of electrocardiogram (ECG) filtering. This can be achieved by many different approaches. This work investigates the influence of three different baseline wander removal techniques on ST changes. The chosen filters were phase-free Butterworth filtering, median filtering and baseline correction with cubic spline interpolation. 289 simulated ECGs containing ischemia were used to determine the influence of these filtering processes on the ST segment. Synthetic baseline wander and offsets were added to the simulated signals. All methods proved to be good approaches by removing most of the baseline wander in all signals. Correlation coefficients between the original signals and the filtered signals were greater than 0.93 for all ECGs. Cubic spline interpolation performed best regarding the preservation of the ST segment amplitude change when compared to the original signal. The approach modified the ST segment by 0.10 mV ± 0.06 mV at elevated K points. Median filtering introduced a variation of 0.33 mV ± 0.29 mV, Butterworth filtering reached 0.16 mV ± 0.14 mV at elevated K points. Thus, all methods manipulate the ST segment.

Keywords: 12-lead ECG; ischemic; signal processing; baseline wander; ST segment; filtering

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1 Introduction

Filtering is a standard signal processing method that is used regularly in clinical routine. Biosignals are typically disturbed by many kinds of interference. Although application of filters seems to be a matter of course, the signals can be modified by filtering enormously. Regarding filtering of the electrocardiogram (ECG), several publications focus on the influence of this process on the part of interest of the signal to be filtered [1]. Especially during diagnostic procedures, filter parameters are chosen very carefully in order not to remove any interesting part of the ECG for diagnosis. For example, ischemic areas in the heart can yield morphological change of the ST segment in the ECG [2]. Such changes need to be preserved after filtering to guarantee the physician an undisturbed signal that still includes all the relevant facts.

In this work, the influence of baseline wander filtering methods are evaluated using simulated ECG data with added synthetic artifacts.

2 Methods

2.1 Data used in this study

Data were used from a previous simulation study [3]. At this place, a short summary of the data generation is given: A cellular automaton was parameterized with action potentials from a monodomain simulation using an ischemia-adapted ten Tusscher model and a monodomain solver [4]. Several ischemia setups were established, each ischemic setup taking 17 AHA segments in the left ventricle into account with a different sizes of the ischemic region. These were applied to the anatomical model of the Visible Man. A 12-channel ECG was extracted from the forward calculated body surface potentials for each lead yielding one QRS complex and the T wave. The sampling rate was 500 Hz. The data consisted of both signals with ST change and electrically silent ischemia. An ischemia condition (IC) proposed in [2] was applied in this work. Signals exceeding a threshold set to 0.99 mV at a specific point in the ST segment were marked as signals with ST change.

2.2 Extending one beat ECG signals

As stated before, each set of ECG signals for a specific ischemic setup consisted of just one beat with a length of approximately half a second. Since baseline wander is mostly located at frequencies between 0 Hz and 0.5 Hz [5], a signal of at least two seconds is needed to include sufficient information in this frequency band. Therefore, each single
signal was extended to a total length of 60 s (see Figure 1). To account for the variability in the RR intervals [6], beat dependent varying numbers of samples were added before and after the original signal. However, no morphological changes were applied to the original beats.

### 2.3 Modelling baseline wander and offsets

In a first step, a model accounting for baseline wander and an offset was introduced. Baseline wander originates from several phenomena, e.g. respiration. The frequency fraction is located between 0 Hz and 0.5 Hz [5]. A simple model was used to represent this kind of interference:

$$b_p(t) = \sum_{k=0}^{50} \cos(2\pi \cdot k \cdot 0.01 \text{ Hz} \cdot t + \Phi_p)$$  

(1)

$b_p(t)$ describes the baseline noise and offset ($k = 0$). $\Phi_p$ is a random phase shift applied to each individual cosine. The phase shift is uniformly distributed in the interval [0; 2$\pi$]. The number of repetitions $P$ was chosen to 50, therefore, $p = 1, \ldots, P$. The signal $b_p(t)$ and its spectrum $|B_p(f)|$ are shown in Figures 3 and 2.

An additive model was used. Therefore, the disturbed ECG signal $s_d(t)$ consisted of the sum of the baseline wander model and the undisturbed signal $s_u(t)$:

$$s_d(t) = s_u(t) + A \cdot b_p(t)$$  

(2)

The constant $A \in \mathbb{R}$ is an amplitude scaling factor used to increase or decrease the influence of the baseline wander on the ECG signal. $A$ was chosen such that the signal to noise ratio was -3 dB. The results in time and frequency domain are shown in Figures 3 and 4. The effect of the added baseline wander interference is especially visible in the frequency band between 0 Hz and 0.5 Hz. Furthermore, peaks at 1 Hz and its harmonics could be observed. These result from the fixed heart rate of 60 bpm.

### 2.4 Determination of ST changes

Physicians often look at the J point to evaluate a change of the ST segment. This point, however, is very hard to determine automatically since there is no hard decision rule on how to find it. Several approaches have been made to find this specific point, e.g. by estimating its position at a fixed time after the R peak [7]. Obviously, this does not account for individual changes of the electrical conduction of the heart. Therefore, in [2] a new method was introduced based on a more dynamic feature: the K point (KP). KP describes the minimum of the envelope signal accounting for all leads in an ECG:

$$t_k = \arg \min_t \left( \max_l |s(l, t)| \right),$$  

(3)

where $t_k$ is the temporal position of the KP, $s$ is a set of discrete lead signals of an ECG and $l$ is the lead of the ECG signal. The corresponding amplitude at KP (KPA) can be found by replacing $\arg \min$ by $\min$. This method was chosen to account for changes that do not occur at a specific instant of time. The IC was investigated at the K point.
2.5 Evaluated filters

Three different approaches for baseline wander removal were investigated regarding their influence on the signal:
(a) a second order infinite impulse response filter of type Butterworth with cutoff frequency at 0.5 Hz and phase free filtering operation resulting in an effective order of four (in the following BW).
(b) a combination of two median filters (as proposed in [8], in the following MED).
(c) a cubic spline baseline correction (as proposed in [9], in the following SPL).

This selection comprised for linear as well as non-linear filtering techniques.

2.6 Performance indices

To evaluate the influence of the filters, several methods were used. First, the similarity between the filtered noisy ECG signal and the original signal was evaluated. This was done by calculating the correlation coefficient (CORR). Furthermore, the l_operator (LOPA) as proposed in [10] was calculated:

\[
\text{LOPA}(x(t), y(t)) = \frac{E(x(t) \cdot y(t))}{E(x^2(t)) + E(y^2(t))}
\]

In contrast to CORR, LOPA accounts for offsets and scaling of any of the two signals.

In addition, the absolute value of the change of the amplitude at the KP (KPAC) was determined. The latter analyses were conducted twice: once for all lead signals, and once for the subset of leads meeting the IC.

3 Results

A set of 289 extended and disturbed 12-lead ECGs was evaluated. Each resulting signal was filtered by all methods separately. To minimize the influence of the random phase shifts \( \phi_p \) in (1), all experiments were performed 50 times with different random values and averaged. These results were averaged over all leads. Mean and standard deviation (std) were calculated for the 289 previously averaged values. The results regarding the introduced performance measures are shown in Table 1 for the whole ECG data set and in Table 2 just for the ECG channels meeting the IC.

Table 1: Results (mean±std) for the whole dataset. KPAC is given in mV.

<table>
<thead>
<tr>
<th>Measure</th>
<th>Unfiltered</th>
<th>MED</th>
<th>BW</th>
<th>SPL</th>
</tr>
</thead>
<tbody>
<tr>
<td>CORR</td>
<td>0.58±0.00</td>
<td>0.95±0.09</td>
<td>0.96±0.00</td>
<td>0.93±0.00</td>
</tr>
<tr>
<td>LOPA</td>
<td>0.51±0.02</td>
<td>0.93±0.13</td>
<td>0.92±0.04</td>
<td>0.93±0.01</td>
</tr>
<tr>
<td>KPAC</td>
<td>0.33±0.21</td>
<td>0.08±0.14</td>
<td>0.10±0.07</td>
<td>0.07±0.05</td>
</tr>
</tbody>
</table>

Table 2: Results (mean±std) for the channels meeting the IC. KPAC is given in mV.

<table>
<thead>
<tr>
<th>Measure</th>
<th>Unfiltered</th>
<th>MED</th>
<th>BW</th>
<th>SPL</th>
</tr>
</thead>
<tbody>
<tr>
<td>CORR</td>
<td>0.58±0.00</td>
<td>0.83±0.13</td>
<td>0.96±0.00</td>
<td>0.93±0.00</td>
</tr>
<tr>
<td>LOPA</td>
<td>0.53±0.03</td>
<td>0.74±0.21</td>
<td>0.90±0.06</td>
<td>0.93±0.01</td>
</tr>
<tr>
<td>KPAC</td>
<td>0.42±0.26</td>
<td>0.33±0.29</td>
<td>0.16±0.14</td>
<td>0.10±0.06</td>
</tr>
</tbody>
</table>

three methods showed small mean KPAC. MED and SPL showed higher std than BW making them less robust methods.

The 104 channels, which met the IC, performed best for SPL (see Table 2). The other methods had a large influence on KPA with values up to 1.89 mV. Correlation based methods were on a high level for SPL and BW, but clearly smaller for MED.

4 Discussion

As most signal channels did not meet the IC, the results for KPAC in Table 1 could not sufficiently substantiate the ST deviation preservation. So, small deviations did only underline the functionality of the filters, as the correlation based methods did that, too.

However, the signals used for Table 2 allowed the evaluation of the influence of the filters on ST deviation. In this case, BW and MED performed worst. Nevertheless, high stds reveal large differences in the results. On the other hand, SPL reached indeed a small std, but the average

Figure 5: Typical result after the filtering process. MED lowered the amplitude at KP to almost 0 mV. ORG: unfiltered extended noise-free signal.
was exceeding the threshold set for ST changes. Therefore, each method seemed to manipulate the KPA. This is problematic since physicians could interpret such a difference as a missing ST change although it was originally present (see Figure 5).

In this study, a baseline wander model consisting of different cosine functions was used. This predicts that some filters could have a crucial impact on the ST segment.

5 Limitations and prospects

The set of filtering techniques that were used in this study was limited to three. Even though there is a vast field of different methods, it was only possible to evaluate a part of them in this work. In future work, the set should be extended to search for an optimal method and optimal filtering parameters.

Although an influence of the filters on the ST segment could be demonstrated, the relation between signal and filtering method has to be investigated in future work to exclude further possible influencing factors.

As the proposed noise model only accounts for baseline wander, possible influences of other noise types cannot be evaluated. Future studies should deal with an extended noise model concerning e.g. for broadband noise, powerline interference, etc.

At last, one should keep in mind, that signals used in this study were generated in simulations with early ischemia. Although covered with some model uncertainties, it was possible to get pure undisturbed ST deviations caused by ischemia.

Author’s Statement

Conflict of interest: Authors state no conflict of interest.

Material and Methods: Informed consent: Informed consent has been obtained from all individuals included in this study. Ethical approval: The research related to human use has been complied with all the relevant national regulations, institutional policies and in accordance the tenets of the Helsinki Declaration, and has been approved by the authors’ institutional review board or equivalent committee.

References