Heart period is defined by P-waves in ECG

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***Abstract*—Heart rate variability (HRV) is a widely used measure to assess emotional arousal and stress level. It measures the variation in the duration of heart cycles. If HRV is determined based on the ECG signal, the duration of heart cycles is conventionally calculated as the time difference between successive R-peaks. However, the heart cycle begins with atrial depolarization, therefore, the onset of the P-wave is a physiologically more appropriate fiducial point to define successive heart cycles. This paper investigates the effect of using the onset of P-waves instead of R-peaks on HRV calculation. Measurements containing ECG signals recorded in Einthoven II lead and one measurement containing simultaneously recorded intracardiac electrograms and surface ECG signals were used. Our results suggest that the classification of successive heart cycle length differences is different depending on whether the onset of P-waves or R-peaks are used as fiducial points.**

***Keywords*—heart period; heart rate variability; electrocardiogram; intracardiac electrogram; P-wave delineation**

I. Introduction

Blood pressure measurement is one of the most commonly used daily procedures in medical examinations and home health monitoring to assess the state of the cardiovascular system. However, the accuracy of the measurement can be influenced by many physiological and external factors [1] [2]. Stress level of the examined person can have a large impact on the accuracy of blood pressure measurement results and may induce incorrect medical conclusions if high stress level remains undetected [3]. Heart rate variability (HRV) is a widely used measure to assess momentary stress level of the tested person [4]. The calculation of HRV is based on the measurement of heart periods (the duration of heart cycles), also designated as beat-to-beat intervals. Heart periods can be measured in different ways. One of the most commonly used methods is to define heart periods as the time difference between successive R-peaks in the ECG signal. However, the heart cycle begins with atrial depolarization, while the R-peak corresponds to ventricular depolarization. Accurate measurement of heart periods should be based on precise detection of the initiation of atrial activity [5]. The P-wave corresponds to atrial depolarization in the ECG signal, however, accurate detection of the onset of P-waves is a challenging task, especially when the amplitude of P-waves is small. In this paper, we calculate HRV values using the onset of P-waves as fiducial points for recordings with high signal-to-noise ratio (SNR) and compare these results to HRV values calculated using R-peaks as fiducial points. Besides surface ECG signals, we analyze a measurement where intracardiac electrogram was also recorded.

II. Materials and Methods

A. *Detecting the Onset of Atrial Activity in the Intracardiac Signal*

Validating the detection of the onset of P-waves can be difficult, because there is no universally accepted rule for the onset and offset of the P-wave [6], moreover, in annotated databases like the QT database [7], manual annotations by experts may be inaccurate in some cases. For validation purposes, we used a clinical recording, where 12-channel surface ECG and intracardiac electrogram (EGM) were measured simultaneously. The intracardiac signals were recorded by a 4-electrode catheter. The bipolar signal of the electrode pair, closest to the sinoatrial node was used to locate the onset of atrial activity. Signals were sampled with 1 kHz sampling rate.

For the detection of the onset of atrial activity in the intracardiac signal, we used the algorithm described by Schilling [8] which is based on the non-linear energy operator (NLEO). The NLEO is a measure for the energy of a discrete-time signal. It is proportional to the squared amplitude as well as squared frequency of the given signal. Application of the NLEO to the EGM followed by filtering and thresholding can be used to analyze atrial activity.

B. *Detecting the Onset of P-waves in the Surface ECG Signal*

In the clinical recording, 12-channel ECG signals were recorded in parallel with the intracardiac signals. Moreover, a measurement series was conducted in laboratory environment, where only ECG in Einthoven II lead was recorded. One healthy senior adult and one healthy young adult participated in the measurement series. Healthy adults had normal ECG with no arrhythmia. 5 measurements were recorded for both tested persons. The recording length was between 100 and 120 seconds. Signals were sampled with 1 kHz sampling rate. The onset of P-waves was detected using the algorithm described by Martínez et al. [9]. The algorithm is based on wavelet transformation of the ECG signal with different scales. For the transformation, a quadratic spline wavelet is used. First, the QRS complex is located. After that, the P-wave is located using thresholds based on the root mean square of the transformed signal. The peak of the P-wave is also detected. In this study, the peak of the P-wave was defined as the local maximum between the P-wave onset and the Q-wave in the corresponding heart cycle.

C. *Detecting R-peaks in the Surface ECG Signal*

Localization of R-peaks was carried out in two steps as described and evaluated in a previous study [10]. The first step is the designation of the QRS complex with any of the usual techniques. In this study, the QRS complex was located as part of the P-wave onset detection. In the second step, the original signal is re-filtered (independently of the filtering in the first step) with two notch filters at 50 Hz and 100 Hz (4th order Butterworth), and a low-pass filter at 120 Hz (3rd order Butterworth) and the maximum value is searched for within the QRS complex. We chose the described method because it showed very high accuracy for simulated noisy ECG signals.

D. *Measurements for Experimentally Induced Physical Stress*

For the analysis of the effect of stress on HRV, data were also analyzed from measurements where short-term physical stress was induced for the tested persons by running 1 floor downstairs then 1 floor upstairs. One healthy senior adult and one healthy young adult participated in the measurement. Data were recorded directly before and immediately after physical stress. The recording length was between 100 and 120 seconds. Signals were sampled with 1 kHz sampling rate.

E. *Characterizing HRV in Short Recordings*

HRV contains dominant frequency components between 0.0033 - 0.4 Hz [11]. Therefore, frequency domain analysis of HRV is not appropriate for short recordings (1-2 minutes) typically applicable before or during blood pressure measurement. For short recordings, time domain analysis is more appropriate. In the present study we used the pNN0_20, pNN20_50 and pNN50 parameters to characterize HRV. pNN0_20 is the ratio of Differences in Subsequent Heart Periods (DSHP) that lie between 0 and 20 ms compared to the total number of DSHP. pNN20_50 stands for the same ratio but for DSHP that lie between 20 and 50 ms. pNN50 designates the ratio for DSHP greater than 50 ms. In a previous study, these parameters reflected changes in stress level in situations, where the widely used pNN50 alone indicated no or only negligible changes in stress level [12].

III. Results

A. *Analyzing the Effect of Fiducial Point Designation Using ECG and EGM Signals*

The effect of fiducial point designation was analyzed using the clinical measurement where 12-channel surface ECG and intracardiac EGM were measured simultaneously. For the analysis, Einthoven II lead was selected from the ECG, because it was also available in other recordings. From the intracardiac recording, the bipolar signal of the electrode pair, closest to the sinoatrial node was used. Figure 1 shows a P-wave in the ECG signal with the detected P-wave onset and the point corresponding to the time point of the onset of atrial activity in the EGM signal.

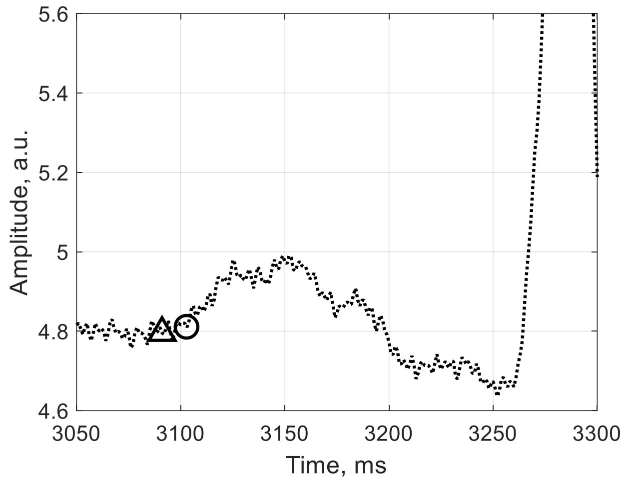

Fig. 1. A P-wave in the ECG signal (Einthoven II lead) with the P-wave onset point (circle) detected by the method described in chapter II.B and the point corresponding to the time point of the onset of atrial activity in the EGM signal (triangle) detected by the method described in chapter II.A.

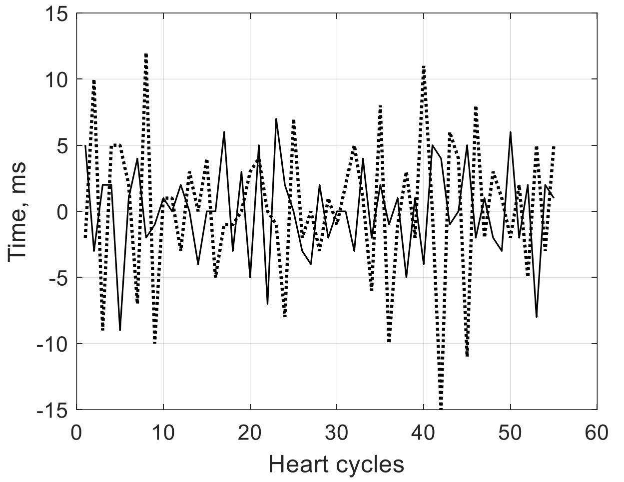

Fig. 2. The differences between heart periods calculated based on tRR, tPP and tOnOn. Solid line: tRR-tPP; Dotted line: tRR-tOnOn.

Heart periods were calculated based on R-peaks from the ECG (tRR), the onset of P-waves from the ECG (tPP) and the onset of atrial activity from the EGM signal (tOnOn). Figure 2 shows the differences between calculated heart periods. Table I summarizes the pNN0_20, pNN20_50 and pNN50 values calculated using three different fiducial point definitions. Note that the length of the recording was approximately 50 seconds (55 heart cycles), so identical values in the cells of the table are not improbable (e.g. pNN0_20 = 30 % means that 16 of 54 DSHP lie between 0 and 20 ms).

The effect of fiducial point designation was also analyzed in recordings, where only ECG in Einthoven II lead was recorded. Recordings from one healthy senior adult (HSA) and one healthy young adult (HYA) were used. The difference between heart periods calculated based on R-peaks and the onset of P-waves (tRR-tPP) for one recording of the senior adult is plotted in Figure 3.

TABLE I. pNN0_20, pNN20_50 AND pNN50 VALUES CALCULATED BASED ON DIFFERENT FIDUCIAL POINTS

	pNN0_20 (%)	pNN20_50 (%)	pNN50 (%)
tRR	32	46	22
tPP	30	46	24
tOnOn	30	40	30

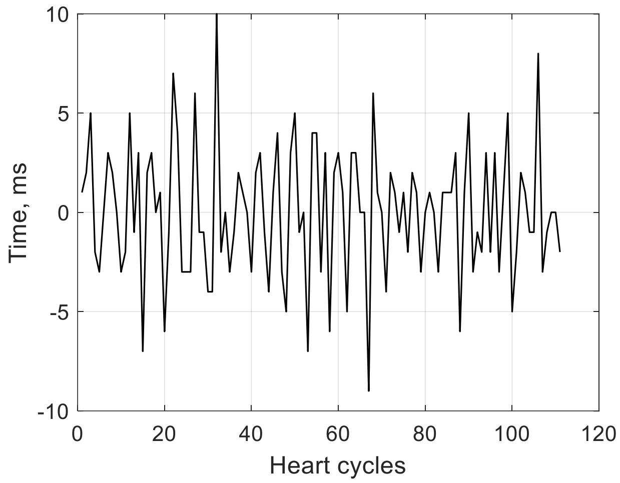

Fig. 3. The difference between heart periods calculated based on R-peaks and the onset of P-waves (tRR-tPP) for one recording of the senior adult.

The average difference in pNN0_20, pNN20_50 and pNN50 values calculated based on R-peaks and P-wave onset points was also calculated. The results are shown in Table II.

TABLE II. AVERAGE DIFFERENCE IN pNN0_20, pNN20_50 AND pNN50 VALUES CALCULATED BASED ON R-PEAKS AND P-WAVE ONSET POINTS

	Diff(pNN0_20) (%)	Diff(pNN20_50) (%)	Diff(pNN50) (%)
HSA	2	2	0
HYA	2	1	1

B. The Effect of Physical Stress on HRV

The pNN0_20, pNN20_50 and pNN50 values were calculated for measurements recorded before and after short physical stress was induced for the tested person. Values were calculated based on both R-peaks and the onset of P-waves. Table III shows the calculated values for both conditions, before stress (Pre) and after stress (Post) based on tRR and tPP, for the healthy senior adult (HSA) and for the healthy young adult (HYA).

In order to investigate the change in the conduction time through the atrioventricular node during regeneration after physical stress, the P-peak-R-peak interval was also calculated. We used the interval between peaks instead of the commonly used P-R interval because the detection of peaks is more robust than the detection of onset points. Figure 4 shows the calculated intervals for both tested persons.

TABLE III. pNN0_20, pNN20_50 AND pNN50 VALUES CALCULATED BEFORE AND AFTER SHORT PHYSICAL STRESS

	pNN0_20 (%)		pNN20_50 (%)		pNN50 (%)	
	Pre	**Post**	**Pre**	**Post**	**Pre**	**Post**
tRR, HSA	56	36	43	48	1	16
tPP, HSA	49	30	50	44	1	26
tRR, HYA	10	8	27	16	63	76
tPP, HYA	10	8	30	14	60	78

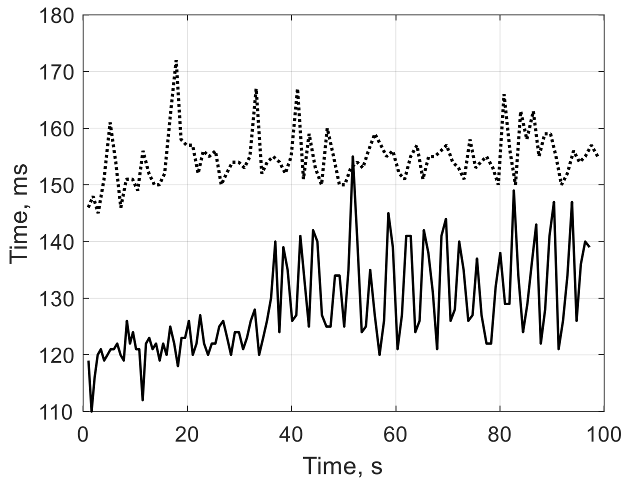

Fig. 4. P-peak-R-peak intevals after short physical stress for the healthy senior adult (solid line) and the healthy young adult (dotted line).

IV. DISCUSSION

The difference in the pNN0_20, pNN20_50 and pNN50 values is less than 2 % if R-peaks and P-wave onsets are compared in the clinical recording. However, if R-peaks in the ECG and the onset of atrial activity in the EGM are compared, the difference is more that 5 % for the pNN20_50 and pNN50 parameters. In the previous study [12], pNN0_20, pNN20_50 and pNN50 values were determined in different physical and psychical conditions. According to the results in [12], 5 % difference can mask the change in stress level between certain conditions.

Recordings from the measurement series, where only ECG in Einthoven II lead was recorded yielded similar results to the clinical recording with respect to the pNN0_20, pNN20_50 and pNN50 differences between R-peak- and P-wave onset-based calculations. The very small difference in pNN50 of the healthy senior adult is in accordance with the fact, that the number of DSHP that exceed 50 ms can be very small for senior adults. It can be even zero for a short recording.

Physical stress has different effect on the pNN0_20, pNN20_50 and pNN50 parameters. For pNN50, physical stress increased values by more than 10 % for both tested persons. The pNN0_20 decreased for both persons, but for the young adult, the amount of decrease is less than 2 %. The pNN20_50 decreased as a result of physical stress by more than 10 % for the young adult and decreased or increased for the senior adult depending on whether R-peaks or P-wave onsets were used for the calculation. The effect of fiducial point designation resulted in differences smaller than 5 % for all parameters in case of the young adult. For the senior adult, differences larger than 5 % appeared for both conditions in the pNN0_20 parameter, before physical stress in the pNN20_50 parameter and after physical stress in the pNN50 parameter. Moreover, the effect of physical stress on the pNN20_50 parameter is an increase if the calculation is based on R-peaks and a decrease if the calculation is based on the onset of P-waves. This result demonstrates that the effect of fiducial point designation can mask the change in stress level between different conditions.

The P-peak-R-peak intervals after short physical stress show an upward trend for the healthy senior adult, with more than 40 ms difference between the shortest and longest interval in the recording. For the healthy young adult, the upward trend can be observed only in the first 20 seconds but the difference between the shortest and longest interval is more than 25 ms. This result suggests that the conduction time through the atrioventricular node during regeneration after physical stress can change significantly in time. Thus, the effect of fiducial point designation on the calculated heart periods is not stable for a person-specific time interval after physical stress.

Interpretation of the results requires consideration of the accuracy of methods used to detect characteristic points in the ECG signal. The accuracy of the method we used for R-peak detection was assessed in [10]. The mean absolute error and standard deviation for a simulated noisy ECG signal were below 1 ms. Although the method was not evaluated on standard databases, we can expect similar results for real recordings because the SNR of the simulated signal was lower than that of most real ECG signals. The accuracy of the method we used for the detection of the onset of P-waves was assessed in [9]. The reported mean and standard deviation of the error of P-wave onset detection is 2.0 ± 14.8 ms for the QT database [7] and -4.9 ± 5.4 ms for the CSE database [13]. These error values are comparable to the effect of fiducial point designation on the heart period calculation (see Figure 3). Therefore, in case of recordings, where no intracardiac signal is available, heart period values based on the onset of P-waves must be handled carefully. R-peaks can be designated more accurately than P-wave onsets, however, the onset of the P-wave is physiologically more appropriate to define heart cycles. Further measurements and cooperation with medical experts can help to define HRV metrics using the information in both tRR and tPP for more accurate assessment of actual stress level.

V. Conclusion

Stress level of the examined person can have a large impact on the accuracy of blood pressure measurement. In this paper we investigated the effect of fiducial point designation on the calculation of HRV. The pNN0_20, pNN20_50 and the pNN50 parameters were investigated. Our results show that using the onset of P-waves in the surface ECG instead of R-peaks can lead to more than 5 % difference in the calculated values and may result in significant differences in stress level assessment. However, the inaccuracy of existing methods for the delineation of P-waves is comparable to the effect of fiducial point designation on heart period calculation. Further research work is needed to improve the accuracy of methods to detect characteristic points in the ECG signal and to assess actual stress level.

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