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Relation between pulse pressure and the pulsation strength in camera-based photoplethysmograms

Abstract: Camera-based photoplethysmography (cbPPG) is an innovative measuring technique that enables the remote extraction of vital signs using video cameras. Most studies in the field focus on heart rate detection while other physiological quantities are often ignored. In this work, we analyzed the relation between the pulse pressure and the pulsation strengths of cbPPG signals for 70 patients after surgery. Our results show a high correlation between the two measures ($r = 0.54$). Furthermore, the influence of technical and medical factors was tested. The controlled impact of these factors proved to enhance the correlation by between 9 and 27 %.

Keywords: camera-based photoplethysmography, remote vital sign monitoring, pulse pressure, clinical monitoring.

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1 Introduction

Camera-based photoplethysmography (cbPPG) is a currently evolving measuring technique that utilizes video cameras for the remote acquisition of vital signs [1]. In many aspects, it resembles the common photoplethysmography (PPG) where emitted light is modulated by the cutaneous vasculature, captured and transformed into a cardiac signal [2]. However, cbPPG has a major advantage over PPG as it simply functions with ambient light and allows the assessment of spatial information instead of being restricted to a punctual measurement [3].

Despite the broad opportunities, most studies in cbPPG focus on methods for the reliable extraction of the heart rate [4]. Other measures such as the blood pressure (BP) are less often addressed. For PPG, various approaches have been explored to estimate the continuous BP or surrogates by using PPG signals [2]. For cbPPG, only a few works exist where either the pulse transit time or the shift between cbPPG signals of different body sites is correlated to the diastolic and systolic BP [5-7]. The pulse pressure (PP), however, is a BP parameter which was not considered so far although it is of high importance by being a risk marker for coronary heart disease and a predictor for all-cause, coronary and cardiovascular mortality [8,9].

In this work, we assessed the relation between PP and the pulsation strength of cbPPG signals (cbPS). We determined cbPS and PP for 70 video recordings and corresponding BP signals, respectively. In addition to correlating the two measures, we also analyzed the impact of technical and medical factors on the relation. We believe that our results open up new perspectives for a remote PP estimation.

2 Material and methods

2.1 Data and technical setting

For the cbPPG tests, we designed and built a mobile measuring setup holding a dual-camera system (see Fig. 1). However, we only used the videos of the RGB camera (IDS UI-3370CP-C-HQ) in our analysis. The camera was set to a frame rate of 100 fps, a resolution of 420x320 pixels, and a color depth of 12 bit. Each patient was recorded for approximately 30 min where the face was chosen as the main recording area (see Fig. 2 (a)). The room's illumination conditions varied and were defined by ceiling fluorescent lighting and natural sunlight. During the measurement, the

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patients mostly remained calm and only moved occasionally. In addition to the videos, we synchronously captured reference signals from the patient monitor, such as the continuous arterial BP (invasive) and the electrocardiogram

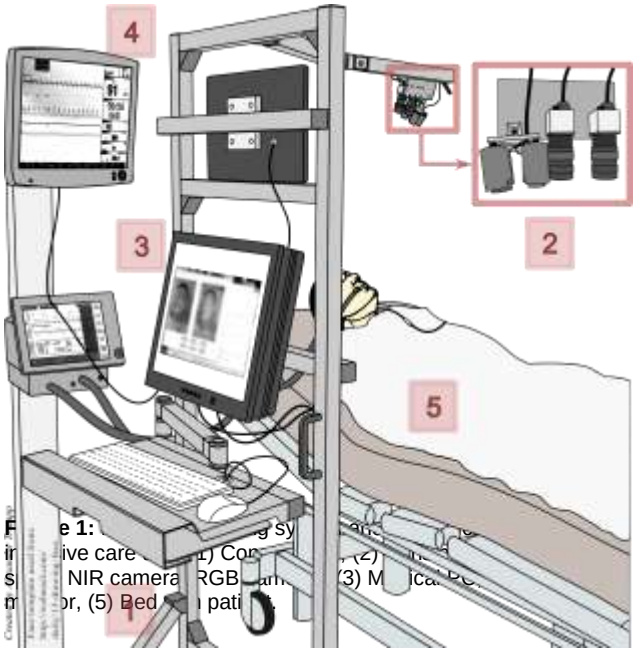


Figure 1: [illegible] intensive care [illegible] (1) Cons[illegible], (2) [illegible] s[illegible] NIR camera, RGB [illegible] (3) M[illegible] m[illegible]or, (5) Bed [illegible] pati[illegible]

Figure 2: Main image and signal processing steps: (a) Manual ROI selection for 10 s segments (segment *n*+1 holds artifacts and is excluded), (b) Minima and maxima detection for an extracted cbPPG signal segment using the reference ECG's R-peaks (green crosses), (c) Extrema detection in blood pressure signal by applying the same steps as for the cbPPG signal.

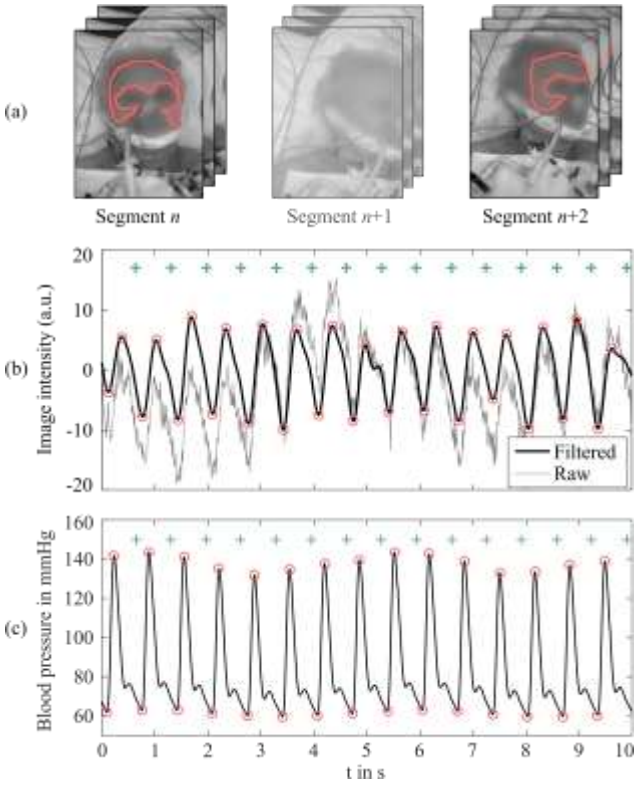
(ECG). Furthermore, individual measures and the applied medication were collected.

2.2 Image and signal processing

For further analyses, we only used the green channel of the videos as it provides the strongest plethysmographic signal [3]. We divided the video streams into consecutive 10 s segments (ca. 180 segments/ patient) due to following methodical steps. Afterward, segments with major motion and light artifacts were excluded in order not to impair cbPPG's BP dependency by such disturbances. For this purpose, we adopted an optical flow technique in which strong variations within the head area could be identified (a more detailed description can be found in [10]). The regions of interest (ROIs) were only selected for the remaining segments. We chose the forehead and the cheeks unless they were not visible. A once defined ROI was held statically until an artifact occurred and was then redefined. Figure 2 (a) visualizes the procedure for an example.

The cbPPG signals were obtained by averaging all ROI pixels for each frame. We calculated the pulsation strength cbPS of these signals for every segment as described in the following. First, a zero-phase Butterworth bandpass filter was applied (order 5, cutoff 30 and 200 bpm). Second, the maximum and minimum of every beat were determined using ECG's preselected R-peaks as starting point for the guided search of the extrema. Third, the median of the differences between maxima and minima was calculated resulting in one cbPS value for each segment. For the continuous BP signal, we used the same procedure to determine the PP values for corresponding 10 s segments. Figure 2 (b) and (c) shows signal examples with their detected diastolic and systolic points.

In order to assess technical disturbances during the cbPPG measurement, we built a segment-wise noise



parameter P_N based on a formula by de Haan and Jeanne [11]. It measures the absolute spectral power of all frequencies f between 30 and 200 bpm that are not related to the heart cycle:

$$\mathbf{P_N} = \sum_{f=30\ \mathbf{bpm}}^{200\ \mathbf{bpm}} \boldsymbol{\Pi}(\boldsymbol{f})|\boldsymbol{X}(\boldsymbol{f})|^{\mathbf{2}}\,, \qquad (\mathbf{1})$$

where $X(f)$ is the Fourier transform of a cbPPG signal segment, and Π is a function between 0 and 1 marking all

frequencies beside the heart rate (derived from ECG) and its first harmonic within a 5 bpm band.

2.3 Evaluation and statistics

Exploratory pretests showed not normal distributed cbPS values which caused nonlinear relations to PP. Therefore, we logarithmized all cbPS values in order to apply linear statistical measures. We initially analyzed the individual segment-based dependency between cbPS and PP. Since we only found low or no correlations, we disregarded this analysis and focused on inter-patient relations. For this purpose, the medians of the cbPS values (logarithmized) and the PP values were calculated for each patient. In the same way, $\bar{P}_N$ was determined as median of the P_N values.

The relation between cbPS and PP was eventually assessed using Pearson's linear correlation coefficient r (p-value specifies significance). We evaluated different factors which presumably had a direct effect on the dependency: (i) $\bar{P}_N$, (ii) hemoglobin concentration Hb, (iii) Nitroglycerin, (iv) no Noradrenalin, (v) the combination of (iii) and (iv). We tested the factors' impact by building subgroups in which r was calculated separately. To divide the patient group, for (i) and (ii), we set numerical thresholds and for (iii) to (v), the states 'given' or 'not given' were considered. Since a potential improvement in r can be a result of the shrinking sample size, we randomly drew the number of patients in the subgroup 1000 times and calculated the mean correlation coefficient (Monte Carlo simulation – MCS). The improvement was then determined relatively to this outcome (in %).

3 Results

Across all patients, we found a high correlation ($r = 0.54$, $p < 0.001$) between cbPS and PP. Figure 3 shows the scatter plot of the 70 point pairs. Furthermore, all factors proved to affect the relation positively (see Table 1). Regarding the noise power, the highest improvement of 9 % ($r = 0.60$, $p < 0.001$) could be achieved when only patients with $\bar{P}_N < 7$ were selected. We observed that subjects with high cbPS values were primarily excluded as a consequence (see Fig. 3). An even greater impact yielded the hemoglobin concentration where the grouping for $Hb > 6.5$ mmol/l involved an improvement of 22 % ($r = 0.68$, $p < 0.001$). The scatter plot shows that particular patients, which caused a high variance, were removed in this case. The medication factors, referring to when Nitroglycerin was given and Noradrenalin was not given, led by themselves to a moderate enhancement (11 % and 14 %) in the correlation between cbPS and PP (see Table 1). However, the AND combination of the two factors provided the largest improvement of 27 % ($r = 0.73$, $p < 0.001$) regardless of the fact that only 24 patients were left in the group. Again, the excluded patients seemed to increase the variance within the linear dependency (see Fig. 3).

Table 1: Results for the correlation between the pulse pressure and the cbPPG pulsation strength (*** $p < 0.001$). Subgroups were built by the listed factors. The first row shows the correlation for the whole data set. The last column depicts the improvement in reference to the first row using a Monte Carlo simulation (MCS).

Factor	Correlation	Number of patients	Improvement (MCS)
-	0.54***	70	-
$\bar{P}_N < 7$	0.60***	47	9 %
$Hb > 6.5$ mmol/l	0.68***	47	22 %
Nitroglycerin	0.62***	40	11 %
No Noradrenalin	0.63***	47	14 %
Nitroglycerin & no Noradrenalin	0.73***	24	27 %

4 Discussion

The cbPS-PP relation is based on physical characteristics of the cardiovascular system. For a steady vessel compliance, an

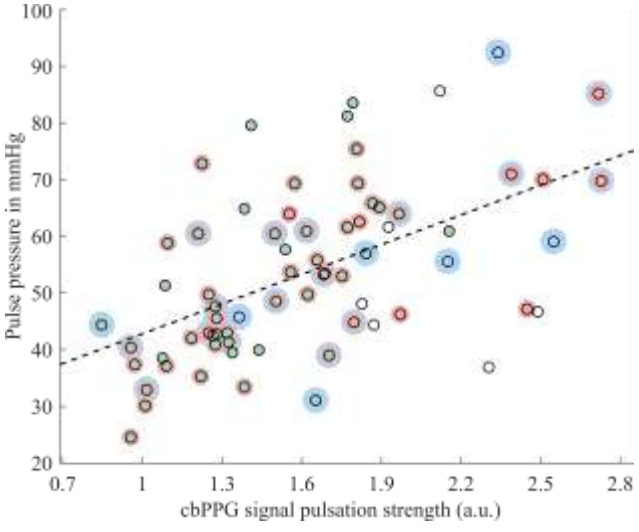


Figure 3: Scatter plot for the relation between pulse pressure and the cbPPG pulsation strength (logarithmized). The dashed line is the regression line for the whole data set (black circles). The colored circles represent the subgroups (green: $\bar{P}_N < 7$, red: $Hb > 6.5$ mmol/l, blue: Nitroglycerin and no Noradrenalin was given).

increasing PP leads to an increase of the transmural pressure which involves an increase of the blood volume. As the blood volume is a main modulating effect in cbPPG [3], for the microvasculature, such an increase would also reflect in cbPS. Nevertheless, there are many factors that play a role in the relation of which only a few will be discussed here.

The noise power is a technical parameter which describes the quality of captured cbPPG signals. The lower $\bar{P}_N$ is, the higher the quality and the better the correlation between cbPS and PP are. However, the missing high cbPS values in the considered group (see Fig. 3) implies the formula to not separate optimally physiological components from degrading noise. The effect of Hb can be explained by hemoglobin's light properties: The higher Hb is, the higher the absorption by light and the better the pulsating character in the cbPPG signal are. This enhancement manifests in a more distinct dependency of cbPS on PP. The found grouping threshold should not be overinterpreted as it highly relies on the sample size. The same holds for the $\bar{P}_N$ threshold. The impact by the medication is attributable to their influence on the vasculature. Nitroglycerin is a vasodilator whereas Noradrenalin is a vasoconstrictor. Consequently, both factors, (iii) and (iv), and the combination (v) involve the separation of patients where peripheral vessels were more dilated than in the complementary group. The dilation improves the perfusion of the microcirculation which leads to a higher cbPPG signal quality and, thus, to a better correlation between cbPS and PP.

Despite the promising results, the dependency of cbPS on PP cannot be explained fully, especially for the intra-patient relations that were disregarded here. The cbPPG signal arises from the cutaneous microcirculation, which is differently controlled than large vessels, where PP was measured. Blood flow may bypass these superficial skin layers in response to autonomous control and thermoregulation, particularly in conditions like recent surgery and anesthesia, extracorporeal circulation or hypovolemia. Hence, the macrohemodynamic PP changes are not inevitably reflected in the cbPPG signal.

5 Conclusion

In this work, we could show that there is a high inter-patient correlation between the pulse pressure and the pulsation strength in camera-based photoplethysmograms. Furthermore, we demonstrated the relation to be positively affected by technical and medical factors. The controlled influence of such factors and the consideration of additional aspects could open up the perspective for a remote PP estimation in the future.

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Author's Statement

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