Flakë Bajraktari*, Jan Liu and Peter P. Pott

Methods of Contactless Blood Pressure Measurement
A Systematic Review

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Abstract: Contactless blood pressure monitoring displays a chance for detecting hypertension and increasing the awareness of cardiovascular diseases. Camera-based methods show high potential for replacing inconvenient cuff-based technology. Blood pressure estimation through pulse transit time (PTT) and other parameters obtained from photoplethysmography (PPG) signal present a promising alternative to conventional blood pressure measurement. In this paper, recent approaches for contactless blood pressure monitoring were reviewed. All of the articles implemented systems based on PPG, whereas most of them used PTT as measuring parameter. The results are reviewed and summarized while pinpointing key challenges and discussing expectations for future research.

Keywords: Vital signs monitoring, blood pressure, camera-based measurement, PPG, PTT

1 Introduction

Blood pressure (BP) has been found to be strongly related to cardiovascular disease and mortality [1]. Among others, it comprises stroke and heart attack which are known to be the major cause of disability and death in the world [1]. Raised blood pressure is responsible for 62% of strokes and nearly 50% of coronary heart disease in developed countries [2]. Although hypertension is a treatable cardiovascular risk factor, it shows low rates in awareness and control. This lacking hypertension control stems from the fact that ubiquitous BP monitoring technologies are not feasible for everyday life in the mass population and often require the help from third parties. BP monitoring at home, which has gained wide acceptance, is performed with automated BP measurement devices. While the recording of BP levels from the brachial artery takes place automatically without stethoscope, it still requires the placement of an inflatable cuff on the upper limb. This application assumes correct application of the sensors in the cuff and therefore constraints the reliability of the measured BP levels [3]. Furthermore, inflatable cuffs are uncomfortable for patients and provide only intermittent BP values, whereas cuffless technologies are mostly invasive and expose the patient to infections [4]. To overcome the limitations of state-of-the-art measuring methods and thus to compensate the lack of awareness of hypertension, there have been investigations towards the development of contactless measurement technologies.

In this paper, a review on non-invasive methods of BP measurement is given, focusing particularly on technologies that do not require any physical contact to the patient for measuring BP levels. We focus on a well-known approach with high potential for ubiquitous BP measurement systems represented by pulse transit time. But also other parameters extracted from photoplethysmography signals are part of the presented papers. This review was initiated to identify and summarize contactless measurement methods in regard to accuracy and applicability in order to demonstrate possible future directions and potential challenges.

2 Methods

The objective of this review is to present the best available information related to contactless BP measurement. Different methods are summarized that could contribute to future research and help assess seminal methods for measuring BP. Existing literature between 2016 and 2021 was reviewed in order to focus on recent advances. Databases searched were Google Scholar and PubMed. Search terms around contactless vital signs monitoring and blood pressure measurement were used. Relevant articles were found by at first considering the title and abstract. For this review only measurement methods without any physical contact between the subject and the measuring device were included. Only English literature was included.

* Corresponding author: Flakë Bajraktari: Institute of Medical Device Technology, University of Stuttgart, Pfaffenwaldring 9, 70569 Stuttgart, Germany, flake.bajraktari@imt.uni-stuttgart.de
Jan Liu, Peter P. Pott: Institute of Medical Device Technology, University of Stuttgart, Germany

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### Table 1: Overview of the reviewed systems for contactless BP measurement.

<table>
<thead>
<tr>
<th>Year</th>
<th>First author</th>
<th>Ref.</th>
<th>Setup</th>
<th>Method</th>
<th># subjects</th>
<th>Data details</th>
<th>Sites</th>
</tr>
</thead>
<tbody>
<tr>
<td>2016</td>
<td>Jeong</td>
<td>[5]</td>
<td>High-speed camera (420 fps), two light sources</td>
<td>PTT from PPG</td>
<td>7</td>
<td>3 females, 4 males, 3 recordings at 3 exertion levels each, age: 20-50</td>
<td>Face, palm</td>
</tr>
<tr>
<td>2017</td>
<td>Huang</td>
<td>[6]</td>
<td>Camera (75 fps), regular fluorescent lamp (400 lx)</td>
<td>PTT from PPG, machine learning</td>
<td>13</td>
<td>3 females, 10 males, 10 recordings each, dataset: 1300 pairs</td>
<td>Face, palm</td>
</tr>
<tr>
<td>2018</td>
<td>Oiwa</td>
<td>[7]</td>
<td>Smartphone camera (30 fps), illumination (900-1000 lx)</td>
<td>PTT from PPG</td>
<td>8</td>
<td>1 female, 7 males, age: 22.4 ± 2.7, 4x2 min. rest (1 min. cold stimulus)</td>
<td>Face</td>
</tr>
<tr>
<td>2018</td>
<td>Fan</td>
<td>[8]</td>
<td>Camera (30 fps, 120 fps)</td>
<td>PTT from PPG</td>
<td>6</td>
<td>Age: 20-35</td>
<td>Face, palm</td>
</tr>
<tr>
<td>2019</td>
<td>Luo</td>
<td>[9]</td>
<td>Smartphone camera, light source</td>
<td>TOI, machine learning</td>
<td>1328</td>
<td>Age: ≥18, data collected over 2 years: 2242, 100-139/60-89 mmHg</td>
<td>Face</td>
</tr>
<tr>
<td>2020</td>
<td>Finkelstein</td>
<td>[10]</td>
<td>High-speed camera (429 fps), IR light source</td>
<td>PTT from PPG</td>
<td>2</td>
<td>3x1 min recordings</td>
<td>Face, palm</td>
</tr>
<tr>
<td>2020</td>
<td>Wuerich</td>
<td>[4]</td>
<td>Camera (120 fps)</td>
<td>PTT from PPG, machine learning</td>
<td>5</td>
<td>3 females, 2 males, age: 24-27, 15x30 sec, exercise, 90 pairs each</td>
<td>Face, palm</td>
</tr>
<tr>
<td>2021</td>
<td>Ding</td>
<td>[11]</td>
<td>Camera (30 fps)</td>
<td>PWHA from PPG</td>
<td>16</td>
<td>8 females, 8 males, age: 18-35, deep breath, sports, 98-151/59-110 mmHg</td>
<td>Face</td>
</tr>
</tbody>
</table>

### 3 Results

Contactless BP measurement mainly uses PPG with the aid of a camera. Camera-based PPG, also known as iPPG, is similar to contact-based PPG with the difference that ambient light is used instead of dedicated light sources. Many investigations using contactless PPG have been conducted focusing on heart rate and respiratory rate detection. In recent years, investigators have attempted to use camera-based PPG for BP estimation [11]. The relationship between BP and PTT has been investigated in many studies and represents a promising approach to noncontact BP measurement. PTT depicts the time delay of the pressure wave between a proximal and a distal arterial site of the body, such as face and palm, and can be estimated by the use of their waveforms. It is inversely related to the BP [12]. An overview of the works included in this review is given in Table 1.

In the paper of Jeong and Finkelstein, the correlation between PTT and BP is used to estimate BP contactless by analyzing serial skin color images [5]. The generation of a high number of images is assumed to achieve a higher accuracy regarding the time lag between pulse wave arrivals at two different body sites. Therefore, a high-speed camera with 420 frames per second (fps) is used to record the changes of skin color caused by blood pulsation including two LED light sources, which are perpendicularly positioned to the face and hand palm. To register BP changes during relatively short period of time, different levels of exertion of the seven participants were obtained. For processing the video recordings, the green color intensities of the regions of interest (ROI) from face and palm were extracted. Considering the absorption of green light correlating with the blood volume, raw iPPG could be obtained. The mean average inter-person correlation between systolic BP and PTT was -0.80 ± 0.12. The authors studied the correlation only regarding systolic BP.

A few years later, Jeong and Finkelstein implemented the same methodology [5] using a high-speed camera with an infrared (IR) light source with 850 nm wavelength instead of the visible light from the LED light source [10]. For acquiring the iPPG and further the iPTT signal, relevant ROIs were extracted as before. The red component pixels were then summated and filtered to obtain relevant information for BP estimation. This work does not include a direct comparison of the accuracy to their work in 2016. The experiments were conducted with only two participants and showed results that are very different for each subject regarding iPTT. For the first participant, the value lies between 12.84 and 13.76 ms. For the second, it lies between 7.14 and 8.43 ms.

Huang et al. applied the iPTT by exposing the face and palm to the camera and extracting the green channel of relevant areas in the image [6]. The researchers use a digital
camera with 75 fps. Moreover, machine learning is deployed to enhance the accuracy by implementing transfer learning using the MIMIC II database. Thus, no tedious process for building a personalized model is necessary since the k-nearest neighbourhood (kNN) prediction model generalizes by using available data from intensive care unit (ICU) patients. Since there is no open database for both BP signals and images from face and palm, the researchers created their own dataset. Collected data included 13 subjects and several experiments with a regular fluorescent lamp providing approx. 400 lx. In total, 1300 pairs of data, consisting of BP signals and videos, were collected. Systolic and diastolic BP levels could be estimated. Regarding the systolic BP, the root mean square error (RMSE) could be reduced to 14.02 compared to [5] that does not utilize a machine learning algorithm (RMSE = 15.08). The RMSE of the diastolic BP amounted to 7.38.

Further investigations have been made by adding information about the temperature of the relevant region in order to measure more accurate BP levels [7]. Oiwa et al. make use of the facial skin temperature, which reflects changes in the blood circulation. It has been found that there is a correlation between skin temperature and the measured BP exists. This study on the one hand examines the correlation between facial PPG and mean BP. On the other hand, the investigators show that there is a relation between skin temperature and mean BP. Those two research areas were not combined. The PPG system consists of two subsystems which are the face tracking system and the facial PPG extracting system. First, ROIs were found, such as cheeks or forehead. Thereafter, the RGB signals of five obtained ROIs were pre-processed and underwent an independent component analysis (ICA). In this way, the influence of exterior lighting could be eliminated. For measuring the temperature, the same ROIs from the tracking subsystem were used and temperature was registered at 1 fps with a resolution of 0.1 °C. The experiments included a resting phase and a cold stimulus phase where subjects were instructed to put their right hand in 14 °C water for one minute.

PPG and temperature signals were both obtained by individual linear regression analysis. Illumination was chosen to be 900-1000 lx. Eight participants were included in the experiments. Results show a maximum error of 12 mmHg between measured and estimated mean BP using facial PPG components and a correlation coefficient of -0.682 between facial PPG amplitude and measured mean BP. At the same time, the mean absolute error between measured and estimated mean BP was 3.46 mmHg, whereas the correlation coefficient between nasal skin temperature and measured mean BP resulted in a value of -0.768. A research including both PPG and temperature measures in one system has not been conducted.

Fan et al. developed an algorithm to improve the quality of the remote PPG signal using adaptive Gaussian models [8]. In order to reduce influence of rigid head and hand movements, an adaptive tracking system to follow the ROIs for BP measurement was implemented. Six subjects were registered. The results show that there is an improved correlation between BP and the developed PTT method. The average inter-person coefficient between systolic BP and PTT amounts to -0.840 ± 0.11, whereas the one between diastolic BP and PTT is -0.666 ± 0.10.

The work of Wuerich and colleagues is as well based on remote PPG from face and palm ROIs [4]. In order to attain the PPG signal from the RGB image, the green channel was used due to the haemoglobin absorption of green light peaks. Additionally, chromatic adaption was applied to the ROIs to avoid color artefacts caused by scene lighting. To obtain accurate BP values, machine learning, particularly a regression model, was implemented. Furthermore, a calibration based on reference BP values was performed in order to establish a correlation between PTT and BP. A dataset of five subjects was created. Results show a mean error of 0.18 ± 5.50 mmHg for diastolic BP and 0.01 ± 7.71 mmHg for systolic BP. Although adaption techniques were performed, PPG signals show a sensitivity to lighting conditions and movement.

Instead of PTT, more recent approaches extract the pulse width at half amplitude (PWHA) which is inversely correlated to BP [11]. Ding and colleagues found that PWHA is stronger correlated to BP than other morphological parameters of PPG, including PTT. A camera with 30 fps is used to find ROIs and extract the PPG signal with an approach that removes non-cardiac signals with a multi-wavelength combination of RGB signals. The BP levels of 16 subjects were analyzed. Despite the strong correlation between PWHA and BP, PTT is recommended to be included for higher accuracy.

Different from the presented works above, there has been an approach that is gaining increasing attention by researchers in this area. Remote PPG has been augmented by Luo and colleagues with a technology called transdermal optical imaging (TOI) [9]. TOI separates each video image into multiple layers – the bitplanes. By applying a machine learning algorithm, haemoglobin-rich signals are extracted, and melanin-rich signals are discarded. Bringing the layers back together results in a map of haemoglobin concentration across the face. This way, noise and susceptibility to skin tone variations can be eliminated, which indicates a robust signal. By attaining the before-mentioned map, facial blood flow oscillations can be detected, from which systolic, diastolic, and pulse BP are derived. In this work, a smartphone and a light source for sufficient lighting were used. This method extracts several ROIs from the face and then applies TOI. Data from
2242 subjects with normotensive BP ranges was collected over 2 years. The used multilayer perceptron models predicted a systolic and diastolic BP within 5 ± 8 mmHg of reference measurements. The mean accuracy of predicted systolic, diastolic, and pulse BP resulted in 95%.

4 Discussion

Contactless and unobtrusive BP measurement concepts using image-based methods were presented. Mainly PTT that was derived from PPG signals was implemented in order to estimate BP levels. The results of this method show that there is a correlation between PTT and BP. Nonetheless, BP is strongly dependent on individual vessel parameters such as stiffness. Therefore, regular calibration is required which at the same time displays a fundamental limitation to chronic BP monitoring. It turns out to be difficult to compare the different concepts since different parameters are used for evaluation. The correlation coefficient which lies between -1 and +1, where ±1 indicates the strongest possible relation between two parameters and 0 the weakest possible relation, was used in most of the papers [5–9]. This measure shows weaknesses concerning outliers. Simultaneously, error parameters, such as RSME [6], mean or maximum absolute errors in mmHg [4, 5, 7, 11], and percentual accuracy [9] were values for evaluating in other papers. This inconsistency makes direct comparison across the reviewed articles difficult. Additionally, the research groups use different hardware (cameras, light sources) with specific attributes and individual experiment setups.

In general, image-based signal extraction methods are limited to ambient conditions such as illumination, motion, and temperature. The experiments in the reviewed articles contain a static setup and do not represent the conditions, which take place in potential future settings. To tackle this problem, mathematical models or machine learning algorithms were implemented. Regarding the BP measuring systems that use machine learning, measurement accuracy was improved compared to systems without machine learning techniques. The main limitation these systems are confronted with are the unavailable or the small databases of BP signals and their corresponding videos. Furthermore, the cost factor should be considered within the limitations when using a high-speed camera. A general statement concerning the features of a PPG signal, such as PTT, PWHA, or the processing method, such as TOI, cannot be made since there are no extensive studies until now. Additionally, the listed studies, with one exception, only include two to 16 subjects. A representative statistic is not shown.

In conclusion, much progress has been made on contactless BP measuring methods, especially via PTT. Still, significant in-depth research needs to be done to overcome before-mentioned limitations and enhance accuracy without compromising convenience.

Author Statement
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References