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Validation of Skin Perfusion Monitoring by Imaging PPG versus Laser Speckle Imaging

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Abstract: Assessment of skin perfusion can reveal signs of deterioration and help to prevent critical states. Commonly applied clinical tests to capture skin perfusion are subjective and often hard to quantify. Laser speckle contrast analysis (LASCA) is a technique that can capture skin perfusion at high spatial and temporal resolution. LASCA requires, however, a complex setting and is not suited for monitoring under clinical conditions. Imaging photoplethysmography (iPPG) might be an easy to use alternative. However, direct comparisons of LASCA and iPPG, and thus proves of iPPG's capabilities to capture skin microperfusion, are rare. In this work, we compare the longitudinal development of the amplitude of green channel and near-infrared iPPG and LASCA after application of a hyperemic test. Our results show statistically significant increases in amplitude over time in all modalities. The maximum increase in median normalized amplitude is 1.281 for the green channel, 0.594 for near-infrared and 1.111 for LASCA. Median Spearman's rank correlation coefficient of the amplitude for green channel and LASCA is $r = 0.89$ and $r = 0.71$ for near-infrared and LASCA.

Keywords: imaging photoplethysmography, laser speckle contrast analysis, perfusion, remote sensing, microcirculation

1 Introduction

In critical illness, global cardiovascular parameters often remain stable, although the microcirculation is already constrained. The skin perfusion can serve as an early indicator for incipient complications and thus contains high clinical value [9]. Simple clinical tests to evaluate skin perfusion play a surprisingly important role. The capillary refill time (CRT) and the Mottling Score (MS) can indicate an undersupply of the inner organs, show complications after surgery and have prognostic value [1, 3, 8, 13]. However, CRT and MS are subjectively evaluated, limitedly quantifiable and only intermittently available.

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Today, maybe the most powerful method to evaluate skin perfusion is laser speckle contrast analysis (LASCA) [4]. LASCA is based on the interference patterns of backscattered light. The amount and velocity of red blood cells blurs the image, thus reducing the contrast [5] . The measurement equipment is quite expensive and LASCA is only suitable for short-term measurements. Imaging photoplethysmography (iPPG) is a low-cost approach to capture physiological variables, which has become immensely popular in recent years [11, 14]. iPPG uses cameras to record the skin and exploits subtle variations in the intensity of the detected light. iPPG overcomes the drawbacks of LASCA and also is affected by the superficial perfusion. Thus, iPPG can be seen as having great potential to monitor skin perfusion. However, while many current works direct at heart rate extraction from iPPG, few works addressed iPPG's potential to monitor the strength of skin perfusion and, to the best of our knowledge, only two works conducted direct comparisons to LASCA [2, 10]. One of these works could show a correlation of LASCA and green channel iPPG during whole body heating and a cognitive test [10]. We extend such works by considering a novel stimulus and measurement site. Furthermore, we include NIR as an additional wavelength for iPPG.

This work covers the comparison of the longitudinal development of the perfusion assessed by iPPG to reference LASCA measurements upon a hyperemic test. The stimulus is applied by an ointment that contains nicoboxil and nonivamide, which are known to cause vasodilation and thus an increase in skin perfusion [12]. We hypothesize that we are able to capture such effect by an increased amplitude in iPPG.

The remainder of this work is structured as follows. In section 2 we describe the used data, methods and statistics. Section 3 and section 4 provide results and discuss them and section 5 gives an outlook over future works.

2 Methods and Materials

2.1 Data

The used data originates from own experiments invoking 15 healthy volunteers (5 female, 10 male; age 25.5 ± 5.3 years) of Caucasian origin. All subjects gave written informed consent. We recorded the forearm using an RGB (UI-3370CP-

C-HQ, IDS) and a near-infrared (NIR) (UI-3370CP-NIR-GL Rev.2, IDS) camera with a color depth of 12 bit, a resolution of 1936×1216 pixels for RGB and 1536×1536 pixels for NIR and a frame rate of $21\,\mathrm{fps}$. The distance between the cameras and the forearm was approximately $40\,\mathrm{cm}$. The recordings took place in a controlled environment using indirect artificial illumination by two spotlights (Walimex pro LED Sirius 160 Daylight 65W, WALSER GmbH & Co. KG) and a ring light for direct NIR illumination (SVL Ring Light RC130-850, Stemmer). Both illuminations affect the NIR recordings, but before the experiment we experimentally validated the ring light to be essential. As reference, we used LASCA measurements (Perimed-PSI-System NR, Perimed) with a frame rate of $21\,\mathrm{fps}$.

Subjects were recorded in a supine position. Before recording, we marked a rectangular region of interest (ROI) of $4\,\mathrm{cm} \times 12\,\mathrm{cm}$ on the right forearm (see figure 1). For iPPG (RGB and NIR were carried out simultaneously) and LASCA, we conducted measurements of $20\,\mathrm{s}$ duration alternately six times, beginning with a baseline (BL) recording of iPPG and then LASCA. After BL measurements, we applied the ointment in the ROI. Between each of the following intervals (ST1 to ST5) a pause of approximately $5\,\mathrm{min}$ is included to ensure a pronounced effect of the ointment [12].

One recording had to be discarded due to technical problems, thus 14 recordings remained. Additional recordings were excluded by further processing steps. Details on the further exclusion are given in section 2.3.

2.2 Processing

The following section describes the processing of the data including signal formation, filtering, ensemble averaging and feature extraction.

iPPG Signal Formation: Our analysis invoked intervals of $10\,\mathrm{s}$ from each video (BL to ST5). To acquire iPPG signals from our videos, we manually defined rectangles within the marked are on the forearm as our ROIs in the first frame of the first interval (BL). For each of the following intervals (ST1 to ST5), we shifted the ROI to fit slightly changed body positions, if necessary. During the duration of each interval, the ROIs remained static. We obtained iPPG signals by averaging all pixels inside the ROI. The signals were then inverted to resemble the conventional PPG and linearly interpolated to a sampling rate of $2000\,\mathrm{Hz}$. Figure 1 shows an example of the defined ROIs.

Signal Processing: We filtered the iPPG signals with a bandpass filter (5th-order Butterworth filter with cut-off frequencies of $0.4\,\mathrm{Hz}$ and $8\,\mathrm{Hz}$). We had to apply an additional bandstop filter (cut-off frequencies of $0.75\,\mathrm{Hz}$ and $0.85\,\mathrm{Hz}$) to remove artifacts caused by the ceiling light. Single beats from the iPPG signals were detected with the method of Lazaro et al. [7]. The method considers the steepest ascent as the detection point t_i. Around each detection t_i we defined a beat segment in the interval $[t_i - 0.45 \cdot \widetilde{\mathrm{BBI}}; t_i + \widetilde{\mathrm{BBI}}]$, where $\widetilde{\mathrm{BBI}}$ is the median length of beat to beat intervals (BBI) within the considered interval. All detected beat segments were correlated pairwise. We discarded beat segments with a mean pairwise correlation lower than 0.3. The remaining segments were ensemble averaged and potential linear trends were removed to form a beat template. The median number of usable beats for template generation per measurement site was 9.

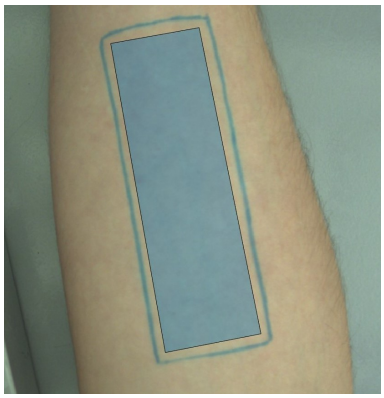


Fig. 1: Exemplary ROI definition. The outer blue line shows the area where the ointment was applied. The blue filled area indicates the actual ROI used for iPPG formation.

LASCA Processing: The Perimed-PSI-System provides variance (σ^2) and intensity ($\overline{I}$) frames. σ refers to the spatial standard deviation of the speckle intensity, whereas $\overline{I}$ denotes the mean intensity over an area of 3×3 pixels. The product of the instrument specific coherence factor β and the ratio of σ and $\overline{I}$ yields the contrast image C:

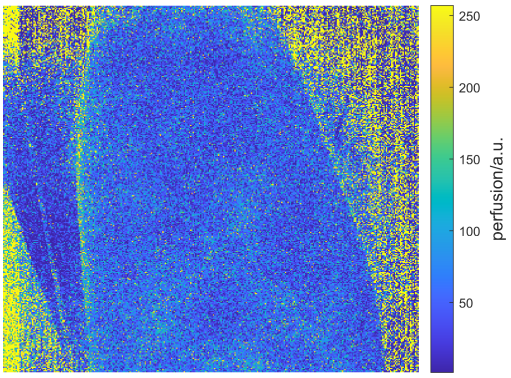
$$C = \beta \cdot \frac{\sigma}{\overline{I}} \,. \tag{1}$$

The perfusion image P is then calculated from C and the signal gain k as follows:

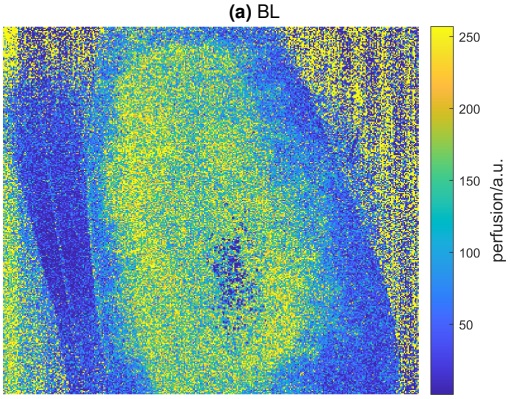
$$P = k \cdot \left(\frac{1}{C} - 1 \right) \,. \tag{2}$$

As β, k is instrument specific. β ensures $P = 0$ for static objects. k is a calibration factor and ensures equal perfusion values for different instruments on a motility standard. We calculated perfusion images for all frames. Figure 2 shows exemplary perfusion images of a subject for two intervals. Then, we determined the mean of a ROI within the perfusion image, yielding one mean perfusion time series per subject.

Feature extraction: We opted to analyze the amplitude (maximum of the template) of the iPPG and the mean of the perfusion time series for each interval.



(a) BL



(b) ST4

Fig. 2: LASCA perfusion image for an exemplary subject over time. The perfusion is depicted as a false-color image.

2.3 Statistical Assessment

We excluded subjects according to the following exclusion criteria: (1) Heart rate was within bandstop filter range (two subjects). (2) Template generation failed due to too few beats in the iPPG signal of a single interval (four subjects). Finally, eight recordings remained for statistical analysis.

To evaluate the effect of the ointment, we first conducted a Friedman test for each recording setup on a significance level of $\alpha = 0.05$. For significant Friedman test results, we conducted Wilcoxon signed-rank tests as post-hoc tests between BL and all other intervals (BL vs. ST1, BL vs. ST2, BL vs. ST3, BL vs. ST4, BL vs. ST5), thereby creating non-orthogonal contrasts. Thus, we used the Holm-Bonferroni correction to adjust the p values of our post-hoc tests with the respective correction factor $(k - i + 1)$ (with k being the number of conducted tests and i the rank of the p values sorted in ascending order) [6]. As a measure of effect size, we calculated the difference of medians for all statistically significant comparisons. For visualization purposes, we normalized the amplitudes to the mean of all intervals.

We also used Spearman's rank correlation coefficient to assess the relationship between mean perfusion and the amplitude of the green and NIR channel iPPG for all subjects.

3 Results

Figure 3 depicts the behaviour of the amplitude for all modalities over all intervals. For better visibility, we omitted outliers in those plots (values are defined as outliers if they are greater than $q_3 + 1.5 \cdot \text{IQR}$ or less than $q_1 - 1.5 \cdot \text{IQR}$, where q_1 is the first quartile, q_3 is the third quartile and IQR is the interquartile range). Friedman test yielded statistically significant results for all modalities. Amplitudes increase significantly for all modalities between BL and ST3, ST4 and ST5 ($p < 0.05$). A significant increase between BL and ST2 ($p < 0.05$) can be observed for LASCA and the green channel. The maximum increase in median normalized amplitude is 1.281 for the green channel, 0.594 for NIR and 1.111 for LASCA. Median Spearman's rank correlation coefficient of the amplitude for green channel and LASCA is $r = 0.89$ and $r = 0.71$ for NIR and LASCA.

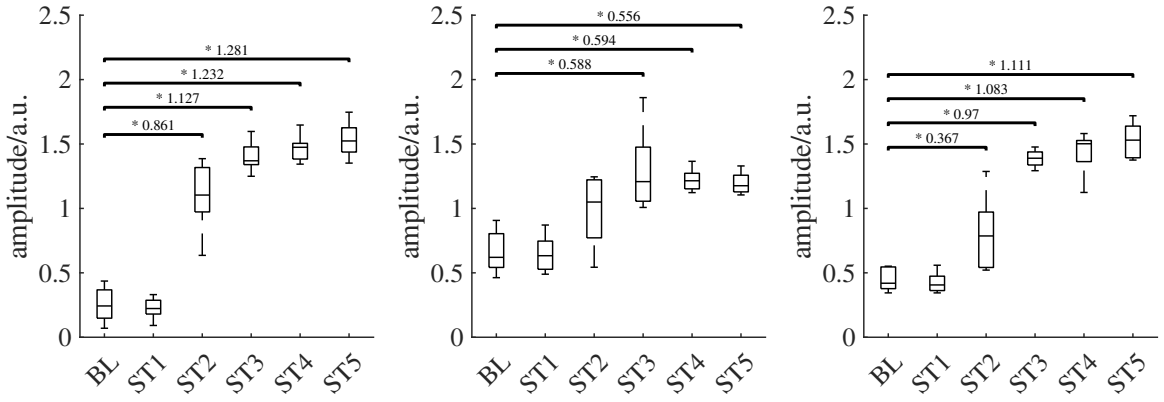
4 Discussion

We assume the used ointment leads to vasodilation [12] and thus stronger perfusion. We do not expect any other factors to impact the PPG. In LASCA, particle velocity is correlated to contrast, i.e. a static pattern yields a contrast of $C = 1$ and thus a perfusion of $P = 0$ (see equation 1 and 2), whereas P increases with red blood cell velocity and amount [4, 5].

As expected, the results show a significant increase in perfusion amplitude for our LASCA measurements. The iPPG captures the blood volume changes and thus exhibits a greater amplitude over time. Generally, the same trend, i.e. an increase of the amplitude over time, can be observed for all modalities, which is according to our expectations.

The effect of the stimulus is less pronounced in NIR when compared the other modalities. This could be due to limited signal quality of the NIR recordings leading to spurious results. Another possible explanation is the differing penetration depth of the modalities. Deeper vessels reached by NIR may be affected by the ointment to a lesser extent than superficial ones.

Our findings with regard to the relationship of LASCA and iPPG confirm the results of previous works [2, 10] and demonstrate the benefit of using green channel iPPG over NIR.



(a) Green channel of RGB **(b)** NIR **(c)** LASCA

Fig. 3: Results for the analysis of the amplitude over all analysis intervals, depicted by boxplots. If significant, post-hoc tests' outcome is denoted by * $p < 0.05$, ** $p < 0.01$ or *** $p < 0.001$ and the effect size is given. Outliers are not shown.

5 Conclusion and Outlook

Our results indicate that iPPG can be used as an alternative to LASCA to assess longitudinal development of perfusion. To further strengthen iPPG as an alternative, approaches to examine the perfusion in a two-dimensional way, as it is possible with LASCA, should be investigated. This would exploit spatial information beyond averaging in a ROI.

Author Statement

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