Evaluating Pauses in Holter ECG Signals

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Abstract

Background: *Information related to pauses in heart activity is an important output of ECG Holter monitoring reports. This information should be quickly assessed from inter-beat (RR) intervals only (a naïve approach). However, evaluating pauses in Holter ECGs recorded during usual daily activities can be more challenging due to signal lower quality. In this paper, we propose a method to improve pause detection in heart activity from Holter ECG recordings.*

Method: *We used 978 recordings (length 45 seconds, 1-lead ECG, sampled at 200 or 250 Hz) with a known longest RR interval (from 1.12 to 19.0 seconds, mean duration of 2.72 ± 1.26 seconds). QRS complexes were detected by a convolutional neural network with a recurrent layer. This study started with the automated removal of suspicious QRS complexes by a QRS amplitude. Then we iterated through RR intervals, seeking saturated areas, missed QRS, or a strong noise; potentially, examined RR intervals were further refined. The longest interval was reported for each recording.*

Results: *A mean difference between computed and expert values was 0.079 ± 0.433 and 0.046 ± 0.120 seconds for the naïve and the proposed approach, respectively. The ability to find severe pauses (equal to or longer than 4 seconds) showed an F1 score of 0.95 and 0.97 for naïve and the proposed method.*

Conclusion*: Our results showed that the proposed method improved pause detection in Holter ECG recordings compared to the naïve approach.*

1. Introduction

Pauses in heart activity mean that there is not any QRS complex for a period longer than two seconds. Pauses of intermediate length (2-3 seconds) are associated with a higher cardiovascular event risk [1].

Pauses longer than 3 seconds (excepting sleep and medication reasons) are an indication for pacemaker implantation [2].The exception is atrial fibrillation where pauses up to 4 seconds may be considered normal [3]. If the pause is longer than four seconds, it is considered health threatening arrhythmia and may result in death. Pauses may be caused by variety of reasons: bradycardia, post-tachycardiac pauses, pauses in atrial fibrillation or an atrial flutter (Fig.1A), sinus arrest (Fig.1B and D), during

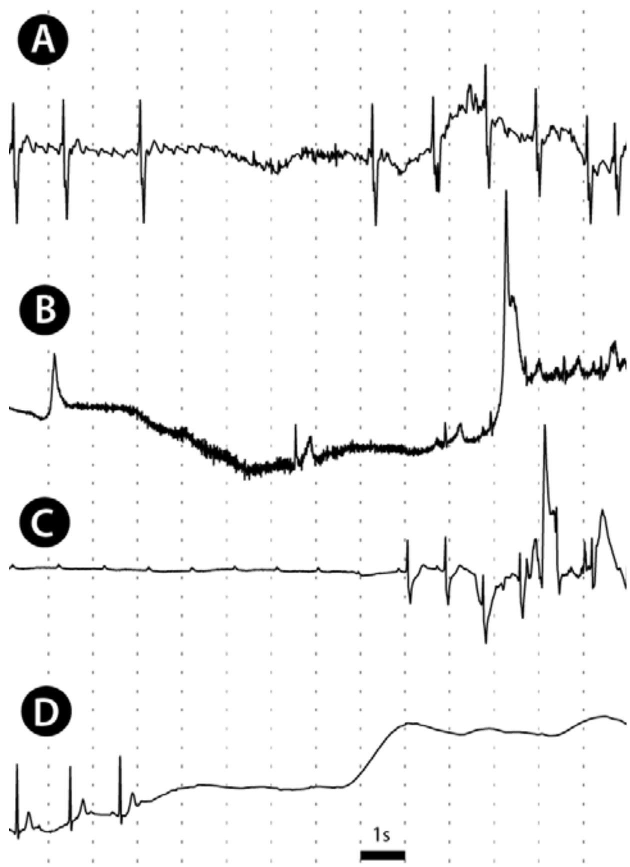

Figure 1. Examples of real pauses in Holter ECG signals. A 5s pause during atrial flutter (A), the end of 19s pause (sinus arrest) followed by another 3s pause (B), end of 12s pause during 2nd degree AV block (C). D shows a start of 13s long SA pause.

an AV block (Fig.1C) or sleep apnoea. Also, ventricular tachycardia and ventricular fibrillation may lead to asystoles.

Detecting pauses in patients in supine resting position seems straightforward, consisting only of evaluation of inter-beat (RR) intervals (a naïve method). However, Holter recordings acquired during usual daily activities are more challenging. Patient usual activities result in an increased amount of noise because of movements or bad electrode contact. Furthermore, long pauses inevitably lead to a loss of consciousness; a standing patient will fall. Therefore, much noise can be produced during a pause; however, such an event cannot be just rejected as a noisy signal, although it is. In this paper, we amied to improve the detection of pauses in Holter ECG recordings.

2. Method

2.1. Data

We used 978 ECG Holter recordings (samples at 200 or 250 Hz, duration 45 seconds) acquired during usual daily activities (Medical Data Transfer, s. r. o., Brno, Czechia). Recordings were suspected of containing pauses longer than 2 seconds. We manually measured real pauses in recordings (Fig.2). QRS complexes were automatically found by JOSEPH software (ver. 0.3.91, ISI of the CAS and MDT, s.r.o., Brno, Czechia). Input the presented method is a one-lead ECG signal and a list of QRS annotation marks (Fig.3A).

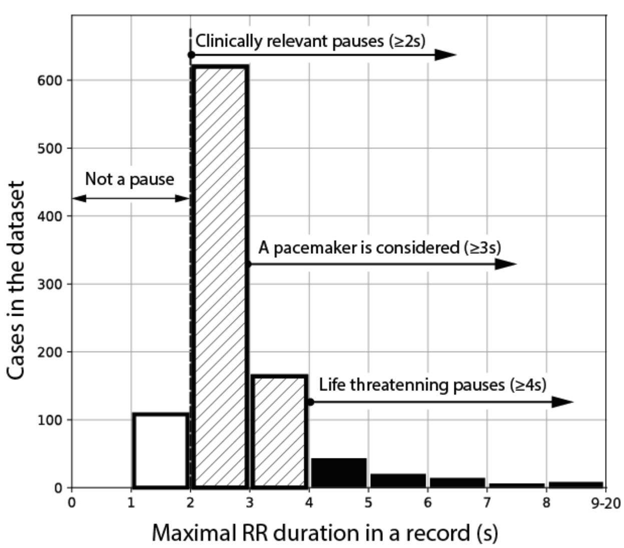

Figure 2. Distribution of maximal pauses in the dataset. Clinically relevant pauses are equal or longer than 2s. Above three seconds, a pacemaker might be considered; life-threatening pauses are longer than 4s.

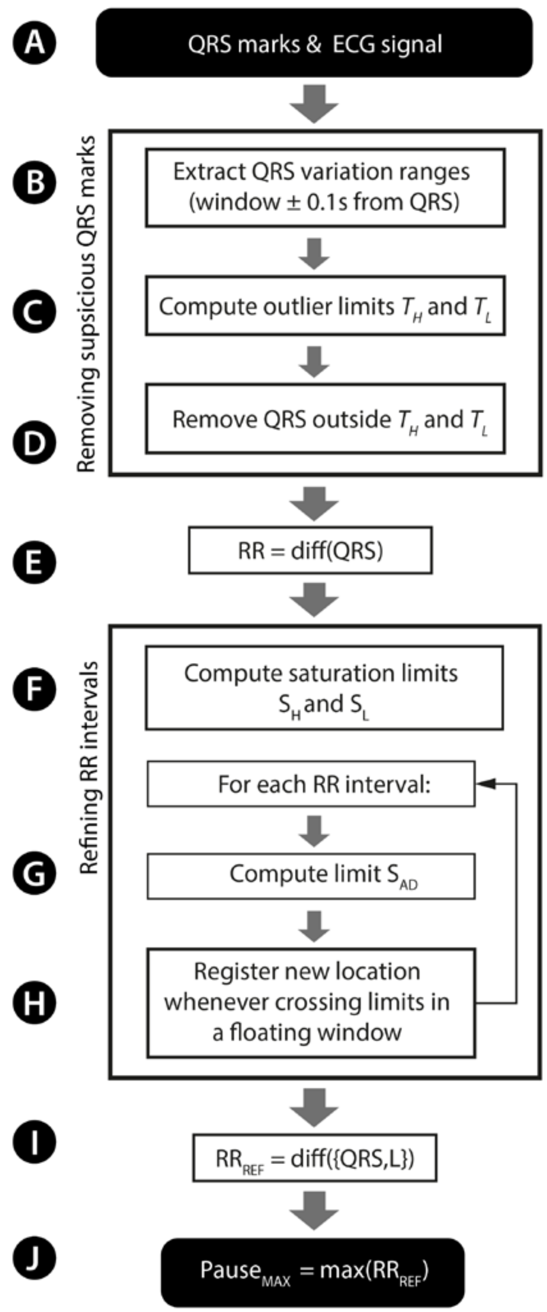

Figure 3. Method flowchart. QRS marks and ECG signal (A) are used to extract a list of variation ranges (B). Limits (C) are used to remove suspicious QRS marks from the list (D). Next, RR list (E) is acquired from QRS positions; saturation limits (F) are computed. For each RR interval, we compute the slope limit (G). We iterate through the RR interval and refine it whenever the signal properties exceed limits (H). Finally, we report maximal distance from the updated RR list (I) as a maximal pause (J).

2.2. Processing

2.2.1 Removing suspicious QRS

Suspicious QRS complexes are removed (Fig.3B-D) in the following block. We extract variation ranges of each QRS from a window centered to QRS annotation marks (length 0.2 s). Next, outlier limits T_H and T_L are defined (Fig.3C):

$$T_H = mean(VRS) \cdot M$$
$$T_L = mean(VRS) \cdot M^{-1}$$

where VRS is the list of variation ranges and M is a constant set at 4 (obtained from optimization, Fig.5A).

QRS complexes with variation range higher than T_H or lower than T_L are removed from the list of QRS annotation marks (Fig.3D)

A list of RR intervals is derived from a list of QRS annotation marks (Fig.3E).

2.2.2 Refining RR intervals

Now, each RR interval will be inspected and refined into smaller parts where needed (Fig.3F-H). Reasons for refinement are saturated areas, missing signals, or areas with very strong noise. We compute limits to check saturation (Fig.3F):

$$S_H = max(ECG) - VR_D$$
$$S_L = min(ECG) + VR_D$$

where VR_D is a variation range of the whole ECG signal divided by 20. However, such limits may lead to incorrect results when signal baseline forms the lowest or the highest border of the ECG signal. Therefore, we use the following check:

$$S_{HC} = mean(ECG) + 10 \cdot VR_D$$
$$S_{HL} = mean(ECG) - 10 \cdot VR_D$$

If the $S_H < S_{HC}$, then $S_H = S_{HC}$. Analogically for the lower limit, if $S_L > S_{LC}$, then $S_L = S_{LC}$. Now we iterate through each RR interval. For each RR, we compute limit S_{AD} (Fig.3G) based on summed absolute differences:

$$S_{AD} = \frac{\sum|diff(A)| + \sum|diff(B)|}{2}$$

where A and B are ECG vectors (length 0.2s) centered at the first and second QRS complex, respectively.

Next, we will examine the RR interval in a floating window, excluding 0.2 sec from borders. In the floating window (length 0.3, step of 0.1s), we evaluate saturation and summed absolute differences. If window values exceed saturation limits S_H or S_L, examined location is added into a list of additional points L. Also, if a summed absolute difference exceeds limit S_{AD}(corrected by vectors length) more than K times, the current location is added to the list L (Fig.3H). The K was optimized to a value of 2.

A list of refined intervals RR_{REF} is built from both QRS marks and additional points L (Fig.3I). Finally, the longest interval is reported as a maximal pause (Fig.3J).

2.3 Optimization

We searched for optimal values of constant M (for outlier limits) and K (for summed absolute derivates in RR intervals). We found optimal values of M and K at 4 and 2, respectively (Fig.5).

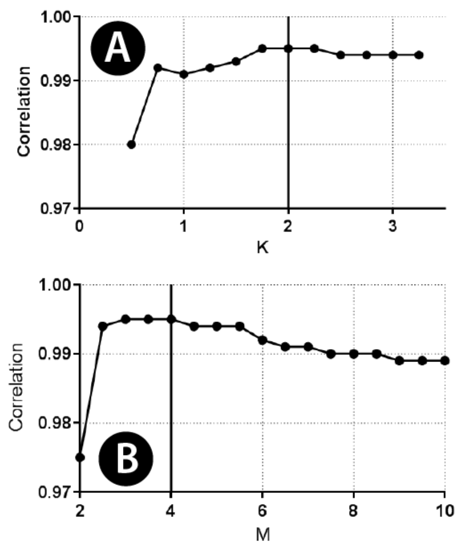

Figure 5. Optimization of coefficient K (A), affecting the influence of the S_{AD}. We also optimized coefficient M, affecting the removal of outlying QRS complexes (B). Performance was measured as a correlation between expert and automatically computed length of the longest pause in a measurement.

3. Results

We evaluated 978 recordings reported to contain a pause longer than 2 seconds. Manual measurement of pauses shown a mean pause duration of 2.72 ± 1.26 seconds; minimal and maximal pauses were 1.10 and 19.00 seconds, respectively. Furthermore, manual measurement revealed 108 recordings without a pause longer than 2 seconds.

The performance of the proposed solution was compared to the naïve approach in several ways. First, we compared the Pearson correlation between manually and automatically evaluated pauses for both methods. We received r = 0.938 and r = 0.995 for the naïve and the proposed method, respectively. We also measured the mean difference between manually and automatically obtained maximal pauses, showing 0.079 ± 0.433 s and 0.046 ± 0.120 s for the naïve and the proposed method.

Also, we inspected how the proposed method would improve the localization of recordings with life-threatening pauses (i.e., longer than four seconds). We found that the F1 score of the naïve method was improved from 0.947 to 0.970, obtained by the proposed method.

Finally, we evaluated counts of recordings in groups by pause difference. Tab. 1 shows how the proposed approach affects the amount of incorrectly detected cases by the pause length difference.

Table 1. An amount of incorrectly evaluated maximal pauses using the naïve and the proposed method.

Difference	Naïve	Proposed
> 0.1 second	81x	64x
> 0.5 second	18x	4x
> 1.0 second	11x	2x

4. Discussion and Conclusion

The presented approach improves the detection of pauses in Holter ECG recordings. The method removes suspicious QRS (Fig.6A) resulting from the QRS detection method, which is forced to detect QRS even in very noisy Holter ECG. The method removes saturated areas from inter-beat intervals (Fig.6B), effectively shortening their total length. Also, the method removes false QRS detected in areas containing only P-waves during AV Block (Fig.1C), pointing to the disadvantage of the used QRS detector.

However, the proposed method also quantifies some pauses incorrectly, as shown in Fig. 6C with hardly detectable but probable QRS in the middle of the false pause. Also, Fig.6D shows a shorter reported pause due to the falsely detected beat.

The presented approach decreased the number of false pauses and allowed more effective validation of results by specialists. However, our results also suggested that training data of used Holter ECG QRS detector should be extended with recordings with pauses.

Acknowledgments

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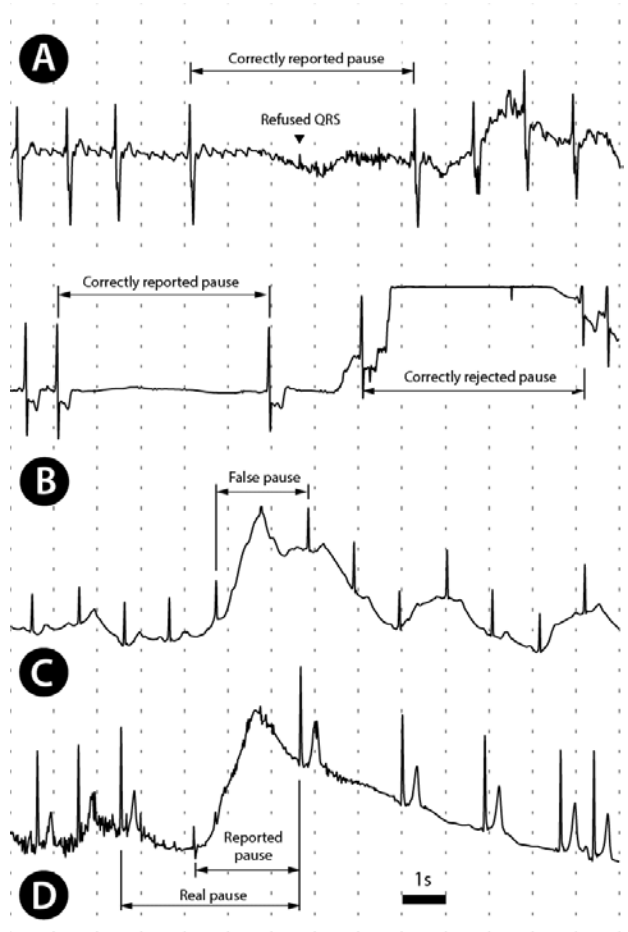

Figure 6. Cases of correctly (A, B) and incorrectly evaluated pauses (C, D)

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