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Modified Allen Test Assessment via Imaging Photoplethysmography

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Abstract: The modified Allen test (MAT) is a widely used tool to examine the perfusion capacities of the arteries (ulnar or radial) of the hand. In clinical practice, MAT is utilized to ensure that in the event of occlusion, remaining vessels guarantee sufficient hand perfusion. This work shows that perfusion assessment via imaging photoplethysmography (iPPG) can be used to assess MAT. We captured the hands of seven subjects with a standard RGB camera while performing a MAT. Out of these captured video recordings, the iPPG signal was extracted via plane-orthogonal-to-skin transformation. Based on these extracted signals, we derive the heart rate, signal-to-noise ratio, DC parameter, and correlation with a reference iPPG signal to determine if an Allen test was pathological or inconspicuous. For all seven subjects, the results of our MAT assessment were identical to the medical expert's assessment. This paper presents a procedure and initial thresholds for objectively evaluating and quantifying MAT. We show how globally and locally calculated parameters can be used to assess the perfusion of the investigated hand. This analysis makes it possible to quantify the exact point in time when the perfusion is again sufficient. If a reperfusion problem occurs, we are able to localize the spatial regions of occurrence. The presented hardware setup is affordable and can be easily installed and used in every doctor's office.

Keywords: Imaging photoplethysmography, modified Allen-Test, Perfusion Assessment, Blood Flow, Heart rate.

1 Introduction

In the past years, the possibility of measuring vital parameters camera-based has created a lot of attention [7]. The underlying technique is typically referred to as imaging photoplethysmography (iPPG) or remote photoplethysmography (rPPG). This approach is based on the fact that oxygenated blood absorbs more light than the surrounding tissue. Thus, variations in blood volume in the human circulatory system affect the light reflected from the subject's tissue surface to the camera that is capturing the scene. The research regarding iPPG addresses many life situations and application scenarios, such as sports and fitness [12], security applications [6], and medical applications [9]. After initial methods based on capturing human faces under laboratory conditions [6–8], more and more applications under realistic conditions have been investigated in recent years [9]. Besides the face, the skin surface of the hand is the body region most frequently examined in the context of iPPG [11]. In the medical field, iPPG is adapted to contactless patient monitoring (e.g., heart rate, respiratory rate) and provides added value during surgical interventions, e.g., in skin flap transplantation [10] and kidney transplantation [9].

In this work, we focus on the modified Allen test (MAT), a widely spread tool to examine the perfusion capacities of the arteries of the hand. MAT is used in clinical practice to ensure that the remaining vessel, in the event of occlusion of any cause, guarantees sufficient perfusion [2]. During the test, an artery is occluded, and no blood flows into the hand; after a specific time, the artery is opened, allowing blood to flow into the hand again. MAT has been established as the appropriate screening tool in clinical applications, for example, in anesthesia and intensive care (before arterial cannulation), in cardiology (before coronary angiography and radial artery harvesting for coronary artery bypass graft surgery), and in plastic surgery (prior to the removal of a radial forearm flap) [3]. As a non-contact method for testing hand perfusion, hyperspectral imaging (HSI) has already been proven valuable [5]. It shows a good correlation to the results of MAT, and anatomical anomalies can be visualized. In comparison, we use an RGB video as input, which has the advantage of using standard equipment already available in hospitals [10]. IPPG from an RGB video is an objective, measurable, and reproducible method. Thus, it has optimal properties for the assessment of MAT.

The difficulties with MAT are the lack of unanimous definitions of thresholds and the subjectivity in determining when reperfusion is complete [3]. Therefore, in this work, we suggest an iPPG-featured MAT, which helps to quantify the test result. We show how globally and locally calculated parameters can be used to assess the perfusion of an investigated hand.

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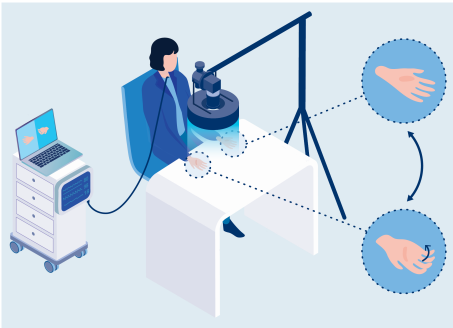

Fig. 1: Setup of the performed data acquisition. The subject is seated on a chair and lays both hands flat on a table. An RGB camera and a light source are focused perpendicularly onto both palms. Throughout the recording, the subject's vital signs are measured via ECG.

2 Allen Test

The Allen Test was first described in 1930 by EV. Allen; the test was developed to diagnose thromboangiitis obliterans [1]. Today, the modified Allen Test (MAT) is used regularly to analyze the ulnar and radial artery, which supply the hand with oxygenated blood [2, 3]. The reperfusion time provides information about the efficiency of the tested vessel and reperfusion within 3 s to 12 s is considered physiological [3].

MAT is a simple and inexpensive tool, but it also has limitations: it requires the cooperation of the patient for its correct performance, there is no unanimous agreement on the time of adequate arterial compression, the interpretation of the test results is not objective, and the execution of the technique can generate false positives (due to a forced hyperextension of the wrist during the test) or false negatives (due to insufficient compression of the artery) [3].

3 Data

As shown in Fig. 1, subjects were seated during the recording, and their hands rested on a table. The elbow joints were slightly flexed. We used a Basler MED ace 5.1 MP 75 RGB camera (Basler AG, Germany) and an LED ring light (Walimex, South Korea) to capture the hands. All sequences were recorded with a resolution of $2048\,\text{px} \times 2448\,\text{px}$ and a frame rate between 30 fps to 60 fps. Each subject was connected to a vital sign monitor (VitaGuard 3100, GETEMED, Germany) to measure the electrocardiogram (ECG) as ground truth during the recording. The camera continuously recorded both hands. The top row of Fig. 3 illustrates the individual steps of a MAT, which are then applied to each hand and artery (i.e., four times in total). A medical expert performed the MAT on both hands, testing the sufficient perfusion by the radial and ulnar arteries. The recordings and analysis can be split into four consecutive *blocks*, each focusing on a different hand and artery: #1 right-hand radial, #2 left-hand radial, #3 right-hand ulnar, and #4 left-hand ulnar artery. The test of each hand-artery combination was performed as follows: A baseline recording was taken for 20 s. The examiner continuously occluded the ulnar and radial arteries for the next 60 s. First, the patient was asked to pump his wrists for 20 s, then the ischemia recording was performed for 20 s on the steady open palm. This was followed by another 20 s of pumping by the patient. The examiner then opened one of the arteries while keeping the other occluded. The reperfusion was recorded for 30 s. The second artery was opened subsequently, and the full reperfusion recording was taken for 20 s.

The described recording makes it possible to compare the ischemic and reperfusion state with the earlier recorded baseline. A video of at least 520 s was captured by recording each subject's four blocks in a row. Seven healthy subjects (6 male, 1 female) were recruited from the Fraunhofer Heinrich Hertz Institute staff (Berlin, Germany). Informed consent for data collection and pseudonymized and anonymized data storage was obtained from all subjects.

4 Method and Assessment

Our performed MAT perfusion analysis is based on global and local parameters calculated from the extracted iPPG signal. The global parameters are computed from a one-dimensional iPPG signal extracted from a video recording of the hands during MAT. The local parameters are determined from the iPPG signal and resolved at the pixel level in the region of interest (ROI). Due to the best results under different illumination conditions and the excellent signal quality [9], we use the Plane-Orthogonal-to-Skin Transformation (POS) to extract the iPPG signal (locally and globally) from the input video [12]. The two iPPG resolutions (local and global) require different prepossessing steps, which are explained in detail in [9].

We split each video frame into left and right hands. As ROI, we define the visible skin tissue segmented by threshold-based skin segmentation. Each analyzed video *block* (see Sec. 3) of the recorded MAT is split into *baseline*, *ischemia*, and *reperfusion* for the hand of interest. At the same time, we use the recording of the opposite hand as a *reference* recording. We extract the iPPG signal from the reference hand and use this signal to calculate the correlation with the reference signal. We also extract the heart rate from the iPPG reference signal and then use this heart rate to calculate the signal-to-noise ratio (SNR) of the iPPG signal of the analyzed hand.

We assess the perfusion during MAT based on the SNR (see [9]), the direct current (DC) parameter [4], and the correlation with a reference signal (see [9]). These values are calculated globally - one scalar value per analyzed time window - and locally - resulting in a 2D map where each spatial position is assigned to the calculated parameter for this corresponding position. For the MAT, it is known that sufficient blood flow through the hand is restored within $12\,\mathrm{s}$ [3]. Therefore, we choose an analysis with a sliding window of $10\,\mathrm{s}$ (step size $1\,\mathrm{s}$).

To assess the perfusion of the hand, we compare the mentioned parameters during the *ischemia* and *reperfusion* state with the prior calculated *baseline* values. We classify MAT as correctly performed if, followed by the occlusion of both arteries, the analyzed SNR and reference correlation decrease, and the DC parameter increases; thus, an ischemic state can be classified. The local maps also show whether the occlusion of the arteries was correct if no iPPG signal of appealing quality was present in the entire image area. If pathological findings were present, the local maps could be used to identify poorly perfused regions. Low-frequency and permanent blood volume fluctuations resulting from, e.g., respiration and artery occlusion are usually attributed to a PPG signal's direct component (DC) [4]. Therefore, the DC parameter is suitable for monitoring the ischemia and reperfusion during a MAT. After opening the examined artery (ulnar or radial), we expect the analyzed parameters to be back in the range of the *baseline* values. The MAT is assessed as inconspicuous if the *reperfusion* values have reached the *baseline* range after $12\,\mathrm{s}$ at the latest. All analyzed parameters influence each other and are dependent on each other. Only if all parameters show a corresponding course can the MAT be evaluated.

5 Results

This section shows exemplary results of an MAT of an arbitrarily selected subject (male, 34 years) and analysis block (right hand, radial artery).

Global Analysis. In Fig. 2, the trajectories of the globally calculated parameters are displayed. The *baseline* shows the level that should be reached during the *reperfusion*. The reference correlation during the reperfusion is with a maximum of $\rho_{ref} = 0.76$, below the baseline, but still has a sufficient level. Since the arteries are occluded for over $60\,\mathrm{s}$, it may take a while for the reference correlation to reach its baseline level. However, the plot shows a steady increase and the reference correlation eventually converges to the initial value. On the other hand, the SNR during reperfusion (SNR between $0.31\,\mathrm{dB}$ to $2.85\,\mathrm{dB}$) exceeded with the first analyzed window the level of the baseline (SNR between $-0.4\,\mathrm{dB}$ to $1.1\,\mathrm{dB}$), which means that the hand is sufficiently perfused. The DC plot shows that after approximately $6\,\mathrm{s}$, the parameter reaches a steady level within the range of the baseline. The global parameters shown in Fig.2 reveal that the analyzed artery adequately supplies the hand with blood. Perfusion reaches the baseline level within $6\,\mathrm{s}$ to $10\,\mathrm{s}$, indicating rapid and complete reperfusion of the hand through the analyzed artery.

Local Analysis. Fig. 3 shows the resulting local maps for the analyzed subject. The displayed maps show the parameters for the first analyzed time window for each part. During *ischemia*, the SNR and reference correlation over the whole spatial region can be classified as noise, indicating that the arteries are completely occluded. After the radial artery is opened, the parameters in the *reperfusion* maps increase and look almost identical to the corresponding baseline maps. This indicates that, on average, there is an equivalent signal quality compared to the baseline during the first $10\,\mathrm{s}$ of reperfusion. With this local analysis, we can visualize that each hand region is completely reperfused. The local maps during reperfusion (see Fig. 3) also show that the ulnar artery is still occluded and the hand is perfused via the radial artery. The supervised physician did not detect any abnormalities in the tests performed. As every patient in our data set was healthy, we did not expect any pathological Allen tests and had not detected any in our analysis.

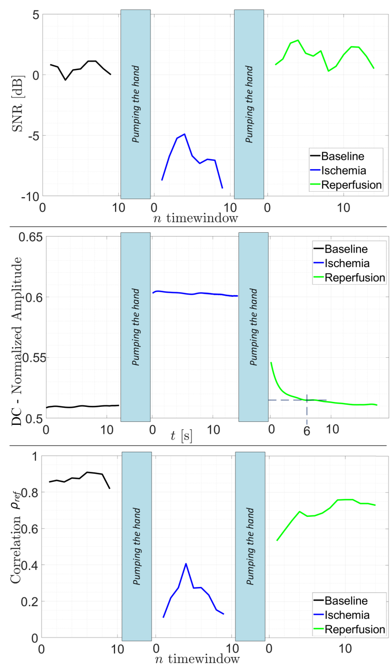

Fig. 2: Global parameter of the analyzed states baseline, ischemia, and reperfusion. At the top is the SNR of the examined person, in the middle is the DC parameter, and at the bottom is the correlation with the iPPG signal of the other hand.

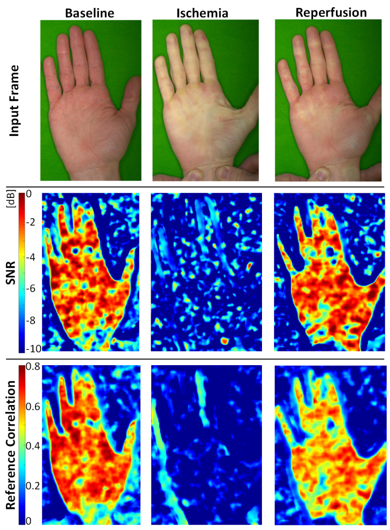

Fig. 3: For each of the examined states, this figure shows an input image in the top row, the local SNR map in the middle, and the reference correlation map of the subject examined at the bottom.

6 Discussion

Since the monitoring and analysis of the MAT using iPPG is new, no comparable reference values could be found. To establish this method, threshold values for each parameter (SNR, reference correlation, and DC parameter) must be defined to distinguish between the states *perfused* and *ischemia* robustly. We are planning a clinical study to retrieve data to determine these thresholds. Moreover, this study would increase the chance of capturing a pathological subject. We plan to use camera equipment available in the clinical environment to obtain practical values from the study.

7 Conclusion

In this work, we analyzed the data of seven healthy subjects, and all MATs were inconspicuous. It is shown that the analyzed parameter of each examined hand and artery of each subject reached baseline level within 10 s. The results show a reliable differentiation between *baseline*, *ischemia*, and *reperfusion* for all analyzed parameters. We showed that continuous monitoring and quantitative assessment of the MAT is possible with a simple setup consisting of an RGB camera and an LED ring light (see Sec. 3). We achieved comparable results to [5] without purchasing an expensive HSI camera. Similar to [5], we can visualize the analyzed parameters in 2D maps and assign these parameters to the corresponding spatial position, providing us with additional information compared to MAT performed in the field. Our setup is imaginable in every doctor's office to support the medical expert during MAT. The examiner would receive direct feedback on the correct performance of MAT. Additionally, the findings can be verified with objective and reproducible results from the iPPG analysis.

Author Statement
This work was funded by the German BMBF under Grant No. 16SV8602 (KIPos). The authors state no conflict of interest. Informed consent has been obtained from all individuals included in this study. The research related to human use complies with all the relevant national regulations institutional policies and was performed in accordance with the tenets of the Helsinki Declaration, and has been approved by the author's institutional review board or equivalent committee.

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