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Vasomotor assessment by camera-based photoplethysmography

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Abstract: Camera-based photoplethysmography (cbPPG) is a novel technique that allows the contactless acquisition of cardio-respiratory signals. Previous works on cbPPG most often focused on heart rate extraction. This contribution is directed at the assessment of vasomotor activity by means of cameras. In an experimental study, we show that vasodilation and vasoconstriction both lead to significant changes in cbPPG signals. Our findings underline the potential of cbPPG to monitor vasomotor functions in real-life applications.

Keywords: camera-based photoplethysmography; cold face test; contactless monitoring; photoplethysmography imaging; PPG; vasoconstriction; vasodilation.

1 Introduction

Camera-based photoplethysmography (cbPPG) is a novel measuring technique that allows the contactless acquisition of vital signs using normal video cameras [1]. Similar to common photoplethysmography (PPG), an optical signal, which is related to the cardiac cycle, is derived from the microvascular bed of tissue. In contrast to PPG, cbPPG can be operated at a distance without an dedicated light source only using ambient light [2]. Furthermore, it overcomes the drawback of a punctual measurement as signals can be extracted arbitrarily from spatial video regions that contain skin [3].

Despite the far-reaching opportunities, most works on cbPPG focus on methods for robust heart rate detection [4]. However, the physiological origin of cbPPG signals and their behavior in the cardiovascular system are not completely understood yet. Only few studies have addressed measurable effects beyond the heart rate.

Our work is directed at the feasibility of assessing peripheral vasodilation and vasoconstriction by means of cameras. Both effects are induced externally by accepted techniques, and appropriate video recordings are evaluated. Results provide further understanding for cbPPG signal's origin and its behavior during vasomotor stimuli.

2 Material and methods

2.1 Vasomotor stimuli

Different interventions are known to induce vasoconstriction. The cold face test (CFT) is a non-invasive method that provokes a reaction in the autonomic nervous system by applying a low temperature stimulus on facial regions. Beside bradycardia, CFT causes peripheral vasoconstriction [5]. An inverse effect is simply achievable by an abrupt increase of the ambient temperature which leads to an acclimatization of the body and causes vasodilation [6]. Within this study, dilation is generated by a halogen lamp (heat radiation) whereas constriction is induced by CFTs.

2.2 Data and technical setting

Experiments were conducted indoors with 10 healthy subjects (9 male, 1 female) between 21 and 33 years (24.9 $\pm$ 3.35 years). All participants were informed about experiment's procedure and gave a written agreement. During cbPPG measurements, they lied relaxed on a tilt table and were asked to remain calm. We recorded the inner arm (shoulder to wrist) using an industrial camera (IDS UI-3370CP-C-HQ) at a frame rate of 300 fps, a resolution of 1024 $\times$ 200 pixels and a color depth of 12 Bit. Figure 2 shows the recording area for an example. Driven by a constant current, a three spot halogen lamp (3 $\times$ 75 Watts electrical power) was exclusively adopted as illumination. The lamp was aligned directly towards the arm and therefore also had a heating effect. In addition to the video

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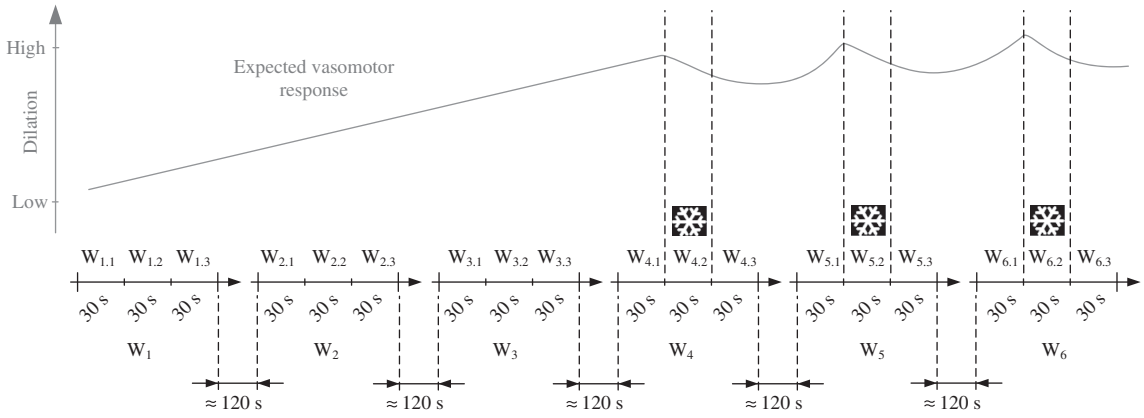

Figure 1: Experimental protocol. In gray, the assumption for the peripheral vasomotor activity is shown.

recordings, we synchronously captured subjects' electrocardiogram (ECG).

2.3 Experimental protocol

Figure 1 depicts the experimental protocol. Each experiment started with a resting phase. In order to treat this phase equally regarding the following CFTs, it was separated in three tests (W_1, W_2, W_3), each of them holding three subwindows of 30 s ($W_{i \in \{1,2,3\}, j \in \{1,2,3\}}$). After the resting phase three subsequent CFTs were carried out for every participant (W_4, W_5, W_6). Each CFT started with a 30 s baseline ($W_{i \in \{4,5,6\},1}$). After the baseline, an ice pack was applied to the forehead and remained there for further 30 s ($W_{i \in \{4,5,6\},2}$). The ice pack reached laterally to the temples. Eyes were not covered in order to avoid the ocular reflex. After removal of the ice pack, the subjects were recorded for further 30 s ($W_{i \in \{4,5,6\},3}$). The time between all tests was approximately 120 s. For each test, one video (90 s) was recorded separately leaving a total of 10 × 6 videos.

Figure 1 also depicts the assumptions for the peripheral vasomotor activities. The vasodilation effect, induced by warming, should manifest in a trend over the whole experiment. The vasoconstriction effect, caused by the CFT, should occur in each window W_4, W_5 and W_6. Note that such assumptions are qualitative, and interindividual differences must be expected (e.g. on the onset of vasoconstriction during CFT).

2.4 Image and signal processing

For further processing, we only used videos' green channel since it was shown to provide the strongest plethysmographic signal [3]. In each video, the arm was manually

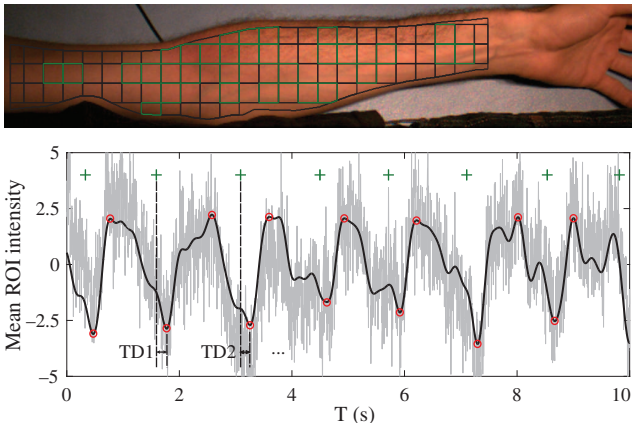

Figure 2: Recording area with set ROI (black) and ROI (green) to extract optimal cbPPG signal (bottom). The plot shows the raw (gray) and the filtered (black) signal with detected extrema (red), determined by using ECG's R-peaks (green).

selected as static region of interest (ROI). The wrist and skin edges were excluded because they often yield cbPPG signals that are in counter phase to wanted signals [7]. Blocks of 32 × 32 pixels were fitted in the ROI and truncated when they exceeded the border (see Figure 2). Over all videos, between 70 and 100 blocks were built (82.2 ± 7.9). As the signal quality varies considerably between blocks, only a subset of blocks should be used. Therefore, from each block, a cbPPG signal was extracted by averaging its containing pixels for every frame. All signals were detrended and bandpass-filtered by a Butterworth filter (order 3) with cutoff frequencies of 30 and 200 bpm. The minima of signals' beats were detected based on R-peak's positions that were annotated in the reference ECG. Time delays (TDs) were then calculated as temporal differences between these peaks and the found minima (see Figure 2, bottom). The reason behind this procedure is that in high quality signals, minima will correspond

to the start of systoles. In that case, variations in TDs just result from variations in the pulse transit time. Such variations are small compared to variations which appear in low quality signals. For poor signals, minima are not necessarily related to the beginning of systoles but occur randomly with respect to the R-peak resulting in a high standard deviation of TDs.

For further analysis, the signals from 30 blocks holding the lowest standard deviation of TDs were averaged (unfiltered) to build video's optimal cbPPG signal s_{opt}. The raw signal s_{opt} was detrended and bandpass-filtered, and this time, minima as well as maxima were detected using the reference ECG. We determined beats' height (distance between minimum and maximum) and built a pulse signal h_{opt}. Every h_{opt} was divided in consecutive 30 s windows and the median over each window was calculated resulting in 6×3 pulse values $h_{cam(i,j)}$ per subject.

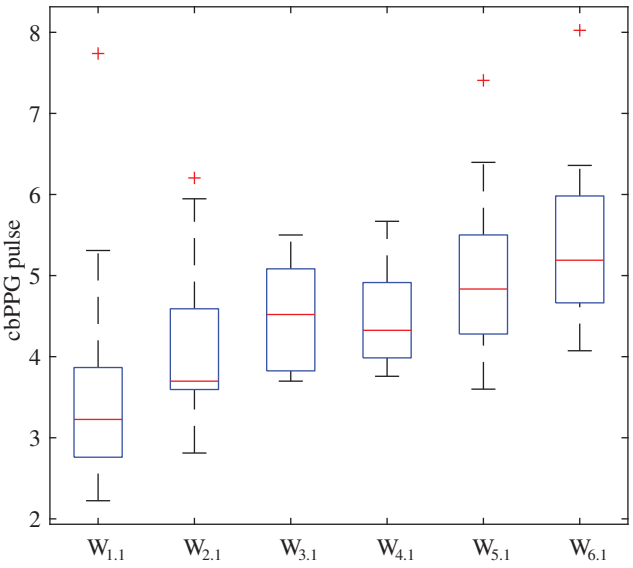

Figure 3: Results for analysis of vasodilation, depicted by boxplots of cbPPG pulse values h_{cam} for each baseline window (overall patients).

2.5 Evaluation and statistics

The trend effect (vasodilation) was analyzed using the first window of each test $W_{1,1} - W_{6,1}$. We assumed the pulse values continuously to increase over the six windows. To measure this dependence, we first calculated Spearman's *roh* between $h_{cam(i,1)}$ and $W_{i,1}$ over all subjects (10 values per window). Second, Page's test was applied to validate the significance of the trend. The test provides a test statistic L which was transformed into a common p-value.

For the three CFTs (vasoconstriction), we assumed the pulse values to decrease from subwindow 1 to 2 and increase again from subwindow 2 to 3. Due to high intraindividual variations, values $h_{cam(4-6,j)}$ were normalized on the median of h_{opt} from the respective video (4–6): $\hat{h}_{cam(4-6,j)}$. First, a Friedman test was used to determine if significant differences among the groups $\hat{h}_{cam(4-6,1)}$, $\hat{h}_{cam(4-6,2)}$ and $\hat{h}_{cam(4-6,3)}$ are existent. Second, a post-hoc analysis according to Schaich and Hamerle was applied to explicitly test for significant differences between subwindows 1 and 2, 1 and 3, and 2 and 3.

3 Results

The effect of vasodilation is clearly shown by a distinct dependence of pulse values $h_{cam(i,1)}$ on windows $W_{i,1}$, yielding a correlation of $\rho = 0.53$. Furthermore, the assumed positive trend in these values proved to be highly significant ($L = 825$, $p < 0.001$). Figure 3 depicts the behavior of the pulse values. Considering the changes between values' median, the largest increase (0.82) can be found from $W_{2,1}$ to $W_{3,1}$ and the lowest one (0.36) from $W_{5,1}$ to $W_{6,1}$. Against our expectations of a monotonous increase, a slight decrease (0.20) occurs from $W_{3,1}$ to $W_{4,1}$. Moreover, pulse values in $W_{4,1}$ show to hold the smallest interquartile range (IQR), whereas values in $W_{1,1}$ and $W_{2,1}$ have the biggest range between the minimum and maximum whisker.

Results show that also the vasoconstriction effect can be detected by cbPPG. Pulse value groups $\hat{h}_{cam(4-6,1)}$, $\hat{h}_{cam(4-6,2)}$ and $\hat{h}_{cam(4-6,3)}$ during the CFT were tested to be significantly different ($p = 0.041$). Post-hoc analyses proved the expected decrease in the normalized pulse values from subwindow 1 to 2 ($p_{1-2} < 0.001$), as well as an increase from 2 to 3 ($p_{2-3} = 0.040$). No significant difference was found between subwindow 1 and 3 ($p_{1-3} = 0.37$). Figure 4 depicts the pulse values in each group $W_{4-6,1}$, $W_{4-6,2}$ and $W_{4-6,3}$. Considering values' median, the highest change occurs between group 1 and 2 (0.224). Furthermore, values in group 2 feature the largest IQR, as well as the largest range between the minimum and maximum whisker. Over all subjects, the strongest vasoconstriction effect was found in the last window W_6.

4 Discussion

Subjects' body (or arm) acclimatizes gradually over experiment's time. We expected the largest vasodilation effect

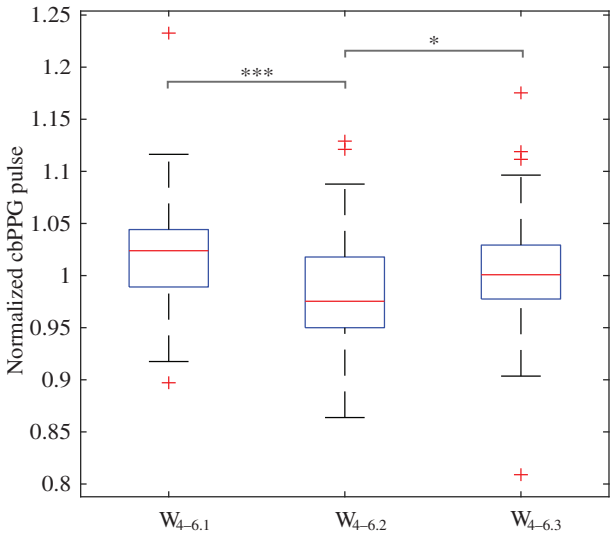

Figure 4: Results for CFTs, depicted by boxplots of normalized cbPPG pulse values $\hat{h}_{cam}$ for each subwindow (overall patients and replications). If significant, post-hoc tests' outcome is denoted by $*p \leq 0.05$ and $***p < 0.001$.

at the beginning and a saturation towards the end. The lowest increase in pulse values' median between $W_{5,1}$ and $W_{6,1}$ confirms the latter assumption, whereas the largest increase between $W_{2,1}$ and $W_{3,1}$ should actually take place between the first two windows. This shift could be generated by single outliers. The high variation in $W_{1,1}$ and $W_{2,1}$ can be explained by different starting conditions of the subjects (temperature of place they came from, effect on circulation after lying down). The drop in W_4 is possibly caused by an additional sympathetic arousal in expectation of the first CFT.

For the CFTs, windows of 30 s proved to be suitable to assess the effect of vasoconstriction. Pulse values' increase in $W_{4-6,3}$ reflects subjects' recovery from the test and the overlaying trend effect. The generally high variation in $W_{4-6,2}$ can be explained by individual differences regarding the CFT reaction: vasoconstriction's strength, time delay between ice pack's application and actual reaction.

A drawback of our protocol is the influence of warming during the CFT since warming and the CFT both lead to opposite effects. Nevertheless, the significant decrease in pulse values as a result of the CFT underlines cameras' potential to monitor vasomotor activity. The strongest impact of the CFT in W_6 furthermore supports the idea of saturation in vasodilation.

5 Conclusion

Our analyses prove that vasodilation and vasoconstriction can be assessed by means of cameras. This finding opens up a number of applications directed at monitoring vasomotor activity as a result of central or even local interventions or processes. However, suitable ROIs have to be identified in order to successfully apply cbPPG. Pretests already show further potential for improvement by applying an adaptive ROI selection.

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Author's Statement

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