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Is 50 Hz High Enough ECG Sampling Frequency for Accurate HRV Analysis?*

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Abstract— With the worldwide growth of mobile wireless technologies, healthcare services can be provided at anytime and anywhere. Usage of wearable wireless physiological monitoring system has been extensively increasing during the last decade. These mobile devices can continuously measure e.g. the heart activity and wirelessly transfer the data to the mobile phone of the patient. One of the significant restrictions for these devices is usage of energy, which leads to requiring low sampling rate. This article is presented in order to investigate the lowest adequate sampling frequency of ECG signal, for achieving accurate enough time domain heart rate variability (HRV) parameters. For this purpose the ECG signals originally measured with high 5 kHz sampling rate were down-sampled to simulate the measurement with lower sampling rate. Down-sampling loses information, decreases temporal accuracy, which was then restored by interpolating the signals to their original sampling rates. The HRV parameters obtained from the ECG signals with lower sampling rates were compared. The results represent that even when the sampling rate of ECG signal is equal to 50 Hz, the HRV parameters are almost accurate with a reasonable error.

I. INTRODUCTION

Heart rate variability (HRV) analysis has become a non-invasive tool for studying the operation of autonomic nervous system. The analysis of beat-to-beat heart rate can be approached in several ways such as time domain analysis, spectral analysis and non-linear analyses. The first step in analyzing HRV, is measuring the time intervals between consecutive R-peaks of the electrocardiogram (ECG) signal. In order to reach reliable results, signal acquisition and processing methods, such as sampling rate of the ECG signal must be properly chosen.

A low sampling rate may decline the accuracy in detection of R-wave fiducial points, which causes changes in the heart rate variability parameters. According to a previous research, the optimal range of sampling rate for spectral analysis of HRV parameters is between 250 and 500 Hz or even higher [1]. However, due to deterministic nature of the ECG signal, interpolation techniques can be used until some extent to restore its original waveform and improve the temporal as well as amplitude accuracy of searched fiducial points. In the study of Merri et al. was shown that lower sampling rate may behave satisfactorily only if an appropriate algorithm of

interpolation is used to estimate the original R-wave fiducial points [2].

Garcia-Gonzalez et al. showed in [3], by using relatively low ECG sampling rate of 125 Hz, that a bias error as well as uncertainty in frequency domain HRV parameters HF and HF/LF are highly dependent on the accuracy of the R-peak detection, especially when the HRV is very small.

The effect of different ECG sampling frequencies on the spectral parameters of HRV were also evaluated by Ziemssen et al. in [4]. In their study the original ECG sampling frequency was 500 Hz and the simulated sampling frequencies were 200 and 100 Hz.

In contrast to the result of Garcia-Gonzalez et al., Ziemssen et al. concluded that there is not any significant impact on spectral parameters for ECG with lower sampling frequencies. However, they showed that if there is a pathologically decreased variability in RR intervals (RRIs) in patients, spectral parameters could be significantly influenced when lower ECG sampling frequencies.

In [5], Hejjel and Roth have studied the consequences of digitization errors on the time domain HRV parameters. They resampled model tachograms with different ratios and compared the obtained HRV parameters. They have argued that the optimum sampling rate for ECG signal to get accurate time domain HRV parameter without interpolation is 1 kHz. They noticed that beyond time domain HRV parameter, pNN50 presents the poorest accuracy and precision by decreasing ECG sampling interval.

In this article, the influence of different sampling rates of the ECG signal on certain time domain heart rate variability parameters is studied. Especially, it is tried to conclude what would be the lowest reasonable sampling rate that still produces adequate HRV accuracy. It is shown that even as low as 50 Hz sampling rate may be adequate for obtaining time domain HRV parameters with reasonable accuracy.

Motivation for trying to find the lowest possible ECG sampling rate that still enables accurate HRV analysis is the increased interest towards small, wearable and networked physiological monitoring devices, which commonly are strongly energy limited. In general, these devices benefit from low sampling rate, especially if the application requires transmitting the whole ECG signal to a receiver where a cardiologist usually needs to make a visual inspection in addition to HRV parameters.

II. Materials and Methods

A. Signal Database

- Combined measurement of ECG, breathing and seismocardiogram (CEBS) Database consisting 60 records from 20 healthy volunteers was used in the evaluation. The records have been acquired in supine position using a Biopac MP36 data acquisition system (Santa Barbara, CA, USA). Channels 1 and 2 of the system were devoted to measure conventional ECG (leads I and II, respectively) with a bandwidth between 0.05 Hz and 150 Hz. Each channel has been sampled at 5 kHz. In this work, lead II ECG signals with 5-minute length were used. The main reason for choosing this database was the high sampling rate and resolution of the ECG signals, which enables comparison between the HRV parameter calculated from high quality signal and signals resampled to lower sampling rates. The CEBS database is publicly available at Physionet database archive [6].

- A high-noise ECG signal was recorded at Department of Automation Science and Engineering of Tampere University of Technology, to demonstrate the effect of using the same sampling rate as the dominating frequency of external interference. The sampling rate of the signal was 250 Hz and the pass-band of the analog filters of the ECG amplifier was 0.5 - 40 Hz. This recording contains significant amounts of 50 Hz power-line interference. The purpose of this measurement was studying the effect of down-sampling the ECG signal with power-line interference on its HRV parameters.

From CEBS Database, for every subject, firstly the ECG signal was down-sampled by different ratios to create signals that demonstrate ECG recorded with different sampling rates. The further procedures are described in the following:

B. Signal Down-sampling

To evaluate the impact of low sampling rate on heart rate variability components, the CEBS signals were down-sampled by factor 10, 20, 25, 32, 40, 50, 80, 100 and 125. Since the CEBS signals were originally sampled at 5 kHz, then the down-sampled ECG signals were sampled at 500, 250, 200, 156.5, 125, 100, 62.5, 50 and 40 Hz, respectively.

It should be noted that decimation requires an anti-aliasing filter before it to avoid overlapping of replicated signals in frequency domain. Therefore, an 8-order Butterworth low-pass filter with cut-off $f_s/(2*factor)$ (f_s is sampling frequency and *factor* is ratio of down-sampling for each down-sampled signal) was applied on the original ECG signal before down-sampling to prevent aliasing.

C. Interpolation

A common way for improving the QRS detection accuracy is using R-wave interpolation. Cristov and Daskalov showed in [7] by using the cubic interpolation a resolution of 1 ms and deviation of ± 1 ms was achieved in more than 99% of the RR intervals for the sampling rate of 250 Hz compared to the original 1 kHz sampling rate. For the worst cases with 100 Hz sampling rate, the same resolution was preserved in 90.5% of the RR intervals. In this work a cubic interpolation method was used to produce sampling rate equal to 5 kHz.

It is worth mentioning that for a healthy person the shape of the R-wave is close to symmetric in which case cubic spline method can estimate R-peak location with sufficient accuracy from down-sampled ECG signals. But generally the shape of the R-wave can be altered as a result of certain cardiovascular diseases. Thus, the shape of the R-wave may be clearly non-symmetric which causes cubic spline interpolation to be less accurate.

D. QRS Detection

A well-known QRS detection algorithm proposed by Pan and Tompkins in 1985 was applied on the original and down-sampled ECG signals to detect the R-wave fiducial points [8]. The Pan-Tompkins method recognizes QRS complexes based on analyses of the slope, amplitude, and width. The algorithm includes filtering, derivative, squaring and integration steps.

First of all, a band-pass filter reduces T wave interference, baseline drift and power-line interference, if present. Then, derivative procedure suppresses the low frequency components of P and T waves, and provides a large gain to the high-frequency components arising from high slopes of QRS complex. The squaring operation emphasizes on high-frequency components in the signal that related to QRS complex. At the end, the squared waveform passes through a moving window integrator. Since rising edge of the integration waveform corresponds to QRS complex then the fiducial point can be determind as the peak of the R-wave [8] and [9].

Eventually, by obtaining the R-wave fiducial points, the RR intervals for each signal were calculated as the time intervals between successive R peaks of the ECG signal.

E. Time Domain HRV Parameters

To compare the heart rate variability indices between original ECG signal and down-sampled versions of it, some widely used linear and non-linear time domain parameters were calculated. The parameters were implemented based on their standard definitions in [10] as following:

- SDNN: Standard deviation of all RR intervals
- RMSSD: Root mean-square of successive differences of adjacent RR intervals
- pNN50: Percentage of pairs of adjacent RR intervals differing by more than 50 ms from all RRIs
- SD1: Standard deviation of data against the axis x = y in Poincaré plot
- SD2: Standard deviation of data against the axis, which is orthogonal to the axis x = y in Poincaré plot (crosses this axis at the mean value of the data)

Poincaré plot is constructed by plotting the RRI as a function of itself with a delay of 1 sample.

Signal processing was done with MATLAB software (R2014b) from MathWorks Inc., Natick, MA, USA. The

TABLE I

| ECG Signal	SDNN (ms)	RMSSD (ms)	pNN50 (%)	SD1 (ms)	SD2 (ms)
Sampled at 5 kHz (Original)	53.6499	50.5568	36.2745	35.8061	66.7802
Sampled at 500 Hz	53.6499	50.5568	36.2745	35.8061	66.7802
Sampled at 250 Hz	53.6502	50.5593	36.2745	35.8078	66.7798
Sampled at 200 Hz	53.6506	50.5605	36.2745	35.8087	66.7800
Sampled at 156.5 Hz	53.6515	50.5624	36.2745	35.8100	66.7807
Sampled at 125 Hz	53.6512	50.5603	36.2745	35.8085	66.7810
Sampled at 100 Hz	53.6526	50.5632	36.2745	35.8106	66.7821
Sampled at 62.5 Hz	53.6522	50.5659	36.2745	35.8125	66.7813
Sampled at 50 Hz	53.6495	50.5802	36.6013	35.8226	66.7707
Sampled at 40 Hz	53.6481	50.5172	35.9477	35.7780	66.7916
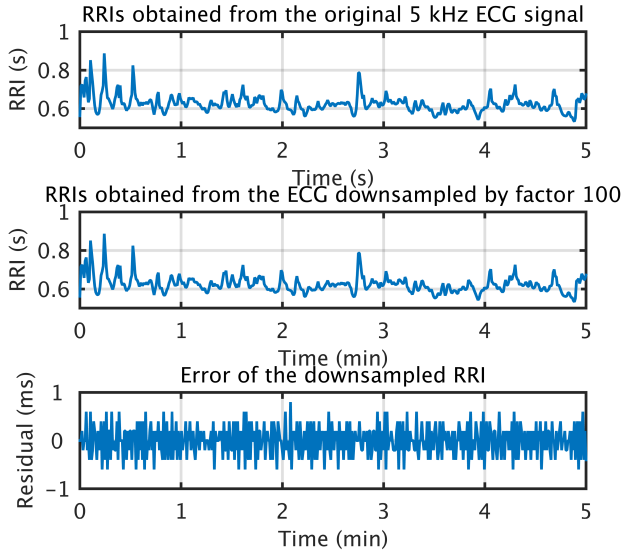
Fig. 1. RR Intervals for subject b002, top: obtained from original ECG (sampled at 5 kHz), middle: obtained from down-sampled ECG (sampled at 50 Hz), bottom: difference of above RRIs

accuracy and precision of heart rate variability parameters that were computed by our method were validated with Kubios software, which is an open license HRV analysis software developed in Univerty of Kuopio, Finland. [11].

III. RESULT AND DISCUSSION

Certain time domain HRV parameters were separately analyzed for every subject of CEBS database. Fig. 1 from top to bottom, shows the RRIs obtained from the original, the resampled ECG signal of subject b002, and the difference between these two RRIs, respectively. It is seen that even when the time resolution of the signal sampled with 50 Hz is 20 ms, the R-peak locations can be approximated by interpolating with such accuracy that the maximum absolute error of RR-interval is less than 1 ms. Furthermore, the mean absolute error (MAE) and root mean squared error (RMSE) are computed for RRIs which for this subject are equal to 2.6906×10^{-4} ms and 3.2945×10^{-4} ms, respectively.

In Table I, the HRV parameters introduced in previous

section are presented for subject b002, which were computed from the original and the down-sampled ECG signals by different rates. The results of Table I confirm that HRV parameters of the down-sampled ECG signals with much lower sampling rate than their original (5 kHz) and then interpolated, can still be retained accurate with a reasonable error. For this subject, even with 40 Hz sampling rate, the error of the HRV parameters is very small.

For the measured noisy ECG signal, which was only down-sampled by factor 5, all the procedure mentioned in the method section was performed except applying the anti-aliasing filter. Because when the sampling rate is exactly the same as the frequency of the interference, the interference is aliased to 0 Hz frequency, causing only a DC offset to the signal. Also, a little mismatch in these frequencies is tolerable because a small difference introduces a slowly varying component, which is similar to baseline wandering, to the observed signal. This component can be removed by high-pass filtering in normal ECG processing.

In Fig. 2, on the left-top panel, short piece of the measured ECG signal recorded at 250 Hz including power-line inter-ference and left-bottom panel the resampled ECG signal are shown. On the right side, their power spectra are illustrated. Furthermore, HRV parameters were computed for this signal as well, that resulted in less than 1% relative error for all the HRV indices except pNN50. pNN50 represents the poorest accuracy with the relative error 30%. Eventually, it can be seen that how well the 50 Hz peak is removed by down-sampling the noisy ECG signal (sampled at 250) with factor 5, while due to interpolation, the HRV parameters except pNN50 are assessed with acceptable error. It should be mentioned that due to the interpolation, there is some power also above 25 Hz in the bottom-right power spectrum.

Results displayed in Table II indicate HRV parameters for 5 different subjects from CEBS database. HRV indices were computed from their original ECG signals (sampled at 5 kHz) and the down-sampled signals (sampled at 50 Hz). In addition, the relative error of each parameter was calculated for every subject. By studying the average of relative errors for HRV parameters beyond all the 5 subjects, it can be concluded that SDNN, RMSSD, SD1 and SD2 are accurate with less than 1% error and pNN50 with 1.21% error for the interpolated ECG signal that was down-sampled to 50 Hz.

| Data		SDNN (ms)	RMSSD (ms)	pNN50 (%)	SD1 (ms)	SD2 (ms)
Subject b002	Actual	53.6499	50.5568	36.2745	35.8061	66.7802
	Measured	53.6495	50.5802	36.6013	35.8226	66.7707
	Relative Error (%)	0.00	0.05	0.90	0.05	0.01
Subject b003	Actual	47.3965	48.1750	34.6821	34.1142	57.6912
	Measured	47.3992	48.1640	34.9711	34.1064	57.6997
	Relative Error (%)	0.01	0.02	0.83	0.02	0.01
Subject b005	Actual	39.0200	38.2400	19.9400	27.0800	48.1400
	Measured	38.0200	38.2300	20.4986	27.0716	48.1352
	Relative Error (%)	2.58	0.02	2.78	0.02	0.01
Subject b006	Actual	83.0377	59.0071	42.8571	41.7920	109.7308
	Measured	83.0524	59.0492	43.5065	41.8219	109.7415
	Relative Error (%)	0.02	0.07	1.52	0.07	0.01
Subject b008	Actual	43.2183	28.3448	7.1130	20.0632	57.6890
	Measured	43.2017	28.3118	7.1130	20.0398	57.6714
	Relative Error (%)	0.04	0.12	0.00	0.12	0.03
	Mean Relative Error (%)	0.53	0.06	1.21	0.06	0.02
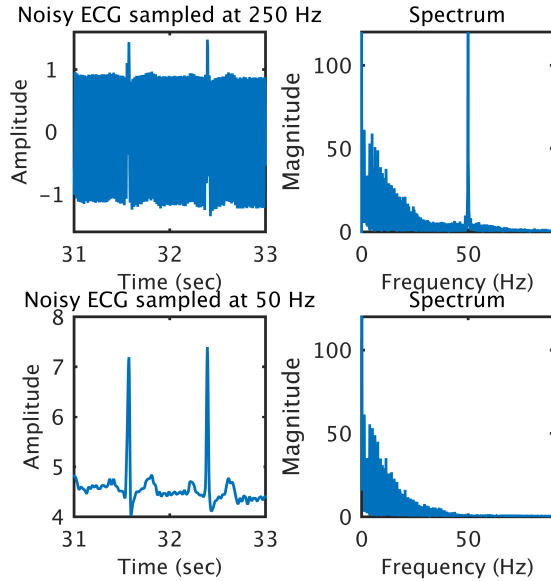
Fig. 2. ECG with power line interference, top-left: short piece of noisy ECG, top-right: power spectrum of the noisy ECG, bottom-left: short piece of down-sampled noisy ECG by factor 5 that was interpolated back to 250 Hz, bottom-right: power spectrum of the down-sampled noisy ECG by factor 5 that was interpolated back to 250 Hz

IV. CONCLUSIONS

It was shown that as low as 50 Hz sampling rate could be used for measuring the ECG signal without compromising the accuracy of the calculated time domain HRV parameters. However, the ECG and especially R-peak waveform is slightly distorted and it should be investigated in the future how much this affects to other ECG parameters than HRV and what would be the minimum sampling rate that produces adequate signal quality for the visual inspection.

The study was performed with database consisting ECG signals recorded from healthy subjects. An important part of the future work is to evaluate the adequacy of 50 Hz sampling rate for patients suffering from cardiac problems and people having decresed heart rate variability.

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