The optimal sampling frequency of the photoplethysmogram for heart rate variability analysis

Doctoral (PhD) Theses

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Introduction

Heart rate variability (HRV) analysis deals with the examination of the delicate oscillations of the time intervals (RR-intervals, RRI) between the reference points of successive cardiac cycles. Under physiological conditions, mainly the autonomic nervous system (ANS) controls the heart rate changes via the sinus node, therefore HRV analysis can be used for the non-invasive investigation of the ANS.

Thanks to the advances in digital signal processing, an exponentially increasing number of clinical studies have investigated the HRV since the 1970's. They recognized its prognostic value in acute myocardial infarction, arrhythmias, dilated cardiomyopathy, diabetes mellitus, and in several other non-cardiac diseases. Today it is considered an independent risk factor for disease progression and mortality in numerous pathologies.

HRV analysis can be approached also from the pulse wave recorded by photoplethysmography (PPG), which is called pulse rate variability (PRV) analysis. Smart devices (such as mobile phones, smart watches, smart bracelets, etc.), with the built-in special optical unit, are widely available now in everyday life. They are mainly used to estimate heart rate and detect rhythm disorders. Currently, there is no clear consensus on whether HRV analysis can generally be replaced by PRV analysis, although under certain conditions, PPG can be used instead of ECG.

There are short-term (5-minute-long) and long-term (16–24 hours) HRV analyses discerned. The HRV indices can be divided into three main classes: time domain, frequency domain, and nonlinear parameters. The most common is the time domain analysis, including the average RRI or PPI (MeanNN – mean normal-to-normal interval, MPPI – mean PPI), the SDNN (standard deviation of the normal-to-normal intervals), the RMSSD (root mean square of successive interval-differences), as well as SD1 (standard deviation along the short axis) and SD2 (standard deviation along the long axis) both based on the Poincaré-plot. The parameters in the frequency domain contain the integrals of the high frequency band (HF, 0.15-0.4 Hz), the low frequency band (LF, 0.04-0.15 Hz), the very low frequency band (VLF, 0.0033-0.04 Hz), the ultra-low frequency band (ULF, $\leq$ 0.003 Hz), and the LF/HF ratio. The VLF and ULF are used exclusively in the long-term analysis. The clinically less common non-linear parameters describe the complexity and predictability of the RRI or PPI time series (tachogram): e.g. entropies, fractal dimension, Lyapunov-exponent, or the shape of the Poincaré-diagram.

A relatively new set of parameters are the heart rate asymmetry indices (HRA, e.g. Guzik index, Porta index), which quantitatively characterizes the ratio between the acceleration and deceleration episodes of heart rate. Nowadays, the use of ECG for the extramural investigation of heart rate and HRV parameters is being replaced by PPG technology. The latter is quite easily accessible and it is more convenient for the user, since the PPG signal can be acquired through a single contact point by a tiny optical device without the need of a closed electrical circuit like at the ECG. The PRV analysis is reasonable exclusively in normal sinus rhythm similarly to HRV assessment; however, in the absence of the ECG signal, one can suspect a rhythm disorder from the elevated pulse rate or SDNN and the high number of outliers in the tachogram.

The ECG and PPG signals are mathematically continuous both in time and in amplitude, in other words, they are analog signals that are not directly suitable for digital processing, and thus digitization (analog-to-digital converting) is necessary. According to the Nyquist theorem, the sampling frequency must be at least twice the highest frequency component of the analog signal in order to preserve the essential information of the original signal. Otherwise, the aliasing phenomenon will occur, which can cause significant signal distortion on the digital side. The adequate temporal resolution (sampling interval) is also critical for HRV/PRV analysis. The insufficient temporal resolution can be improved by interpolation, a mathematical method inserting intermediate point(s) between the existing discrete points, consequently reducing the sampling error that is proportional to the temporal resolution. Accurate determining of the beat-to-beat cycle lengths (RRI, PPI) is essential for reliable HRV/PRV analysis (Figure 1). It is critical to find the optimal sampling frequency and possible interpolation on the given wearable platform to assure the required accuracy of RRI or PPI detection with the lowest energy consumption, extending its availability with one battery charge.

According to the Task Force (Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology, Circulation, 1996, 93: 1043-1065), a 250-500 Hz sampling frequency of the ECG signal is required without interpolation for reliable HRV measurement. With an appropriate interpolation method, 100 Hz sampling frequency can be sufficient for accurate QRS reference point (fiducial point) detection. Our previous investigations demonstrated that 1 kHz sampling of the ECG assures correct HRV analysis even in case of seriously reduced variability series.

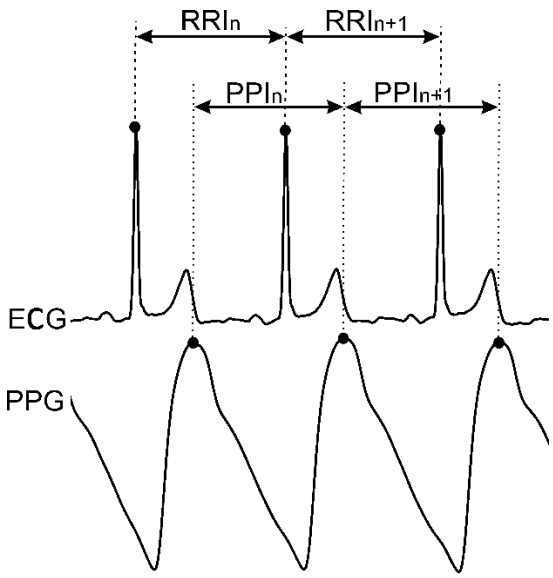

Figure 1. The upper part shows the detection of the R-waves of the ECG signal and RRI calculation, the lower part is on the peak detection of PPG wave and PPI formation. (In practice, the detection is frequently at the half amplitude level of the ascending slope or at the peak of the derived signal.) ECG – electrocardiogram, PPG – photoplethysmogram, PPI – PP-interval, RRI – RR-interval.

Several studies investigated the effect of the sampling frequency on the HRV/PRV accuracy; usually 50-1000 Hz sampling is recommended depending on the population and other circumstances, however one paper concluded that as low as 25 Hz sampling frequency may be sufficient for accurate PRV analysis, additionally without interpolation. These studies highlight that there is no consensus regarding the minimal, still appropriate sampling frequency for PPG signal acquisition for reliable HRV/PRV measures. A relatively low sampling frequency is proper to determine the average heart rate even without interpolation, but a higher sampling frequency is needed to calculate the HRV/PRV parameters. In wearable devices, the possibly lowest sampling interval is crucial, since the operating time of the given device with one charge can be extended, however, the accuracy of the measurement cannot be sacrificed. The sampling frequency can be reduced in case of subsequent interpolation techniques, though the complex computations can lead to higher energy consumption at the microprocessor.

Aims

1. Creating an *in silico* model of variable PPG signals with predefined parameters, and recording high-resolution simultaneous ECG and PPG signals from healthy volunteers

2. Defining the minimally required sampling rate by decimation in order to get accurate mean heart rate from *in silico* and *in vivo* PPG signals

3. Defining the minimally required sampling rate by decimation in order to get accurate PRV parameters from *in silico* and *in vivo* PPG signals

4. Defining the minimally required sampling frequency in order to get accurate PRV parameters from decimated *in silico* and *in vivo* PPG signals after interpolation

5. Comparing parabola approximation and cubic spline interpolation in terms of their accuracy and computational speed, the latter affecting power consumption

Methods

In silico photoplethysmogram analysis

We generated four PPG waves of five-minute lengths with 1 kHz temporal resolution. The PPG signals with sinus arrhythmia were modeled as a sinusoidally narrow-band frequency-modulated cosine wave with OriginPro 2017 software (OriginLab Corp., MA) using the following equation (Eq 1.), where *t* is an independent variable in ms:

$$PPI[t] = A + A \times \cos\left[\frac{2\pi}{PPI_{mean}} t + \frac{f_{dev}}{f_{mod}} \sin\left(2\pi \times \frac{f_{mod}}{1000} t\right)\right] \quad \text{(Eq 1.)}$$

The mean pulse rate (PPI_{mean}) was set to 937ms equivalent to 1.067 Hz carrier frequency, that means 64.03 beat/minute average heart rate. The modulation frequency (f_{mod}) was 0.23 Hz in two PPG series imitating the respiratory sinus arrhythmia at 13.8 breath/minute, and in the other two signals it was chosen 0.11 Hz mimicking the low frequency band HRV. The maximum frequency deviation (f_{dev} or span) was 0.05 Hz and 0.01 Hz simulating normal and seriously reduced variability signals, respectively.

The four, 1 ms temporal resolution master (reference) PPG waves were decimated at 2, 5, 10, 20, 50, 100, 200, 303, 350, 400, and 500 ms, in other words, we degraded the temporal resolution of the signals, thus simulating the lower sampling frequencies. Each of the decimated signals was interpolated back to 1 ms resolution using cubic spline method. The master, decimated and interpolated PP-intervals were determined by simple positive peak detection, from the generated tachograms, the PRV analysis was performed with Varian v2.3 software developed by László Hejjel. The most frequently used time domain parameters of heart rate variability: MPPI, SDNN, RMSSD; the frequency domain parameters: HF and LF bands with the LF/HF ratio were calculated using the FFT method. The reliability of the parameters was evaluated with the relative accuracy error (RAE%) according to the following equation (Eq 2.):

$$RAE\% = \frac{X_{D/IP} - X_{MASTER}}{X_{MASTER}} \times 100\% \quad \text{(Eq 2.)}$$

where $X_{D/IP}$ is the actual parameter of the decimated or interpolated signals, X_{MASTER} is the actual parameter of the Master (reference) series. RAE<5% was considered acceptable. Visual assessment of the Poincaré-plot was used as a non-linear method.

Analysis of the human photoplethysmograms

In the study 31 young, healthy, and physically active volunteers were enrolled with 18 women and 13 men, their mean age was 24.8±2.6 years. The study was approved by the Regional Ethics Committee (approval number: 7535-PTE 2019). The volunteers were asked to refrain from smoking and alcohol consumption, coffee or caffeine-containing drinks four hours before the data acquisition. During the orthostatic adaptation period of 15 min, the subjects were equipped with the sensors, educated for the metronome-controlled breathing, and were informed again about the study principles. During the data acquisition, talking and movements were prohibited. Four 5-minute-long signals were obtained from each participant with four breathing patterns: 1. spontaneous breathing, 2. inspiration triggered at 4500 ms period, 3. inspiration-expiration triggered at 1:1 ratio, 4. inspiration-expiration triggered at 1:2 ratio at 4500 ms cycle length, resulting in altogether 124 files, which were stored in our database for further off-line analysis.

The BioSign HRV-Scanner plus Study version 3.05 (BioSign GmbH, Ottenhofen, Germany) was used for data acquisition. The ECG, PPG and respiratory signals were registered simultaneously. The sampling rates were 1000 Hz for ECG, 500 Hz for PPG and 50 Hz for respiratory signal. The PPG signal was interpolated to 1000 Hz by cubic spline method after 20 ms moving average filtering in HRVScan_Merge v2.1 special software developed by László Hejjel. After a careful visual assessment, n = 57 high-quality master PPG records with less than or equal to two missed beats in the associated decimated and interpolated series from 2 ms up to 200 ms decimation were selected for further analysis. The master PPG signals were decimated by 2, 5, 10, 20, 50, 100, 200 and 500 ms which means 500, 200, 100, 50, 20, 10, 5 and 2 Hz sampling frequency. The signals were then interpolated back to 1 ms resolution by cubic spline interpolation and parabola approximation before the PPIs were detected. The tachograms were created by simple positive peak detection, the HRV and HRA parameters, and the RAEs (Eq 2.) of the given parameters were computed. RAE below 5% is considered tolerable. The MPPI, SDNN and RMSSD were calculated as time domain parameters, the SD1

and SD2 as Poincaré-plot parameters, the Porta- and Guzik indices were also computed as Poincaré-plot based HRA parameters. For visual analysis we generated Poincaré-plots. The resulting total processing times of the interpolation and the peak-detection of master, decimated and interpolated series were assessed.

Results

In silico photoplethysmogram analysis

The peak detection found all 319 PPIs down to 5 Hz sampling frequency (200 ms), and 400 ms sampling rate (2.5 Hz) after interpolation in the *0.23 Hz modulated normal variability* (f_{dev}=0.05 Hz) series. The MPPI was within 5% RAE down to 3.3 Hz sampling frequency (303 ms), when interpolation was applied, even the sampling rate of 2.5 Hz (400 ms) was sufficient. Without interpolation, the SDNN required 50 Hz (20 ms) sampling, when we interpolated back to 1 ms, the RAE was within 5% down to 3.3 Hz sampling frequency (303 ms). The RMSSD was more sensitive to the low sampling rate: without interpolation a minimum of 100 Hz sampling frequency (i.e. 10 ms) was required (RAE=2.674%), whereas with interpolation 3.3 Hz (300 ms) was acceptable (RAE=0.321%).

In the *0.23 Hz modulated low variability* series (f_{dev}=0.01 Hz) with 3.3 Hz (303 ms) sampling, all peaks were found (n=319) accurately, interpolation improved detection down to 2.5 Hz (400 ms). The MPPI were similar to those seen in normal variability series. The SDNN showed worse reproducibility compared to the normal variability series: it requires 200 Hz (5 ms) sampling for accuracy on the contrary to the normal variability series with 50 Hz, while with interpolation, 10 Hz (100 ms) sampling is sufficient to maintain the RAE below 5%. The beat-to-beat variability parameter RMSSD was the most sensitive: without interpolation: it required 2 ms sampling (500 Hz) for accurate values (2 ms: RAE=1.56%, 5ms: RAE=6.789%), and 100 ms resolution (10 Hz) when interpolation was applied.

In the *0.11 Hz modulated series with normal span* (f_{dev}=0.05 Hz), similar results were obtained as for the 0.23 Hz modulated series, except the RMSSD parameter, where a higher sampling frequency was required (without interpolation 200 Hz, with interpolation 10 Hz).

In the *0.11 Hz modulated low span* group, the SDNN needed similar sampling intervals to the one with 0.23 Hz modulation and f_{dev}=0.01 Hz span. The RMSSD could not be reproduced within RAE<5% even at 500 Hz sampling frequency.

The 0.23 Hz modulated signal contains exclusively high frequency (HF) band component, whereas the 0.11 Hz modulated series includes just the low frequency (LF) band. In the *0.23 Hz modulated normal variability* signals, the HFNU parameter is accurate down to 100 ms sampling interval, with interpolation down to 400 ms. In the *0.01 Hz span* group, 350 ms resolution is required without interpolation to assure RAE below 5%, with interpolation 400

ms sampling rate was enough. In the *0.11 Hz modulated normal variability* series, the LFNU is still accurate at 20 ms sampling interval; when interpolation is applied, 200 ms sampling can be sufficient. In low variability series 5 ms sampling is needed for accurate results; with interpolation, the sampling interval can be up to 303 ms.

The Poincaré-plot analysis showed that at least 2 ms decimation without interpolation is required to obtain a visually acceptable shape of the cloud nearly identical to the master signal; a lower resolution gives a rasterized set. The fine structure of the Poincaré-plot can be successfully restored at down to 100 ms sampling, whereas it cannot be restored at all at 200 ms or higher sampling intervals even by interpolation, despite the fact that the time domain parameters are accurately reconstructed by interpolation down to 303 ms decimation.

Analysis of the human photoplethysmograms

Figure 2 illustrates the peak region of the master, 50 ms decimated and then interpolated PPG signals with the corresponding tachograms. The error resulting from the inferior temporal resolution of the decimated signal is clearly visible (showed by the arrow at the peak region), as well as the recovery of the peak due to interpolation.

We detected an average of 370 beats/record in the selected n=57 five-minute-long PPG signals. The RAE of the number of detected beats was below 1% except at 500 ms sampling rate and its interpolation and parabola approximation. The MPPI was also within 5% RAE down to 200 ms (5 Hz) sampling, and the 500 ms decimation series cannot be restored with interpolation. The SDNN was accurate down to 20 ms sampling, which means 50 Hz sampling frequency. With cubic spline and parabola interpolation, 10 Hz (100 ms) decimation gives a RAE still below 5% (4.45% and 3.95%, respectively). The RAE of the sensitive RMSSD parameter remained within 5% at 20 ms (50 Hz) decimation, whereas with interpolation 50 ms (20 Hz) sampling rate is sufficient at this measure.

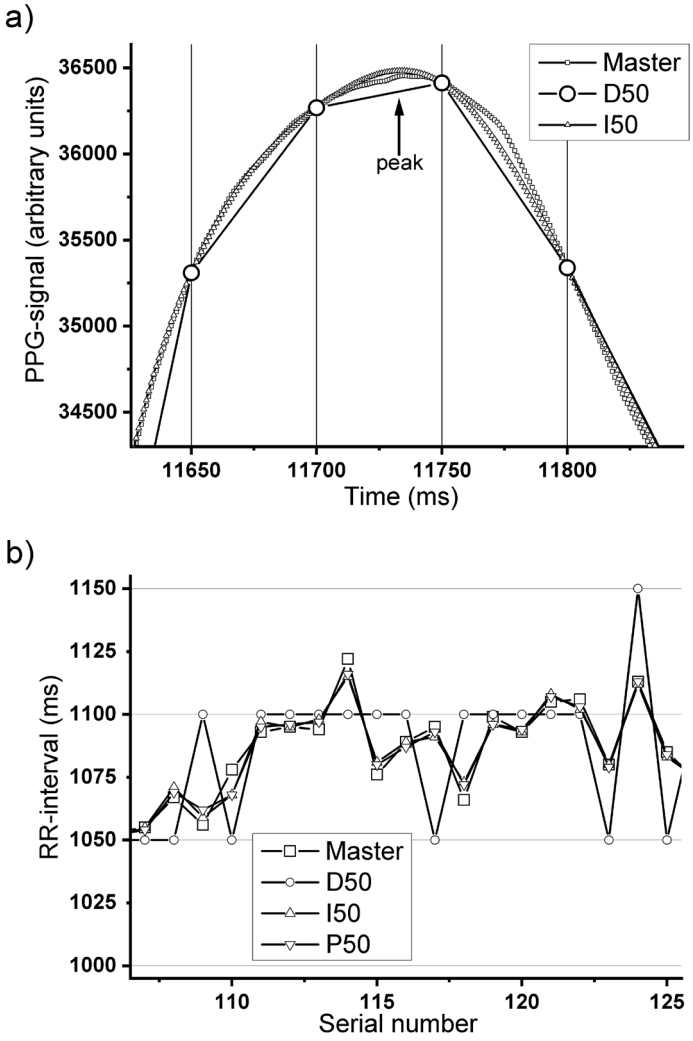

*Figure 2. The peak region of the reference (**Master**), 50 ms decimated (**D50**) and cubic spline interpolated (**I50**) photoplethysmogram signals (**a**), and the corresponding tachograms (**b**). The tachogram was also computed by parabola approximation (**P50**), by definition, here there is no associated photoplethysmogram.*

SD1 is accurate down to 50 Hz sampling frequency, SD2 remained within 5% RAE down to 20 Hz sampling. The cubic spline and parabola interpolation methods improved the accuracy at the low resolution series: SD1 with interpolation is accurate down to 20 Hz sampling frequency; while 10 Hz is sufficient at SD2. Amongst the HRA parameters, the Guzik index is somewhat more sensitive to the low sampling rate compared to the Porta index. Without interpolation, the RAE was within 5% at 20 ms sampling interval at the Guzik index, whereas 50 ms sampling was required at the Porta index. With cubic spline interpolation 50 ms and 100 ms sampling rates are sufficient for Guzik and Porta indices, respectively. The parabola approximation also improved the accuracy at both parameters: down to 100 ms (10 Hz) sampling assures the RAE below 5%.

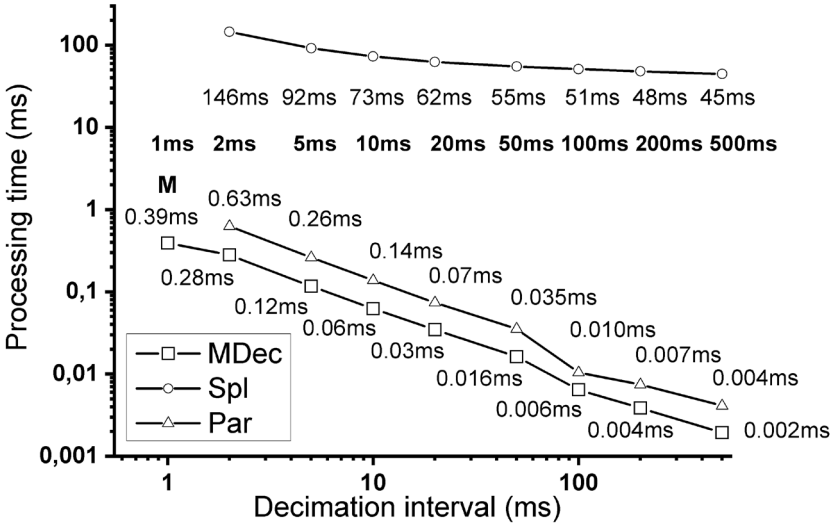

*Figure 3. The mean processing times (ms) for peak detection (and interpolation) in master and down sampled 5-minute series (**MDec**) at 2, 5, 10, 20, 50, 100, 200 and 500 ms sampling intervals, as well as in cubic spline interpolation (**Spl**) and parabola approximation series (**Par**).*

The mean processing time (Figure 3) of peak detection in master (1 ms resolution) signal was 0.39±0.017 ms. Lower sampling rates correspond to faster peak detection (i.e. less points to scan). Parabola approximation and peak detection requires about two times longer period at each corresponding sampling intervals. Cubic spline interpolation and peak detection needs significantly higher processing times (45-146 ms).

The Poincaré-plot analysis (Figure 4) shows that the shape of the cloud disappears completely at a sampling frequency of 10 Hz (100 ms), only a few points appear; but the interpolation restores the cloud almost perfectly. On the contrary, the original cloud shape cannot be recovered at all by interpolation in the 200 ms decimation series.

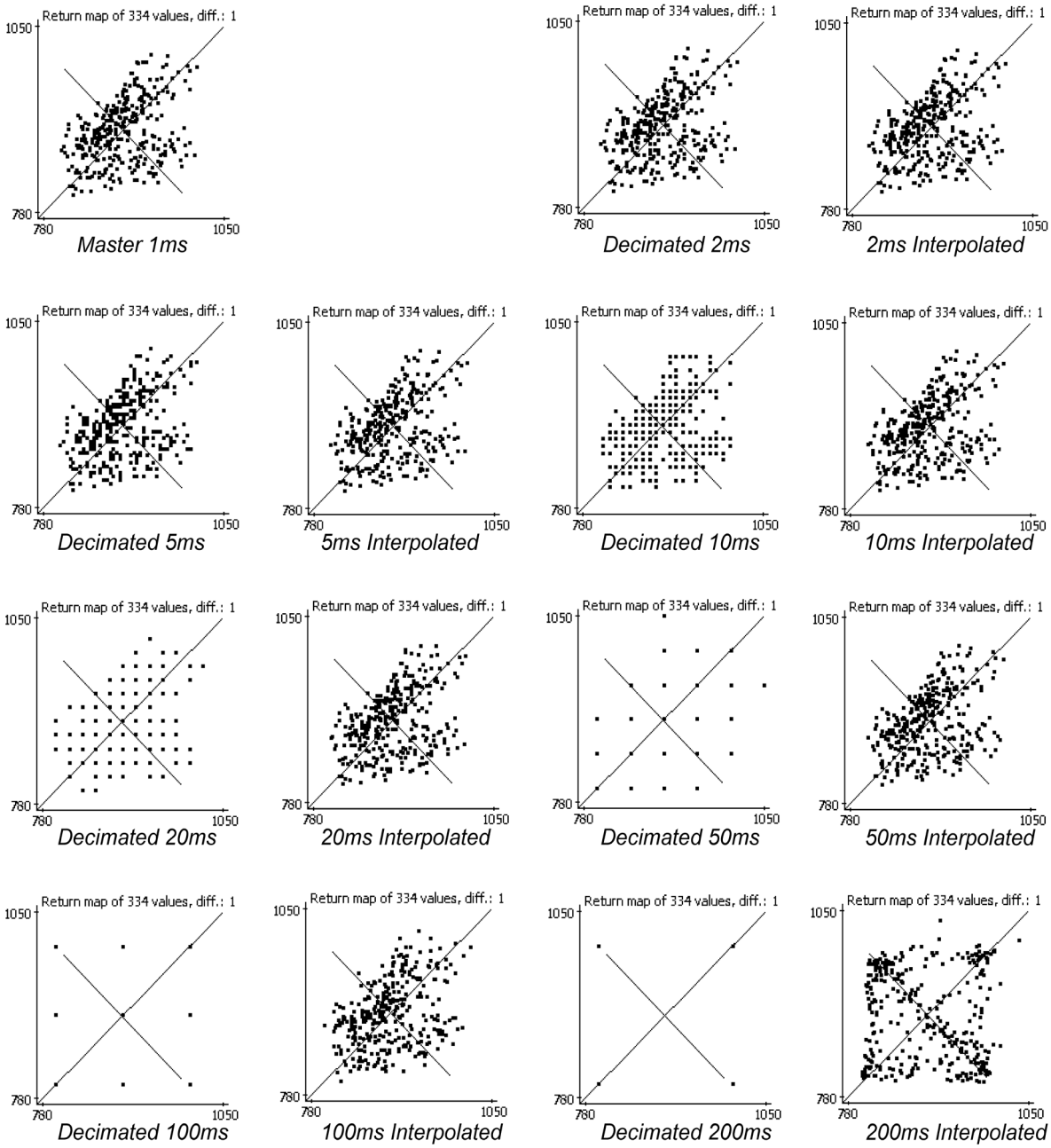

Figure 4. The Poincaré-plots from the tachograms of the master, the decimated and the cubic spline interpolated PPG signals of an individual. The coarse-grained pattern proportional to the temporal resolution and its recovery by interpolation is clearly demonstrated. The original scatter plot cannot be reconstructed at 200 ms (5 Hz) decimation. Note: the plots are saved from Varian v2.3 with its given spatial resolution.

Discussion

In our studies, we investigated the reproducibility of PRV parameters as a function of the sampling frequency on computer-generated PPG signals and on PPG recordings from healthy volunteers with normal variability. In the simulations, the variable PPG signals were modelled by sinusoidally narrow-band frequency-modulated cosine waves. Each sampling frequencies with the exception of the master series were imitated by decimation. The results of the computer-simulated PPG signal analysis reveals that several factors can affect the accuracy of the HRV parameters besides the sampling frequency: the intrinsic variability of the individual, the nature of the parameter chosen and the use of possible interpolation methods. Similar conclusions can be drawn when examining human records. Cubic spline interpolation or parabola approximation significantly improves the accuracy of HRV parameters obtained from PPG signals with poor temporal resolution – within certain limits.

Among the examined time domain parameters in both sections of the thesis, the most sensitive parameter to the sampling interval is the RMSSD measuring the beat-to-beat variability, followed by the SDNN indicating the global variability, and the most robust is the MPPI that almost completely eliminates the sampling error in the five-minute long recordings due to its zero average. By improving the resolution, the interpolation methods will obviously reduce the sampling error related to the uncertainty due to the poor resolution.

Table 1 provides a summary of the sampling intervals required to obtain a relative error below 5 % for the HRV parameters from the recordings of the simulation and from healthy volunteers. The synthesis clearly shows both the dependence on the specific parameter and the "improving" effect of interpolation. In Figure 5, the spectral components of the simulated and human PPG signals are shown. A striking difference between the two spectrograms is the uncertainty (blur) of each band in the human PPG; the synthetic PPG signal contains only the given frequency components and the given frequency modulation; therefore, the spectrogram is very sharp. The synthetic signal does not contain any harmonics since it is a pure sinusoidal fundamental harmonic, whereas the human PPG shows at least two harmonics since it is asymmetric. The simulated signal has constant amplitude, while the recorded signal has also a respiratory amplitude modulation, as shown by the small peak at 0.22 Hz.

Table 1. Maximum sampling intervals (SI) in ms sufficient to achieve RAE<5% of HRV parameters from simulated (0.23 Hz modulation, 0.05 Hz span) and in vivo recordings. MPPI – mean PPI, SDNN – standard deviation, RMSSD – root mean square of successive PPI differences, HFNU – high frequency integral in normalized unit, LFNU – low frequency integral in normalized unit. SD1 – standard deviation along short axis, SD2 - standard deviation along long axis. VP – visual Poincaré-plot analysis, minimum sampling frequency required for preserved morphology. nm – not measured, na – cannot be assessed. Dec – decimated, IPspl – cubic spline interpolated, IPpar – parabola approximated.

	SI (ms, simulated)		**SI (ms, healthy volunteers)**		
Parameter	**Dec**	**IPspl**	**Dec**	**IPspl**	**IPpar**
MPPI (ms)	*937.14*		*817.78 (group mean)*		
SDNN (ms)	*28.78*		*55.36 (group mean)*		
RMSSD (ms)	*36.13*		*53.78 (group mean)*		
MPPI	303	400	200	200	200
SDNN	20	303	20	100	100
RMSSD	10	303	20	50	50
HFNU	200	400	*nm*	*nm*	*nm*
LFNU	*na*	*na*	*nm*	*nm*	*nm*
LF/HF	*na*	*na*	*nm*	*nm*	*nm*
SD1	*nm*	*nm*	20	50	50
SD2	*nm*	*nm*	50	100	100
Guzik	*nm*	*nm*	20	50	100
Porta	*nm*	*nm*	50	100	100
VP	2ms	100ms	2ms	50ms	*nm*

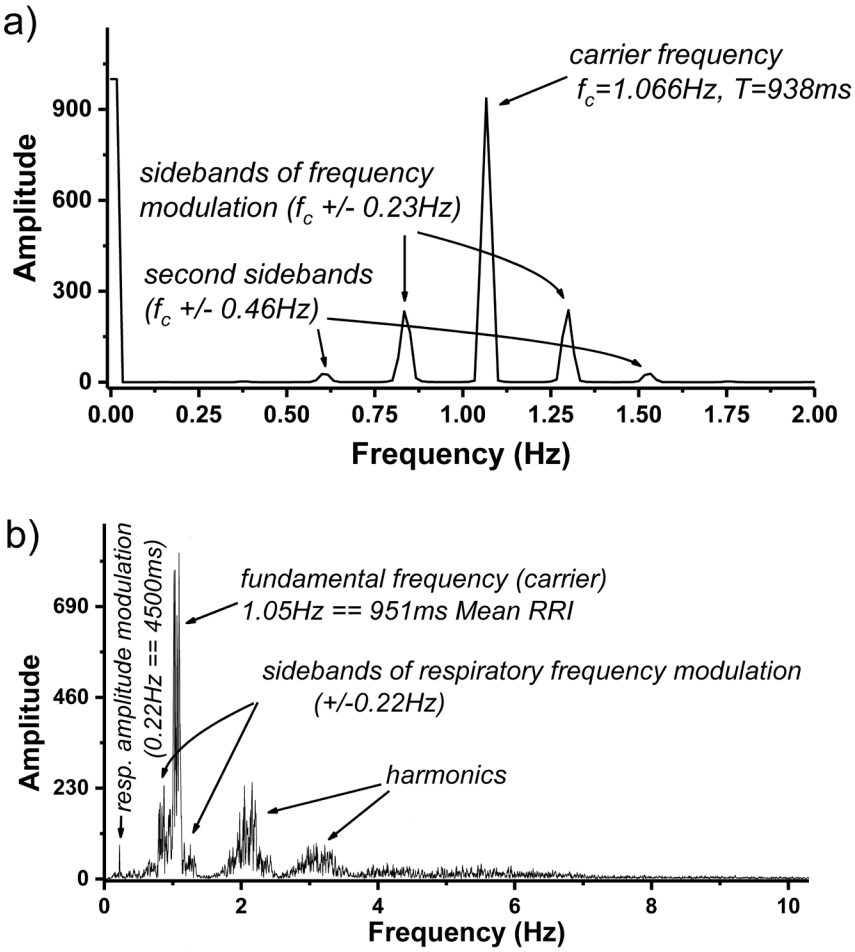

Figure 5. ***a)*** *The frequency spectra of a 1.066 Hz sine wave, frequency modulated at 0.23 Hz representing respiratory arrhythmia. The frequency modulation is expressed in the distance of the sidebands from the carrier frequency.* ***b)*** *The frequency spectra of a real human photoplethysmogram with a mean interval of 951 ms, with first and second harmonics at around 2.1 Hz and 3.15 Hz, respectively. The respiratory frequency modulation sidebands at ±0.22 Hz correspond to the 4500 ms paced breathing of the volunteer. Note the different frequency scale of the two spectra.*

The effective bandwidth of the PPG signal shown in Figure 5 a) is below 1.375 Hz, which implies that a sampling frequency of 2.75 Hz, that is, a sampling interval of 364 ms is sufficient for accurate reconstruction of the signal according to the Nyquist theorem. Our computer-simulated and human studies show that even for a PPG signal with a bandwidth smaller than the ECG, the sampling frequency determined using the Nyquist theorem is not sufficient for accurate HRV parameters without interpolation. In order to preserve the Poincaré-plot morphology, the generated signal requires a 2 ms interval for visual assessment and 100 ms resolution with interpolation, while the same is 2 ms and 50 ms for human PPG. Thus, even in case of the simulated PPG signal we can only approximate the minimum sampling frequency calculated from the Nyquist theorem using interpolation. At human PPG, considerably higher

sampling frequency is needed than expected from the signal bandwidth and Nyquist theorem, even with interpolation.

Based on our observations, the Poincaré-cloud can be much more sensitive to artefacts or noises than the usual statistical parameters. The Poincaré-plot can be an essential method for assessing the accuracy and precision of interpolation or other digital signal processing techniques.

In this study, we also compared the processing times of decimated, cubic spline interpolated, and parabola approximated PPG series. In our investigation (Figure 3), peak detection and interpolation with cubic spline interpolation required 200 times more computation time than parabola approximation, although this is highly dependent on the hardware and algorithm used. These considerations are particularly important in terms of power consumption for mobile or wearable devices, in order to increase the operating time on a single charge. Based on our observations, parabola approximation appears to be a better method, but the optimal sampling frequency and interpolation must be adapted to the actual hardware and software, finding a balance between power consumption, memory requirements, and parameter validity.

Conclusions

Based on our simulation and human studies, the minimum sampling frequency required for reliable HRV/PRV parameters depends on the variability of the examined subject, the nature of the parameter and the possible interpolation method; the latter can significantly reduce the sampling error. Among the methods we used, the cubic spline interpolation requires significantly more computation than the parabola approximation, with the same degree of parameter reliability. In healthy volunteers, the MPPI has satisfactory accuracy with as low as 5 Hz sampling without interpolation by "averaging" the sampling error with zero arithmetic mean, whereas the SDNN and RMSSD require at least 50 Hz sampling frequency without interpolation. With cubic spline interpolation or parabola approximation in the same population, the SDNN will have satisfactory accuracy at a minimum of 10 Hz sampling, while the RMSSD needs a sampling frequency of at least 20 Hz. No less than 50 Hz is required for the exactness of SD1 and the Guzik index, while at least 20 Hz is necessary to calculate SD2 and the Porta index within the 5% error limit. After interpolation, 20 Hz sampling for the SD1 and Guzik index, and 10 Hz sampling frequency for the SD2 and Porta index are required. In order to preserve the shape of the Poincaré-plot by visual assessment, 500 Hz is required without interpolation, while 20 Hz is sufficient with cubic spline interpolation.

Results show that the useful bandwidth of the PPG signal requires a significantly higher temporal resolution than the sampling frequency expected from the Nyquist theorem to provide a RAE below 5%, especially for HRV/PRV parameters of beat-to-beat variability. The Poincaré-plot is a particularly sensitive method for the evaluation of the efficiency of interpolation and other digital signal processing techniques.

Novel findings

- The minimum sampling frequency required to provide reliable HRV parameters, depends on the variability of the subject, the possible interpolation, and the HRV parameter. In case of low variability, the sampling error is relatively “amplified”, as we proved it mathematically. Within certain limits, this error resulting from low sampling frequency of the PPG signal, can be effectively improved by interpolation
- For an accurate PRV analysis, a higher sampling interval is required than would be reasonable based on the useful bandwidth of the PPG signal and the Nyquist theorem, similarly to ECG-based HRV measurements
- Based on the expected spectrum of the PPG signal, the required bandwidth of the system for reliable signal transmission can be estimated, however, the assumed variability of the subject to be tested determines the minimum sampling frequency
- For a specific hardware and software, the required sampling frequency and interpolation can be optimised in terms of power consumption and storage/transmission capacity, still guaranteeing the reliability of the specified HRV/PRV parameters
- The Poincaré-plot can be a sensitive method for the detection of subtle inaccuracies in digital signal processing and for the verification of their correction, which may remain unidentified by conventional tests

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Publications of the author

Original articles the thesis based on

1. **Béres S**, Holczer L, Hejjel L. On the Minimal Adequate Sampling Frequency of the Photoplethysmogram for Pulse Rate Monitoring and Heart Rate Variability Analysis in Mobile and Wearable Technology. Measurement Science Review. 2019;19(5):232-240. DOI: 10.2478/msr-2019-0030 *IF: 0,900, Q3, Cit: 8 (független, MTMT 2022. 09. 27.)*
2. **Béres S**, Hejjel L. The minimal sampling frequency of the photoplethysmogram for accurate pulse rate variability parameters in healthy volunteers. Biomedical Signal Processing and Control. 2021;68:102589. DOI: 10.1016/j.bspc.2021.102589 *IF: 5,076 (2020), Q1, Cit: 7 (független, MTMT 2022. 09. 27.)*

Cumulative impact factors of the original articles related to the thesis: ***5,976*** *Cit:* ***15*** *(MTMT)*
Cumulative impact factors of the author's published original articles: ***12,661*** *Cit:* ***23*** *(MTMT)*

Abstracts and other articles related to the thesis

1. Ajtay BE, **Béres S**, Hejjel L. The oscillating pulse arrival time as a physiological explanation regarding the diference between ECG- and Photoplethysmogram-derived heart rate variability parameters. Biomedical Signal Processing and Control. 2023;79:104033 *(on line available) IF: 5,076 (2021), Q1*
2. Hejjel L, **Béres S.** Comment on 'Pulse rate variability in cardiovascular health: a review on its applications and relationship with heart rate variability'. Physiological Measurement. 2021;42(1):018001. DOI: 10.1088/1361-6579/abd332 *IF: 2,833 (2020), Q1*
3. **Béres S**, Holczer L, Hejjel L. Optical pulse rate monitoring in wearable devices – the minimally sufficient sampling frequency. Cardiologia Hungarica. 2018 May, vol. 48., C suppl., pp 93.
4. Hejjel L, **Béres S**. Optimal sampling rate of the photopletysmogram signal for HRV-analysis in mobile devices: from the in silico simulation to the preliminary clinical studies. Cardiologia Hungarica. 2019, vol. 49., B suppl., pp 12.

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2. **Béres Szabolcs**, Holczer Lőrinc, Hejjel László. Optikai pulzusszám- és szívritmus variabilitás monitorozásához szükséges mintavételi frekvencia. Annual Scientific Congress of the Hungarian Society of Cardiology. Varia II – Hypertonia, Heart rate variability Section. Balatonfüred. 11-14 November, 2020.

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2. **Béres Szabolcs**, Holczer Lőrinc, Kocsis Kinga Katinka, Kiss Rudolf, Bertalan Andrea, Molnár F Tamás, Lénárd László, Hejjel László, Szabados Sándor. Kis-sejtes tüdőkarcinóma szívsebészeti szemszögből – esetismertetés. Annual Scientific Congress of the Hungarian Society of Cardiology. Poster presentation. Balatonfüred. 3-5 May, 2019.
3. **Béres Szabolcs**, Bertalan Andrea, Molnár Zsolt, Hejjel László. Koronária aneurizma – esetbemutatás. Annual Scientific Congress of the Hungarian Society of Cardiology. Electronic poster. Balatonfüred. 4-7 May, 2022.

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