Beat-to-beat Intervals of Speckle & Intensity-based Optical Plethysmograms compared to Electrocardiogram

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Abstract

This study evaluates video sequences obtained by a form of laser speckle imaging (LSI) – referred to as remote camera-derived Speckleplethysmography (rSPG) – in comparison to common clinical parameters (PPG & ECG). For 9 human subjects we illuminated the index finger with a laser (639 nm, 10 mW, spot diameter 5.6 mm), captured video streams with a camera (Basler acA2000-340km, 25 cm distance, 100 fps) and evaluated spatial variations in the captured speckle patterns. We simultaneously collected contact-mode transmissive photoplethysmography (PPG) and electrocardiography (ECG) signals. We derived beat-to-beat (b-2-b) intervals from both rSPG and contact-mode PPG signals and compared both with the ECG R-R intervals 'gold-standard' (3234 heart-cycles in total).

B-2-b interval error distributions of rSPG vs contact PPG showed: mean absolute deviation 10.4 vs 14.2 ms; standard deviation 25.2 vs 30.1 ms.

Two-sample F-test revealed significantly different variances ($p < 0.001$, 99% confidence).

Additional Levene's test: $F(1, 6468) = 37.602$, $p = 0$.

This study demonstrates that contactless camera-derived rSPG can obtain b-2-b intervals at least as good as routine clinical contact-mode transmissive finger clip PPG. This might enable innovative applications.

1. Introduction

Photoplethysmography (PPG) was first reported in 1938 by Hertzman [1]. PPG is based upon electrically recording the amount of light from a non-coherent light source that is diffusely transmitted or reflected by living tissue onto a light-sensitive detector over time. PPG is a ubiquitous physiological monitoring parameter and an amplitude domain technology. The PPG pulse wave is derived from periodic intensity variations, mostly using LED(s) as light source(s) and Photo Diode(s) as detector(s). PPG mostly is captured using non-imaging photodetectors in contact with the skin but can also be derived from remote imaging devices (rPPG), but it is typically more difficult to obtain good rPPG signal quality compared to contact-mode PPG.

Speckle Plethysmography (SPG) was reported in 2018 by Ghijsen et al. [2]. SPG is based upon recording the interference pattern that arises when coherent light is diffusely transmitted or reflected by living tissue onto an imaging detector over time. The SPG pulse wave is derived from periodic variations in the interference patterns. SPG is thus not an amplitude domain technology: If the overall intensity of all camera pixels varies with the same factor, this does not affect the SPG signal (if the camera stays in its linear range). Only spatiotemporal changes in the interference-caused speckle pattern produce a signal (which also includes movement artifacts).

The conversion of laser speckle contrast imaging to time-series signals (SPG) is a relatively young area and the differences between PPG and SPG have not yet been extensively explored, [3], [4], [5], [6], [7]. Due to their different nature, both signals likely contain different information relevant for the analysis of human physiology.

In this work, we built a camera-based setup, capable of capturing laser speckle contrast images at 100fps synchronous with clinical monitors, measuring Electrocardiogram (ECG) and contact-mode PPG, to investigate the practical usability of rSPG for remote heart rate monitoring.

2. Methods and materials

We designed and built a system to record camera signals triggered together with a laser illumination source of 639 nm, synchronous with a physiological data acquisition platform capturing PPG (finger clip) and ECG.

The setup was used to illuminate the index finger of 9 healthy volunteers, and from the recorded video streams we evaluated the spatial variations in the captured speckle patterns. From the same video streams, we also derived the intensity modulation, to check in how far *the same photons* might reveal a useful remote PPG ('rPPG'). The

experimental protocol and safety aspects were approved by the imec Netherlands ethical committee in accordance with national regulations.

2.1. Instrumental assembly

The setup contained an area-scan CMOS camera (Basler acA2000-340km; ROI 512x320 pixels, 100 fps) and a laser diode (Thorlabs HL6358MG - 639 nm, 10 mW, Ø5.6 mm). Laser and camera were both placed in the same plane 25 cm above the target, obtaining reflective images of the index finger in a dim-lit room. The laser was pulsed synchronously with the camera. The laser driver was home-built, based upon an iC-WJZ chip (iC Haus). Investigators and participants wore laser safety glasses.

A physiological data acquisition platform (Biopac MP160) was used to record ECG (Biopac ECG 100C module, collected at 12.5 kHz) and PPG (Finapres Nova with Covidien probe, collected at 12.5 kHz from a 75 Hz Finapres analogue output). Simultaneously, the camera/light-source trigger signal was also recorded (collected at 12.5 kHz). All physiological signals were resampled to match the Finapres sampling frequency.

A microcontroller (STM32) generated a trigger signal to synchronize the Basler camera, light-source and Biopac (synchronizing the physiological reference data with the images, and the camera with the lights). The images were stored in a desktop computer using full camera link communication. See also Figure 1.

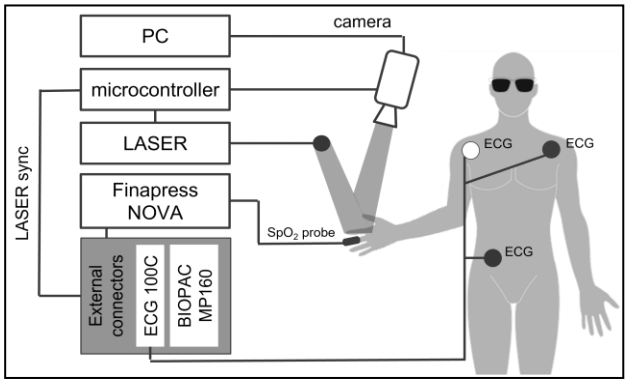

Figure 1. Measurement setup diagram

2.2. Instrumental assembly

The idea behind the application of laser speckle contrast imaging to hemodynamic measurements comes from the speckle theory [8]. When coherent light is projected onto a static surface, it produces a pattern of dark and bright dots (called speckles), caused by destructive and constructive photonic interferences. If the laser would be perfect (infinite coherence length) and nothing would move, the speckle pattern would be static (in practice there are always some variations over time, mainly being dependent on the laser's finite coherence length & bandwidth).

When, however, coherent light is projected onto living tissue, with blood cells flowing beneath the surface, the resulting speckle pattern will fluctuate, modulated by the movement of the blood cells (and other tissue deformations, e.g. induced by pulse wave and respiration). The fluctuation in the speckle pattern is thus mainly produced by the dynamic particles, static particles do not (or hardly) contribute to this fluctuation.

From the same camera video sequence, two different types of fluctuations over time can be derived, by applying two different processing strategies: Intensity-based and speckle-based. Figure 2 depicts both.

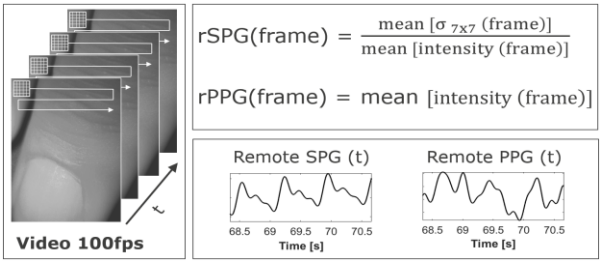

Figure 2. Both applied video processing methods

We based our rSPG approach upon the method described by Ghijsen et al. [2]. Firstly, a standard deviation mask (σ) – sized 7x7 pixels, based on the speckle-pixel size ratio – is scanned across every image. All values resulting from this standard deviation mask-scan are averaged, and this value is then divided by the average pixel intensity of the total original image. This provides our rSPG signal. Secondly, a rudimentary check for 'rPPG' is done by calculating the average intensity per video frame, plotted over time. See Figure 3.

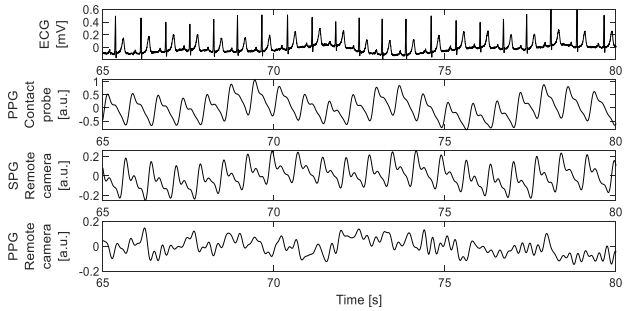

Figure 3. From top to bottom, ECG & contact-mode PPG, plus two results of processing the *same video stream* for rSPG versus overall intensity variations (note that no recognizable rPPG signal is obtained).

2.3. Analysis

For all individual recorded heart cycles, b-2-b intervals were calculated for contact PPG, rSPG and ECG (based on Matlab's function "findpeaks" using "MinPeakDistance" attribute set to the number of samples in 0.5 s). This function detects ECG R-peaks and the *onsets of the upstrokes* (valley) on rSPG and PPG. Then all PPG and respectively rSPG b-2-b intervals were subtracted from the corresponding ECG R-R intervals ('gold standard' reference). This revealed the respective error signals for PPG and rSPG (see Figure 4).

We also calculated the interquartile range ("iqr(x)"), mean absolute deviation ("mad(x)"), range width ("range(x)"), standard deviation ("std(x)") and variance ("var(x)") for the rSPG and respective contact-mode PPG error distributions (see Table 1).

To test whether the b-2-b interval errors of rSPG and PPG have a normal distribution with the same variance, a two-sample F-test was used (Matlab function "vartest2"). To additionally evaluate the variance homogeneity, Levene's test was performed via Matlab function "vartestn" with the attribute "LeveneAbsolute" [9].

3. Results

Figure 4 shows boxplots and histograms of both error signals from a total of 3234 b-2-b episodes (at least 5 minutes for all 9 human subjects).

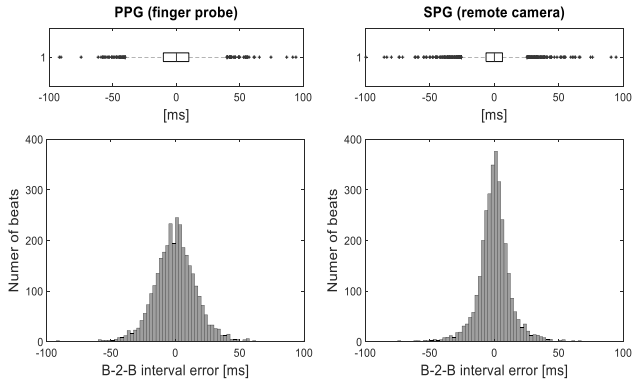

Figure 4. B-2-b time error of simultaneously recorded PPG (left - contact, transmission mode finger probe) & rSPG (right - remote, reflection mode camera-derived), versus ECG (gold-standard). Histogram bar width is 2.5 ms. To zoom in on the differences between PPG & rSPG errors, the time scale is limited to ± 100ms. Outliers beyond these limits (both < 0.5%) were:

- PPG, 10 outliers < -100 ms; 11 outliers > +100 ms
- rSPG,7 outliers < -100 ms; 10 outliers > +100 ms

Table 1. Dispersion of b-2-b error distributions from rSPG & contact-mode PPG, both compared to ECG.

Timing parameters [ms]	rSPG	PPG
Interquartile range	12.7	20.1
Mean absolute deviation	10.4	14.2
Range width	1101	1297.3
Standard deviation	25.2	30.1
Variance	636.7	903.6

The two-sample F-test revealed that the variances of distribution of rSPG and PPG are significantly different (p value < 0.001), with lower and upper boundaries being 0.7624 - 0.9139 (99% confidence interval) for the true variance ratio. But standalone F-tests deserve caution [9]. An additional Levene's test confirmed that the variances for rSPG and PPG error distributions compared to ECG indeed were not equal, F (1, 6468) = 37.602, p = 0.

3.1. Additional observation regarding ambient light

When developing the setup, we noticed a pronounced difference in ambient light response of the speckle-based (rSPG) versus intensity-based processing (rPPG).

In Figure 5, the top trace shows the average intensity of the camera signal, and the bottom trace shows the raw spatial variability signal: [rSPG * mean (frame)]. Note that both traces are calculated from the *same video streams*, only the processing method differs. First, from 36 – 42 s, the window blinds were open. From 42 – 47 s, they were being closed. Finally, from 47 – 56 s, the signal restabilized with blinds closed. Even when zooming in on the intensity-based signals, no useful 'rPPG' is visible. But the *same video stream* reveals a clear and stable rSPG.

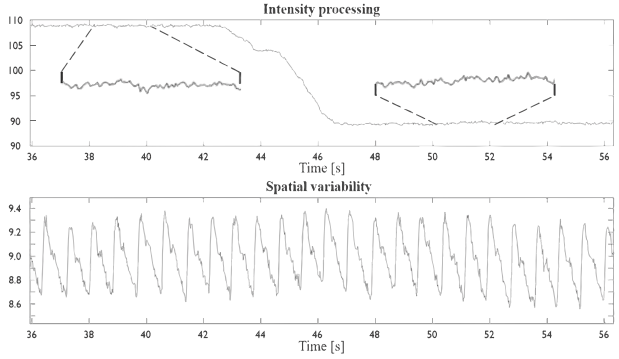

Figure 5. Upon an ambient light change (t = 42 – 47 s), intensity-based processing heavily responds (top trace, with zoomed episodes before and after the light change). In contrast, the raw speckle-based rSPG [rSPG * mean (frame)] remains unaffected by the change of incoherent ambient light (bottom trace).

4. Discussion

In previous research by Dunn et al. contact-mode transmissive SPG had already been reported superior to contact-mode transmissive PPG for HRV estimation [10]. Here, we demonstrate that *non-contact* camera-derived rSPG has an accuracy at least as good as routine clinical contact-mode transmissive finger clip PPG by comparing their respective b-2-b intervals with ECG R-R intervals.

It is also known that the quality of remote camera-based PPG usually is inferior to contact-mode PPG. Moreover, when comparing intensity-based and speckle-based processing of the same video stream, the speckle-based approach shows superior signal quality and suppression of changes in non-coherent ambient light.

Contact-mode PPG and rSPG are both sensitive to movement artifacts, but this study did not investigate this.

5. Conclusion

This study demonstrates that (using ECG as a gold standard) *contactless* camera-derived rSPG can obtain b-2-b intervals with an accuracy at least as good as routine clinical *contact-mode* transmissive finger clip PPG. In contrast to PPG, which is directly affected by ambient light changes, we did not observe such effect on rSPG signals. This might enable innovative applications.

Acknowledgments

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