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Evaluation of a dual-PPG system for pulse transit time monitoring

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***Abstract*— This work presents a new dual-photoplethysmographic (PPG) system for pulse transit time (PTT) monitoring. An experiment has been set up in order to compare the PTT measurement between carotid and radial arteries from two systems: our physiological multimodal platform (PMP) and the Complior® tonometer. This work explores the comparison between such optical and mechanical modalities. The results show that the PPG device tends to overestimate the PTT (RMSE = 16 ms). Furthermore, both mechanical and optical signals have been superposed and demonstrated that pulse morphologies are quite similar.**

***Clinical Relevance*— Carotid-radial pulse wave velocity (PWV) is compared on a small cohort of subjects and significant differences are observed between optical and mechanical-based systems.**

I. Introduction

In many studies, photoplethysmography (PPG) is used for blood pressure monitoring. Distal PPG waveform is used in addition with a proximal electrocardiogram (ECG) waveform to first estimate a pulse arrival time (PAT) and then convert the PAT into systolic/diastolic blood pressure (BP) [1]. Different regression formulas have been proposed in the literature [1,2]. However, such PAT-based approach is limited in accuracy by the fact that the PAT is the sum of one term directly related to the pulse transit time (PTT) and one term related to the pre-ejection period (PEP) (circa 50-100 ms [3]) and thus *does not* correspond *de facto* to a transit time. Such PAT-based approach is thus valid only if the PEP is moderately constant across different physical conditions and across subjects, or if its variations can be neglected [4].

One can circumvent this problem by using a differential approach by subtracting two PATs obtained at two PPG sensor locations. Obviously one can also directly compute the time delay between the two PPG curves (i.e. without ECG) to estimate such transit time [5]. Few works have been considered in this configuration: finger-toe with Popmetre [6], wrist-contralateral finger with CareUp device [7] or locally at the carotid [8].

It is worth mentioning that such method is *not* restricted to PPG sensors and other modalities have been proposed to estimate a time delay between two pulse sensor locations [9,10]. For instance, Complior Analyse® is now a reference method to estimate the pulse wave velocity (PWV) between the carotid and the femoral artery by using piezoelectric force sensors pressed onto the skin [9].

The goal of this paper is to compare such reference method with a new dual-PPG system both in terms of pulse morphology and pulse wave velocities. Indeed almost no validation exists in the literature to compare such inter-modality pulse wave velocities. To achieve this goal, a physiological multimodal platform (PMP) was developed: this system comprises among other things: an ECG, a multi-PPG, a respiration sensor and a blood pressure monitor. It records synchronized physiological signals relevant to the cardiovascular system. The PMP platform will be described in section 2.

Experiments have been performed on a small subset of healthy subjects to evaluate the pros and cons of such dual-PPG system for PTT monitoring. The methods we used for transit time estimation and pulse template are detailed in section 3 and comparisons with Complior system are given next.

II. System description

The PMP is a noninvasive platform developed to validate or setup healthcare paradigms for wearable devices. The platform is based on a sensor hub that embeds generic functions: wireless communication, processing units, storage memory and power management. The HUB provides specific electrical and mechanical interfaces, which allow it to work as a host for stackable sensor modules, each one dedicated to a physiological biomarker.

The HUB board is based on the nRF52840 system-on-chip (SoC) from Nordic Semiconductors, which provides Bluetooth Low Energy 5.0 (BLE) connectivity. The BLE connection between a PC and the HUB allows wireless device configuration, acquisition setup, data streaming and visualization. The HUB is also capable of storing up to 256 MB of raw data for offline processing. This solution offers a high data rate acquisition while keeping the possibility of visualizing the signal quality in real-time, which is a key feature during on-vivo experimentation.

The multi-PPG (MPPG) board consists of a set of MAX86141 analog front-end from Maxim Integrated, each one can drive 3 LEDs and 2 photodiodes. This module can be parametrized during the acquisition setup stage. For this study, it was configured to turn on one LED during the sampling time, while data is acquired simultaneously from the two photodiodes, creating two data samples per module for each trigger signal. The ECG and BP board are comprised of

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one 16-bit resolution ADC each, while the respiratory flow module contains a SDP31 sensor from Sensirion.

A PC software tool was also developed in order to provide users with a graphical user interface that ensures a practical and fast way to configure the platform. This tool works as a BLE central and implements a set of features dedicated to signal visualization, signal quality check and acquisition process automation. It also contains different functionalities dedicated to memory management, data gathering and data conversion.

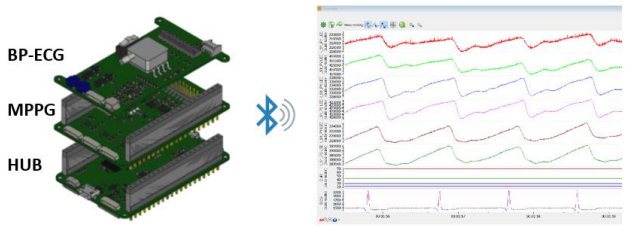

Figure 1. Platform sensor modules and real-time visualization

The firmware running on the HUB's SoC is based on a real-time operating system (RTOS) and a modular architecture. It provides a BLE interface based on the standard Bluetooth stack architecture and guarantees synchronization between the different modules. Its functioning is divided in three main stages:

Setup: during this stage, the firmware works as a BLE peripheral and waits for a BLE connection request from a BLE central device. Once the connection is established, the user can access a set of general attributes such as the sampling frequency, streaming frequency, visualization parameters and storage configuration. The user can also set a custom configuration for each module on the platform.

Acquisition: during this stage the firmware drives a trigger signal that is common to all the modules in the platform; ensuring synchronization between them. Raw data is stored directly in the flash memory on the HUB at ~36 kB/s and subsampled data is optionally streamed to the BLE central at 100 Hz. The PC-side software tool decodes the streamed data and adjust it to the context information given by the device, allowing thus data visualization on real-time (Fig. 1).

Data gathering: in this final stage the user can collect the experience data through a direct USB connection to a PC or wirelessly by a BLE connection to another device.

III. METHODS

The aim of this study was to estimate the PTT between two different body locations using a PPG module on each of them. For this purpose, a custom PMP setup was used, integrating two PPG modules and an ECG module. The BP monitor and respiratory flow modules were disabled for this study.

A. Experiment

This study aims to compare pulse transit time (PTT) measured by a mechanical system (Complior device) and an optical system (dual-PPG PMP). The sites of interest target carotid and radial arteries.

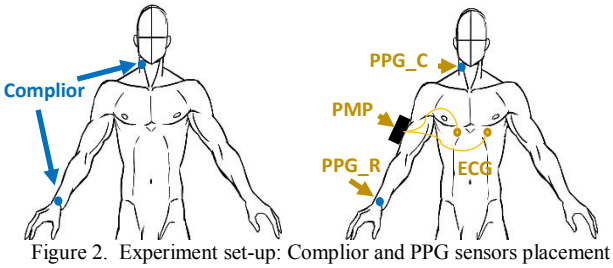

Figure 2. Experiment set-up: Complior and PPG sensors placement

The protocol has been tested on 6 volunteers, aged from 22 to 47 years (31 ± 9) and with systolic BP from 106 to 161 mmHg (126 ± 19), in sitting posture. Approval for this study in the research ethics committee of CEA-Leti organization and informed written consent for all subjects were obtained. As shown in Fig. 2, both devices are used sequentially: first Complior sensors are placed on right carotid and radial arteries. A contact force is applied by Complior clips enabling to maintain the sensors. After removing Complior system, PPG sensors are placed at the same location and the same Complior clips are used to apply identical force on PPG sensors. Acquisition is performed during 2 minutes, for both devices. An infrared LED at 855 nm has been chosen for PPG measurement and the distance between the LED and the photodiode is 9 mm. Sampling frequency is 1 kHz.

Complior piezoelectric raw data are acquired on a dedicated software at 1 kHz and imported into MATLAB. The software also gives access to PTT estimation every 30 s and this will serve us as a reference PTT estimation. The algorithm used by Complior software is a proprietary-implemented tangent intersection (TI) one [11].

B. Signal processing

Pulse wave time transit (PTT) can be estimated either by looking a time differences between fiducial points or by intercorrelation approach.

B.1 Fiducial points approach

The algorithm starts by identifying the local maxima in signal's first derivatives. We denote by t_n^s the time instant of the slope maximum (SM) for the n-th heartbeat.

For each detected pulse, we fit a linear model in the interval $[t_n^s - t_1, t_n^s + t_1]$ as $y_n(t) = \beta_0 + \beta_1(t - t_n^s)$ and defines a new fiducial point t_n^i as $y_n(t_n^i) = m_n$.
The value m_n corresponds to the minimum pulse value in the interval $[t_n^s - t_2, t_n^s]$. Typical values for t_2 is 200 ms, and t_1 is defined for each curve as the maximum value corresponding to a correlation coefficient between the actual waveform and the fitted line of more than 0.999 [11].

PTT can then be obtained by subtracting, for each heartbeat, the corresponding fiducial time at radial artery from the one at carotid artery. PTT can be estimated using SM or tangent intersection (TI) method using one of the following time differences:

$$PTT_n^s = t_{rad,n}^s - t_{car,n}^s$$

$$PTT_n^i = t_{rad,n}^i - t_{car,n}^i$$

The fiducial points can be further exploited to define an interbeat interval (IBI) time series. A heartbeat is deemed to be valid only if $|IBI_n - IBI_{median}| < 0.1 \cdot IBI_{median}$. This strategy allows us to control the quality of the pulse wave.

B.2 Intercorrelation

Another approach consists in dividing the recording in different non-overlapping windows and determine the delay that maximizes the intercorrelation (IC) between carotid and radial (filtered) epochs

$$\rho_{rad,car}(\tau) = E[s_{car}(t)s_{rad}(t-\tau)]$$

A PTT estimation is typically delivered every 15s. A maximum delay of 200 ms was defined, according to physiological a priori.

B.3 Pulse template

From the knowledge of the time instants $\{t_n^i\}_{n=1}^N$, it is possible to perform pulse averaging for both modalities. The beats are first time-normalized to account for heart rate variability and secondly, amplitude-normalized so that the output range of each pulse is [0,1].

B.4 Implementation

The three methods shown in B.1 and B.2 were implemented to process Complior raw data and compare our PTT results with the estimation given by Complior software, used as reference.

For PPG, we make use of the ECG signal to robustly estimate the slope maxima associated with each heartbeat. The processing pipeline starts first by identifying R-peaks in ECG, denoted by t_n^r and look for slope maxima in the interval $[t_n^r, t_n^r + PAT_{max}]$. Physiological a priori on PAT values for carotid and radial arteries was used to define PAT_{max} at 300 ms. Then, SM, TI and IC algorithms are also used to estimate PTT, comparing it to Complior reference.

IV. RESULTS

A. Complior

The PTT monitoring given by Complior software is used as reference and PTT obtained by our 3 algorithms will be thus compared to reference in order to validate our methods. Thus, for each subject, the evolution of PTT for each method along heartbeats can be plotted, as seen in Fig. 3.

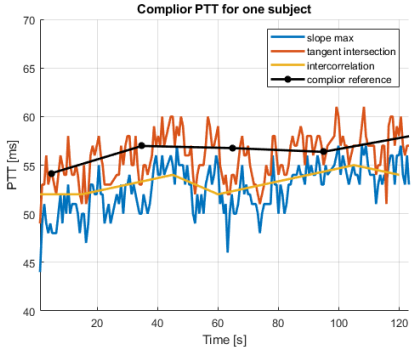

Figure 3. Beat-to-beat time course derived from Complior software (black) and the implemented algorithms applied on Complior raw data (maximal slope, tangent intersection and intercorrelation), for one subject

Fig. 3 demonstrates variations between heartbeats. Comparing the different methods, it appears that tangent intersection (TI) seems to be the most similar to the Complior reference. This is consistent because Complior reference uses a similar algorithm.

To compare the three methods for all subjects, a mean PTT is computed for each method and each subject, and then, correlation coefficient r is measured on mean PTT for all subjects S and also root mean square error (RMSE). Results are summarized in table I.

TABLE I. CORRELATION COEFFICIENT R AND RMSE FOR THE 3 METHODS WITH SM = SLOPE MAX, TI = TANGENT INTERSECTION AND IC = INTERCORRELATION ON COMPLIOR DATA

	SM	*TI*	*IC*
r	0.96	0.97	0.97
RMSE (ms)	4.97	3.90	5.62

The three methods give consistent results with a better RMSE of 3.90 ms and a correlation coefficient of 0.97 for TI algorithm, as expected. SM and IC are quite similar with respective correlation coefficient of 0.96 and 0.97, and RMSE of 4.97 ms and 5.62 ms.

B. Dual-PPG

For valid heartbeats, a mean PTT is measured for each subject. As for Complior data, correlation coefficient and RMSE were measured, compared to Complior reference and summarized in table II.

TABLE II. CORRELATION COEFFICIENT R AND RMSE FOR THE 3 METHODS WITH SM = SLOPE MAX, TI = TANGENT INTERSECTION AND IC = INTERCORRELATION ON PPG DATA

	SM	*TI*	*IC*
r	0.83	0.76	0.82
RMSE (ms)	15.9	16.3	16.6

The three methods have quite similar performances, with RMSE of 15.9 ms for SM, 16.3 ms for TI and 16.6 ms for IC. Correlation is slightly lower for TI with a coefficient of 0.76, compared to SM and IC of respectively 0.83 and 0.82.

Fig. 4 shows the mean PTT value obtained for all subjects, using TI, compared to Complior reference, with error bars representing standard deviations for PPG and Complior.

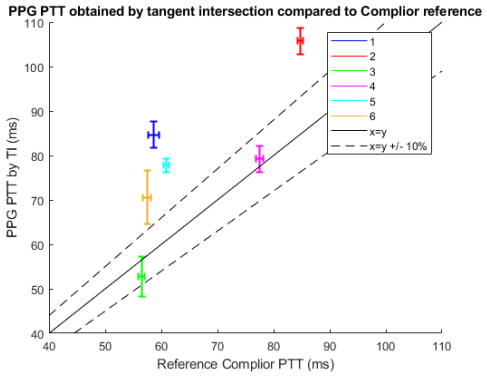

Figure 4. PTT obtained by dual-PPG PMP with TI=tangent intersection compared to Complior PTT reference. Black line represents the bisector and dotted lines +/- 10% of the bisector.

It appears that PTT measured by PPG is longer than Complior PTT. Only 2 of the 6 subjects have a difference of less than 10% compared to reference.

C. *Pulse morphology*

Fig. 5 shows the superposition of Complior and PPG templates for a normalized heartbeat for a particular subject. It can be highlighted that Complior and PPG signals have been acquired ten minutes apart.

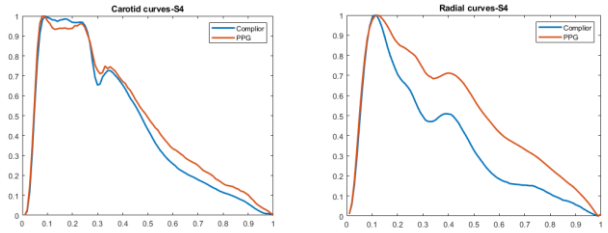

Figure 5. Superposition of Complior and PPG normalized signals for carotid artery (left) and radial artery (right)

This figure shows that mechanical and optical pulse morphologies are indeed very similar. For both techniques, the systolic upslope is identical and some reflections appear at the same instants for carotid and radial pulses. It can also be observed that for this particular subject the radial pulse is different between modalities. The observation was confirmed in all subjects: radial signals are quite different in diastole.

V. Discussion

In this article, a comparison was done between Complior and PPG signals both on transit times and pulse waveforms. A limitation of the study is the impossibility to place both devices simultaneously and at the same body location, a choice needed to be done. As it is difficult to precisely measure the distance between sensors, we chose to place sensors at the exact same body location to directly compare PTT measurement without needing to know the distance, thus sequential measurements have been performed.

Another point influencing the measurement is the force applied by the device on the skin. In this article, the same force was applied on both devices, allowing to obtain comparable results.

Two principal sources can explain PTT differences between PPG and Complior. The main reason is that the physics behind is quite different. In Complior, the pulse is generated by a mechanical deformation of the tissue when pulse wave passes into the artery and creates a distension on its walls, whereas PPG is sensitive to both mechanical deformation and change in tissue absorption [12]. Second, as the measurements were done sequentially, PTT variability during both recordings should be taken into account and could be an explanation for this difference. Literature shows that the autonomous nervous system is indeed modulating the PTT [13] and the state of the autonomous nervous system may evolve during time delay between the two measurements.

Optical and mechanical pulse wave morphology were also compared. It confirms that PPG is sensible to same mechanical deformations than Complior because pulse waveforms are very similar in the systolic phase and reflexions can be observed at the same instants. However, difference during diastolic phase may be explained by a slower relaxation time in tissue absorption changes (seen only by PPG) compared to mechanical deformations. This pulse morphology study also shows that carotid pulse and number of reflexions will vary with arterial age, helping to obtain some information on each subject's arterial compliance.

Finally, only PTT values were given because it is difficult to precisely measure the distance needed for the pulse wave to travel from carotid to radial artery. However, as PWV is the known biomarker, a future work will consist on finding a better way to measure this distance, obtaining PWV values corresponding to the PTT shown in this study.

VI. Conclusion

To our knowledge, this is the first time that optical and mechanical transit times and pulse morphologies are compared. It was shown than pulse waveforms are indeed very similar, whereas PTT measured by dual-PPG between carotid and radial arteries seems longer than PTT obtained by Complior. To confirm this conclusion, a study will be done on a bigger cohort, and an investigation on physiological possible reasons is already in progress. This work shows that having a modular platform helps us setting-up new paradigms in a short time. The latter encourages us to develop add-on modules like electroencephalography (EEG) and electrodermal activity (EDA), to expand the possibilities.

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