Accuracy of Heart Rate Variability Estimation by Photoplethysmography using an Smartphone: Processing Optimization and Fiducial Point Selection

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Abstract— **This work compares several fiducial points to detect the arrival of a new pulse in a photoplethysmographic signal using the built-in camera of smartphones or a photoplethysmograph. Also, an optimization process for the signal preprocessing stage has been done. Finally we characterize the error produced when we use the best cutoff frequencies and fiducial point for smartphones and photopletysmograph and compare if the error of smartphones can be reasonably be explained by variations in pulse transit time. The results have revealed that the peak of the first derivative and the minimum of the second derivative of the pulse wave have the lowest error. Moreover, for these points, high pass filtering the signal between 0.1 to 0.8 Hz and low pass around 2.7 Hz or 3.5 Hz are the best cutoff frequencies. Finally, the error in smartphones is slightly higher than in a photoplethysmograph.**

I. Introduction

Nowadays, there are increasing efforts to create new solutions for personal health monitoring. The advances of the sensors and processing capabilities of smartphones allows us to use these daily devices as health monitors for non-clinical applications with the study of the heart rate variability (HRV) [1], [2].

At the present time, with built-in cameras in these devices it is possible to extract the heart rate time series continuously and, later, analyze several parameters of its variability that are related with the health. The signal is extracted using the photoplethysmographic (PPG) technique applied to the camera of the smartphone, thus an area of fingertip of the subject is illuminated with the flash and recorded simultaneously by the device. Later, it is usually processed offline to recover the pulse wave [3].

Previous studies deal with the accuracy of HRV indexes when the signal is obtained from the smartphone camera using different methods [4], but they do not characterize the beat to beat error so they are useless if another kind of HRV index is intended to be applied.

In this paper, we obtained the PPG from smartphones (SPPG) and from a reference photoplethysmographic sensor (RPPG). Then we performed an optimization process to find which are the best cutoff frequencies for band pass filtering of the SPPG in the preprocessing stage. Later, we characterized for SPPG and RPPG signals the error in the detection of the pulse arrival using five different fiducial points seeking which of them provides a heart rate variability time series more similar to that obtained with a conventional electrocardiogram (ECG). Finally, we evaluated if the error between them can be explained by variations in the pulse transit time (PTT).

II. Materials and Methods

A. Signal Acquisition

Ten healthy subjects have participated in the experiment. Each subject was asked to remain seated, still and with the palms in top of knees during the whole measurement protocol. The experiment was conducted according with the principles of the Declaration of Helsinki (2000).

ECG electrodes, using the standard I lead, were attached to the subjects. Moreover, a Biopac SS4LA photoplethysmograph probe was attached to the right or left index finger chosen at random. These two signals were acquired at 5 kHz using a BIOPAC MP36E acquisition system. Simultaneously, the other index fingertip covered the lens of the camera and the torch of a Motorola MOTO X (2^{nd} generation) or Samsung S5 smartphone chosen at random. A custom developed application for this experiment was used to record 100 seconds of video at 30 FPS and resolution of 640x480 pixels in the smartphone. The algorithm estimates the mean of the green channel, using the GPU, and creates for each frame a timestamp with a resolution of the 1 ms.

B. Pulse Estimator Algorithm

All processing tasks have been processed with MATLAB 2013a except the extraction of the mean of the green channel of the image which is done by the custom application. The algorithm for the extraction of pulse arrival using the smartphone camera has the following steps:

1. The average of the green channel for each frame is computed and its sign is changed because the PPG is working in reflection mode.
2. The lost frames are detected using the timestamp of each frame and interpolated with cubic interpolation.
3. The signal is band pass filtered using a fourth order bidirectional Butterworth filter with cutoff frequencies to be later discussed.

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4. The signal is resampled at 5 kHz in order to have the same sampling frequency that the ECG and the PPG signals coming from the BIOPAC.

5. The interpolated signal is low pass filtered at 7 Hz to remove the high frequency noise introduced when the lost frames are interpolated. This noise affects mostly to the first and second derivative which are later computed.

6. An accurate estimation of the pulse arrival is done using the fiducial points later described

The algorithm used to extract RR time series from RPPG only applies steps 3 and 6 because the others steps are not necessary due to be acquisition of the SPPG signal.

C. *Fiducial Points*

Five fiducial points have been tested as can be observed in Fig. 1. The criterion to select these has been the use of maximums and minimums peaks of the pulse signal and its derivatives. For that reason, the followings points have been chosen:

- Point A: maximum value of the pulse signal in a heartbeat.
- Point B: minimum value of the pulse wave in a heartbeat.
- Point C: maximum value in the first derivative of pulse signal.
- Point D: maximum value in the second derivative prior to point C.
- Point E: valley point in the second derivative after point C.

D. *Cutoff Frequencies Optimization for the Band Pass Filter for SPPG Signal.*

Our objective is to minimize the error in the RR time series estimation when detected using the pulse arrival in SPPG signals as compared to that obtained using the ECG. Our optimization criterion is to minimize the standard deviation of the error (SDE). We estimate the RR time series extracted from ECG using the Pan-Tompkins algorithm as a gold standard time series [5].

In order to optimize the cutoff frequencies, random cutoff frequencies for the filters have been tested using the Monte Carlo method with 8000 iterations for each recording. The search region was constrained from 0.05 to 1.5 Hz for the high pass frequency and from 2 to 10 Hz for the low pass frequency for the band pass filter. The limits of search region had been chosen in order to remove the baseline and the high frequency noise.

The first step in the optimization process was the extraction of the RR time series from the PPG for all measurements and frequencies pairs. Then, they were aligned with the RR from the ECG. Those PPG RR time series whose intraclass correlation coefficient (ICC) with the corresponding ECG RR time series was below to 0.8 were discarded because they contained artifacts. Then, for each measurement, the SDE was estimated by simply computing the standard deviation of the beat-to-beat differences of both RR time series. Because the Monte Carlo procedure generates a random and unevenly distributed curve evaluated

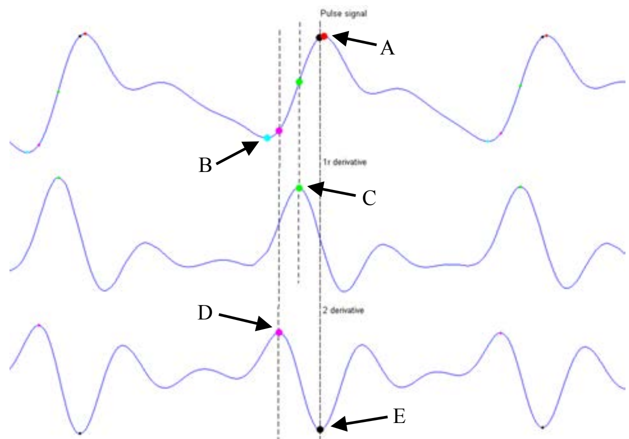

Figure 1. Fiducial points A, B, C, D and E

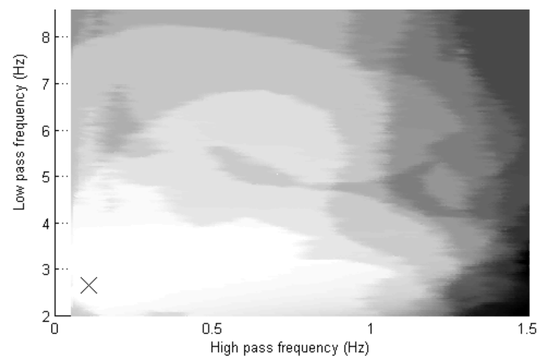

Figure 2. Detection error in the pulse arrival for the fiducial point C. White color indicates less error than dark colors. Cross marks the best pair of cut off frequencies it.

TABLE I. BEST CUT OFF FREQUENCIES FOR SPPG SIGNAL

	High pass Frequency (Hz)	**Low pass Frequency (Hz)**
A	0.625	3.860
B	0.846	5.303
C	0.107	2.726
D	0.752	3.507
E	0.507	2.673

at the tested frequency pairs, we interpolated this curve to create a grid of 500 x 500 points uniformly distributed in frequency. Next, the average value across recordings for each point on the grid was computed. Finally the point that had the minimum SDE was labeled as the best pair of cutoff frequencies for the band pass filter.

E. *Error Characterization for SPPG and RPPG Signals using the best cutoff frequencies*

As in the previous section, we use the RR time series extracted from ECG as a gold standard signal due to the low estimation error of the RR time that they have [6]. In order to calculate the error in the detection of the pulse arrival, RR time series from ECG and PPG are aligned. After, the beat-to-beat differences between them are estimated to obtain the error in milliseconds. This error is characterized by computing the mean (M), the standard deviation (SD), the 2.5% percentile (LB) and the 97.5% percentile (UB) of it. Finally, the similarity between the two time series is estimated by the intraclass correlation coefficient (ICC).

III. RESULTS

A. Best Cutoff Frequencies for the SPPG Signal

An example of the grid created with the Monte Carlo search can be seen in Fig. 2. Light colors represent lower SDE than dark colors. The cross marks the best pair of frequencies for the fiducial point.

Table I presents the results obtained using the optimization process for every fiducial point. As can be seen in it, there are important differences in cutoff frequencies. Note that the variability in high pass frequency in points C, D and E can be attributed to the high stability of SDE between 0.1 and 0.8 Hz as can be observed in Fig. 2

B. SDE Degradation for SPPG when Optimal Frequencies are used.

The Table II presents the SDE when the optimal cutoff frequencies for each recording (tailored optimization) and the optimal cutoff frequencies found in the previous section (global optimization) are used.

From the table II we can observe that in both cases, point E has less mean error than the others. However, it is the point C who has less variance in the error. On the other hand, one way ANOVA test performed on the global optimization results shows that there are very significant differences ($p<0.001$) in the standard deviation of the error and ICC among fiducial points. However, when the Holm-Sidak method is applied, only the point B appears to be significant different from the others.

TABLE II. SDE OF SPPG FOR EACH FIDUCIAL POINT (M ± SD)

	Tailored optimization	Global optimization
A	4.382 ± 2.377	5.920 ± 2.924
B	5.707 ± 2.447	7.401 ± 2.719
C	4.738 ± 2.100	5.358 ± 2.349
D	4.876 ± 2.225	5.921 ± 2.590
E	4.614 ± 2.2281	5.279 ± 2.501

C. Smartphone Error Characterization for Optimal Band Pass Filter

Table III compares the statistics to characterize the error between the RR time series extracted from the smartphone and the ECG signals. As we can see in the table, the ICC coefficient is nearly 1 for each fiducial point, meaning that both time series are almost equal. But using (1) for the best case (fiducial point E, mean SD in table III), the SDE is equivalent to that caused by the sampling error if the ECG was sampled at 78.21 Hz [7].

$$f_s = \frac{1}{\sigma * \sqrt{6}} = \frac{1}{5.220\ ms * \sqrt{6}} = 78.21\ Hz \qquad (1)$$

Finally, one way ANOVA test and Holm-Sidak method has been applied for ICC, M, SD, LB and UB results. ICC and SD appears to have very significant differences in fiducial point B.

D. Photoplethysmograph Error Characterization for Optimal Band Pass Filter

Table IV shows the results for the RPPG using the same cutoff frequencies employed for the smartphone. Note that the cutoff frequencies may not be optimal in this case.

TABLE III. ERROR CHARACTERIZATION FOR SMARTPHONE (M ± SD)

Fiducial point	ICC (unitless)	M (ms)	SD (ms)	LB (ms)	UB (ms)
A	0.989 ± 0.009	0.817 ± 0.935	5.896 ± 2.913	-10.980 ± 5.998	12.355 ± 6.158
B	0.985 ± 0.012	0.711 ± 0.922	7.362 ± 2.693	-13.579 ± 5.331	15.434 ± 5.716
C	0.992 ± 0.005	0.767 ± 0.960	5.403 ± 2.307	-9.638 ± 4.419	11.642 ± 4.707
D	0.990 ± 0.010	0.792 ± 0.916	5.920 ± 2.566	-10.447 ± 4.694	12.228 ± 5.293
E	0.992 ± 0.007	0.780 ± 0.929	5.220 ± 2.525	-9.303 ± 4.530	11.247 ± 5.721

TABLE IV. ERROR CHARACTERIZATION FOR PHOTOPLETHYSMOGAPH (M ± SD)

Fiducial point	ICC (unitless)	M (ms)	SD (ms)	LB (ms)	UB (ms)
A	0.993 ± 0.007	-0.026 ± 0.220	4.720 ± 1.786	-9.858 ± 4.705	10.147 ± 4.497
B	0.989 ± 0.007	-0.096 ± 0.255	6.707 ± 2.341	-13.165 ± 4.329	13.315 ± 4.598
C	0.995 ± 0.003	-0.069 ± 0.175	4.772 ± 1.849	-8.895 ± 3.150	9.952 ± 3.769
D	0.993 ± 0.006	-0.026 ± 0.086	5.343 ± 1.880	-9.920 ± 3.485	10.750 ± 4.093
E	0.995 ± 0.003	-0.077 ± 0.212	4.624 ± 1.283	-9.191 ± 2.744	9.016 ± 2.524

As can be expected, ICC coefficient is almost 1 in all fiducial points meaning that the RR from the RPPG and ECG are very similar. The lack of bias suggests that the error due to changes in PTT has mean 0 but, as SD column of table IV shows, it is not constant and affects the RR estimation. Interestingly, using (1) shows that due to the error introduced by PTT, the error in the best scenario is equivalent to sample the signal at 88.29 Hz [7], which is much less that the original 5 kHz sampling frequency. The results obtained from one way ANOVA presents again that ICC and SD in point B show very significant differences versus the others.

IV. Discussion

If we suppose that the changes in delay between the pulse start at the aorta and the QRS complex are negligible, then the pulse arrival (P) is ideally obtained as:

$$P(n) = R(n) + PTT(n) \qquad (2)$$

For that reason, the time difference between two consecutive pulse arrivals (PP) are:

$$PP(n) = P(n) - PP(n-1) = RR(n) + \Delta PTT(n) \quad (3)$$

Then, the unavoidable error that is made when the PP time series is used as a surrogate of the RR time series is:

$$e(n) = PP(n) - RR(n) = \Delta PTT(n) \qquad (4)$$

The results obtained from RPPG shows to us that the equivalent sampling frequency error is around 88 Hz. Thus, the use of PP to compute certain HRV indexes is not recommended for those indexes that requires a high resolution of RR time series [8], [9]. On the other hand, when the signal is obtained from the smartphone, the error has a slight degradation (compare tables III and IV).

Also, it is remarkable that the bias in the smartphone error suggests that the frame capture in Android devices is near but not exactly 30 FPS and not completely constant. With the use of more accurate timestamps, the mean heart rate could be estimated because the error bias will be negligible.

Finally, a broad study is needed to select which fiducial point is the best due to ten subjects are not enough to show significant differences except for point B that presents bigger errors

V. Conclusions

The best fiducial point to detect the pulse arrival could not be determined because there are no significant differences between points A, C, D and E in this experiment. Only the point B shows more significant error than the others. In the remaining points, low pass frequency for band pass filter is around 2.7 Hz or 3.5 Hz while the high pass frequency is between 0.1 and 0.8 due to the high stability of the SDE. Nevertheless, point E has shown in this study the lower error.

If the RR time series is estimated from the smartphone, sampled at 30 Hz and without artifacts, the main and unavoidable error is due to changes in PTT. Also, there is a small bias that could be compensated with more precise timestamps. The standard deviation of the error is slightly higher than in the case of a RPPG.

Finally the RPPG and SPPG are unsuitable methods to be applied to HRV indexes that require a high resolution of the RR time series.

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References

[1] J. A. J. Heathers, "Smartphone-enabled pulse rate variability: an alternative methodology for the collection of heart rate variability in psychophysiological research.," *Int. J. Psychophysiol.*, vol. 89, no. 3, pp. 297–304, Sep. 2013.

[2] C. G. Scully, J. Lee, J. Meyer, A. M. Gorbach, D. Granquist-Fraser, Y. Mendelson, and K. H. Chon, "Physiological parameter monitoring from optical recordings with a mobile phone.," *IEEE Trans. Biomed. Eng.*, vol. 59, no. 2, pp. 303–6, Feb. 2012.

[3] K. Matsumura, P. Rolfe, J. Lee, and T. Yamakoshi, "iPhone 4s photoplethysmography: which light color yields the most accurate heart rate and normalized pulse volume using the iPhysioMeter Application in the presence of motion artifact?," *PLoS One*, vol. 9, no. 3, p. e91205, Jan. 2014.

[4] J. B. Bolkhovsky, C. G. Scully, and K. H. Chon, "Statistical analysis of heart rate and heart rate variability monitoring through the use of smart phone cameras.," *Conf. Proc. ... Annu. Int. Conf. IEEE Eng. Med. Biol. Soc. IEEE Eng. Med. Biol. Soc. Annu. Conf.*, vol. 2012, pp. 1610–3, Jan. 2012.

[5] J. Pan and W. J. Tompkins, "A real-time QRS detection algorithm.," *IEEE Trans. Biomed. Eng.*, vol. 32, no. 3, pp. 230–236, 1985.

[6] M. A. García-González, A. Argelagós, M. Fernández-Chimeno, and J. Ramos-Castro, "Differences in QRS Locations due to ECG Lead: Relationship with Breathing," in *XIII Mediterranean Conference on Medical and Biological Engineering and Computing 2013 SE - 238*, vol. 41, L. M. Roa Romero, Ed. Springer International Publishing, 2014, pp. 962–964.

[7] M. Merri, D. C. Farden, J. G. Mottley, and E. L. Titlebaum, "Sampling frequency of the electrocardiogram for spectral analysis of the heart rate variability," *IEEE Trans. Biomed. Eng.*, vol. 37, no. 1, pp. 99–106, 1990.

[8] M. A. Garcia-Gonzalez, M. Fernandez-Chimeno, and J. Ramos-Castro, "Errors in the Estimation of Approximate Entropy and Other Recurrence-Plot-Derived Indices Due to the Finite Resolution of RR Time Series," *Biomed. Eng. IEEE Trans.*, vol. 56, no. 2, pp. 345–351, Feb. 2009.

[9] M. A. García-González, M. Fernández-Chimeno, and J. Ramos-Castro, "Bias and uncertainty in heart rate variability spectral indices due to the finite ECG sampling frequency," *Physiol. Meas.*, vol. 25, no. 2, p. 489, 2004.