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Contactless video-based photoplethysmography technique comparison investigating pulse transit time estimation of arterial blood pressure

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***Abstract*— *Background:* Non-contact measurement of physiological vital signs, such as blood pressure (BP), by video-based photoplethysmography (vPPG) is a potential means for remote health monitoring. However, the signal-to-noise ratio of cardiovascular signals within the vPPG is very low. *Objective:* This study investigates the potential of BP estimation from vPPG. *Methods:* In 10 healthy volunteers (4 females, 28 ± 7 years), continuous electrocardiogram, finger BP and video of the face and palm of the hand were recorded. BP was varied by isometric hand grip exercise and leg ischemia. Four vPPG methods were compared: (i) averages of the green (GREEN) color intensity; (ii) the best linear combination of color channels using independent component analysis (ICA); (iii) a linear combination of chrominance-based (CHROM) signal by standardizing the skin color profile; (iv) plane orthogonal to the skin tone (POS) as vPPG signal. These were applied to 14 regions of interest (ROIs) on the face and 5 ROIs on the palm. Pulse transit time (PTT) between ROIs, for all permutations, were calculated and the correlation with BP quantified. *Results:* A significant, negative PTT-BP correlation was defined as success. A maximum success rate of 80% was achieved, occurring for the GREEN, POS and ICA methods only for specific ROIs within the face, but not for any permutation using the hand. *Conclusions:* These results indicate that the use of vPPG for estimation of BP will be challenging. A combination of different vPPG methods and within-face ROIs may yield useful information.**

***Index Terms*— cuffless blood pressure; video-based photoplethysmography; pulse transit time; pulse arrival time.**

I. INTRODUCTION

In the last decade, video-based photoplethysmography (vPPG) has been introduced as a potential means for contactless measurement of vital signs such as heart rate (HR). VPPG is a remote optical method for detecting superficial blood flow, captured from pulse-induced color variation of the human skin. It can be measured under ambient lighting with conventional video devices. If the vPPG pulse is acquired at two anatomical sites, the pulse transit time (PTT) between those two sites can be calculated. PTT is correlated with blood pressure (BP) [1]. Therefore, vPPG acquisition at two sites is a potential method for estimation of BP without use of an inflated cuff (conventional method).

Video-based BP estimation was first reported in the literature in 2015 [2]. Since then, studies varied methodological approaches in terms of the number and the location of regions of interest (ROI) and the techniques for vPPG extraction.

Most studies in this field have only used regions of the face [3], [4]. However, a minority of studies have used regions on the hand in addition to face regions [5], [6]. The final estimation of BP, or PTT in most of these studies, were made from one or two ROIs, though others use up to 17 ROIs solely within the face [3].

The methods for vPPG signal extraction vary from using a single channel color intensity [2], [7], a linear combination of RGB channel intensities [1], [8], [9]to more complex methods such as Eulerian video magnification [10] and bitplane analysis [3]. Among 29 reported studies, vPPG signal is mostly extracted from the green channel (10/29), or a combination of RGB channels using ICA (9/29), CHROM (2/29) and POS (2/29). Red, or combination of red and green channels were also used (4/29) [unpublished review of litreature].

The current study compares vPPG within 19 ROIs across the hand and face, using four methods for vPPG extraction, (i) averages of the green (GREEN) color intensities in the ROI [7], (ii) independent component analysis (ICA) across all color channels [1], (iii) a combination of chrominance-based (CHROM) signals [9] and (iv) plane orthogonal to skin tone (POS) approach [8]. The acute, dynamic relationship between PTT and BP was quantified using these 4 vPPG techniques across the 19 ROIs. Arterial stiffness and BP defines a positive correlation fundamentally , and therefore a negative correlation between PTT and BP. The vPPG technique was defined as successful if a significant negative correlation between PTT and BP was measurable. The success rate across the ROI and vPPG method combinations was compared to find the ROI and vPPG method with the strongest likelihood of providing a reliable PTT calculation method for contactless, cuffless BP estimation.

II. METHODS

A. Experimental procedures

Ten healthy subjects (4 female, 28±7 years, range 20 to 37 years) participated in this study. A lead II electrocardiogram (ECG) and finger BP using the Peňáz technique were acquired continuously from subjects (Edwards Nexfin®,The Netherlands). Video was recorded simultaneously from subjects' face and left palm using a webcam (Logitech HD Pro C920, 30 frames per second, 640×480 pixels). The camera was placed 40-60 cm in front of the face. The participants rested their head on an ophthalmology chin rest and their non-dominant hand on a table with the palm facing upward. This study was approved by the Macquarie University Human Ethics Committee.

For each subject, data and video were recorded, in random order, during 2 minutes seated rest, 3 minutes isometric

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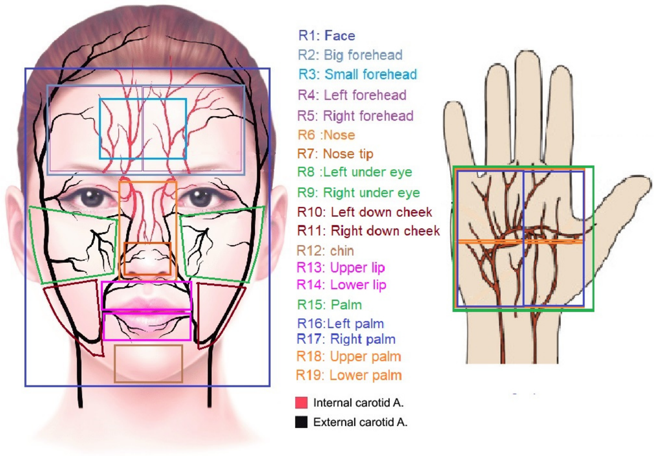

Fig. 1. Regions of interest on the face and the palm. (The image for anatomy of facial arteries is modified from [11].)

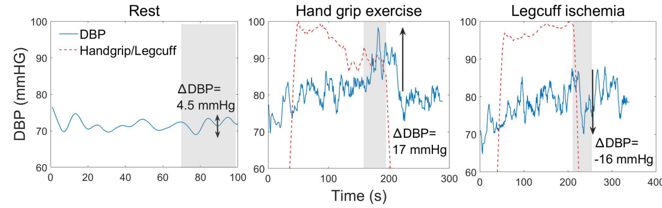

Fig. 2. Example (one subject) of time series DBP at rest, hand grip exercise and leg ischemia. With this subject, both hand grip exercise and leg ischemia altered BP significantly in the transient 30 seconds (Table I).

TABLE I

AVERAGE BLOOD PRESSURE FOR REST AND CHALLENGE CONDITIONS.

	rest	leg ischemia	handgrip
Finger SBP (mmHg)	99±5	107±5	130±7*
Finger DBP (mmHg)	58±2	58±2	77±4*

mean±standard deviation. * $p<0.05$ compared to rest.

hand grip exercise and for 30 seconds following 3 minutes leg ischemia. In leg ischemia test, the legs blood flow are occluded temporarily, by inflating two thigh cuffs above systolic BP (SBP). Participants had 3 to 5 minutes rest after each challenge. Room lighting (fluorescent bulb, 100 lx) and temperature (24°C) were kept constant during all experiments.

B. Data analysis

For each challenge, the final 30 seconds of data and video was extracted for analysis. Fourteen ROIs on the face and five ROIs on the palm (Fig. 1) were selected for analysis.

The GREEN [7], ICA [1], CHROM [9] and POS [8] methods for vPPG signal extraction were used, modified from the iPhys open-source toolbox [12] created for MATLAB. The GREEN method averages the color intensities in the green channel [7]; ICA finds the best linear combination of channels across red, green, and blue using independent component analysis [1]; CHROM standardizes the skin color profile to white balance the video frames and generates a linear combination of chrominance signals [9]; POS uses an orthogonal plane to the skin tone for generating the vPPG signal [8]. The CHROM and POS methods are more robust to artifacts from motion and nonuniform lighting [8], [9].

The passband frequency in the open-source toolbox was expanded to 0.66-3 Hz, corresponding to the lower and upper limits of normal HR (40-180 bpm). The resulting vPPG signals were inverted to resemble a reflected PPG. Data from an extracted pulse was removed: where non-rigid motion artifact was identified due to sudden facial expression or hand movement [13] by dividing the signal into 1-second epochs and the 5% of epochs with the largest standard deviation (SD) of signal amplitude and their corresponding beats discarded; the outlier beats with peak-to-peak time interval values outside the range of 1.5*interquartiles above the upper or below the lower quartiles were removed.

The HR from filtered vPPG signals was estimated by Welch's method as the dominant frequency within the passband range. The absolute HR error for each subject from each ROI were studied between methods.

Beat-to-beat PTT was calculated using both the signals' maxima (peaks) and minima (nadir) of every permutation of ROI and the method with the lowest beat-to-beat HR error was used in subsequent analysis. Negative (non-physiological) PTT values were removed. If most of PTT values were positive in each seriesfurther analysis was conducted. Otherwise, that permutation was deemed not successful. The PTT from ROI permutations and vPPG method was found for each cardiac cycle, averaged over a window of 10 beats, with the diastolic BP (DBP) averaged over that same window as extracted from the finger BP signal.

C. Statistical analysis

ANOVA was used to compare the finger SBP and DBP during rest, hand grip and leg ischemia test, and to compare the accuracy of absolute HR error from four methods. The linear regression between DBP and PTT was quantified per subject, for all permutations of vPPG methods and ROIs and the number of negative, significant correlations quantified. Root mean squared error (RMSE) and R-squared of linear regression between BP and PTT were used to compare methods. Video, signal and statistical analysis was performed in MATLAB R2020b.

III. RESULTS

A BP change was achieved with hand grip exercise but not with leg cuff occlusion for all subjects (Table I). However, Fig. 2 shows an example time series DBP during rest, hand grip and leg ischemia test with a significant change in DBP with both challenges. The range of DBP change for all subjects varied between 16-58 mmHg (35±11 mmHg).

Absolute HR error averaged across all regions was significantly different among the four methods ($p<0.05$). GREEN and ICA had the lowest errors (GREEN: 3±1, ICA: 4±2 bpm), and CHROM and POS had the highest errors (CHROM: 7±5, POS: 11±8 bpm). Beat-to beat PTT were

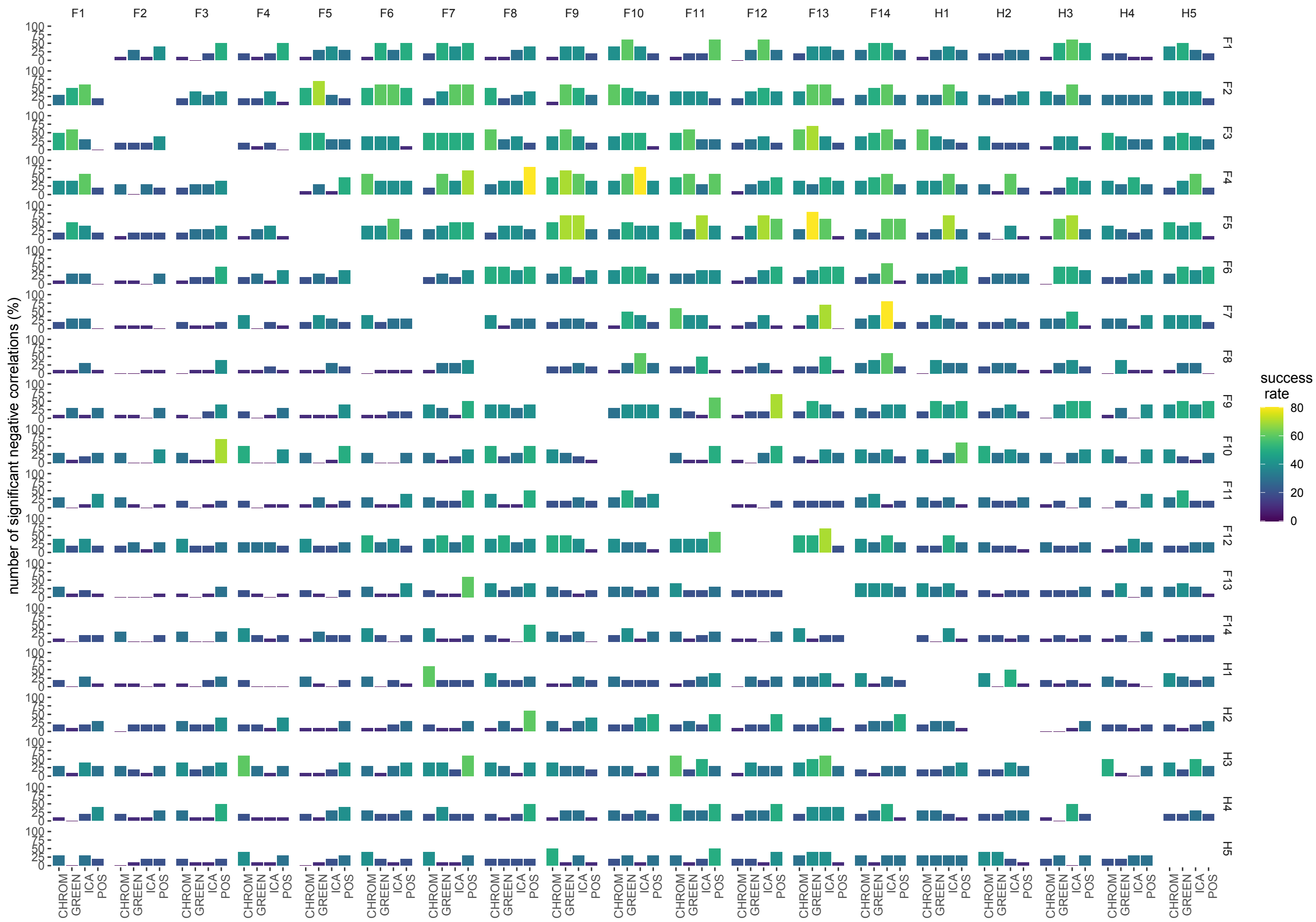

Fig. 3. Success rate, as defined by a significant, negative correlation between PTT and DBP, for the four vPPG methods tested for all permutations of proximal (horizontal axis) and distal (vertical axis) regions of interest. F1:F14 and H1:H5 represent face and hand regions respectively. As an example, the bar plot is column F14, row F7, shows the success rate of 4 methods for DBP and PTT correlation between lower lip (F14) and nose tip (F7). There is negative significant correlation between DBP-PTT for 80% of subjects from this permutation using ICA method (yellow bar).

TABLE II
HIGHEST SUCCESS (80%) VPPG METHOD AND ROI PERMUTATIONS.

method	proximal ROI	distal ROI
GREEN	upper lip (ROI F13)	right forehead (ROI F5)
ICA	left down cheeck (ROI F10)	left forehead (ROI F4)
ICA	lower lip (ROI F14)	nose tip (ROI F7)
POS	left under eye (ROI F8)	left forehead (ROI F4)

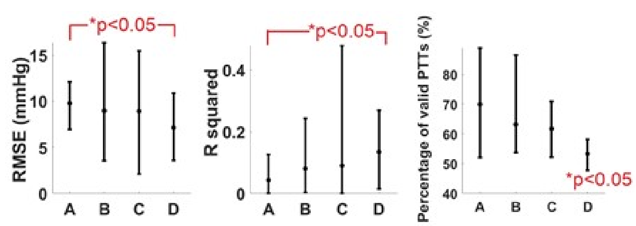

Fig. 4. Linear regression root mean square error (RMSE), R^2 and % physiologically reasonable PTT values for A) GREEN, ROI5-ROI13, B) ICA, ROI 4-ROI 10, C) ICA, ROI 7- ROI 14, D) POS ROI 4 - ROI 8. Plotted mean and maximum-minimum range.

calculated between signals' minima for the GREEN, ICA and POS methods, and between signals' maxima for CHROM method for resulting lower beat-to beat HR error.

Fig. 3 gives the success rate for all physiologically reasonable vPPG method/ROI permutations. The highest success rate for any single vPPG method/ROI permutation was 8 out of 10 subjects, occurring in 4 permutations (Table II). All pairs indicate pulse transit from lower parts of the face to the upper parts. Permutations using the hand did not yield the maximum success rate, the success rate for any palm region to face region was equal to or less than 60%.

Fig. 4 compares the best four methods and ROI permutations for PTT-BP linear regression. Lowest RMSE and highest R^2 was for POS vPPG method for left under eye (ROI F8) to left forehead (ROI F4). However, the percentage of valid beats PTTs was significantly lower for this approach.

IV. DISCUSSION

The approach of some of the recent research studies into contactless BP estimation use machine learning algorithms on several vPPGs or general video signals from multiple regions [3], [5]. Algorithm inputs often also include longer term variables such as the subject's demographic and anthropomorphic information, limiting the use in estimating acute BP changes. The contribution of PTT information for BP estimation is not clear compared to the other input estimators such as age, gender, and health status.

The peak to trough amplitude of the vPPG signal is extremely low, around a 0.4 to 1.2% change in color intensity [13]. Applying a narrow bandpass filter on the vPPG signal is essential yet results in a smoothed sinusoidal-like signal. As shown in this study, this provides a somewhat robust method for HR measurement, but a challenging scenario for PTT measurement.

This study, though small in size, and in mostly young healthy adults, used a pairwise approach to directly compare four common basic methods for vPPG signal extraction and investigated the regression between PTT (from 19 ROI) and DBP as a way of investigating remote BP estimation. SBP was not investigated, as it depends on additional factors than PTT, such as level of sympathetic function and cardiac contractility; thus its estimation increase the complexity of the problem [14].

As there is a longer arterial pathlength from the aortic valve to the palm than from the aortic valve to the face, it was expected that there would be a measurable PTT between back or palm of the hand and face regions [5], [6], [13]. However, this method did not yield a very high success rate in terms of PTT correlation with BP. This might indicate that the signal extracted from the palm region has a ballistocardiogram (BCG) related source rather than vPPG source [9]. BCG is synchronized with ECG, and if it outweighs vPPG, it generates incorrect PTT, while still providing accurate estimation of HR [13]. It could also, more generally, be due to a very weak vPPG signal from the hand across all techniques.

The highest success in terms of PTT-BP correlation was found using "proximal" and "distal" ROIs both from the face (Table II). The ROIs in terms of timing of the pulse transit reflect the anatomy of superficial arteries in the face, as blood flow in the face is, in the broadest terms, from bottom to the top, with the lower face being fed by branches from the external carotid artery with regions around the eyes and forehead from branches originating the internal carotid artery. However, the average number of PTT measurements that were physiologically reasonable (positive) was relatively low as a percentage of the total number of measurements (Fig. 4). This implies vPPG signal noise reduces the confidence in the PTT measurement technique. In some other studies, indexes were introduced to reject or accept vPPG beats [5]. Several of these methods were employed in this study and yet the PTT measurement success rate was not high.

The GREEN, ICA, and POS vPPG methods all yielded a permutation with an 80% success rate. The maximum success rate for any CHROM permutation was 60%. The POS vPPG method was significantly better than the GREEN vPPG method in terms of linear regression RMSE and R^2. This would lead to the conclusion that the POS method is the strongest and CHROM the weakest, though there was no true standout vPPG method and R^2 values were low.

All ten subjects had at least one successful regression among the four permutations identified in Table II. Given the variable success rate between ROI, vPPG method, and variability between subjects, it may be that no one, single method or ROI combination is optimal and an averaging or selecting algorithm is required to make image-based PTT estimation of BP a possibility. This type of information, beyond general predictors of age and anthropomorphic BP correlates, is required for acute BP measurement. The limited information in the vPPG signal for PTT calculation presents a complex challenge for its use in BP estimation. However, given the correlations found in this study, overcoming that complexity is not necessarily insurmountable.

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