Photoplethysmography and electrocardiography for real time evaluation of pulse transit time

A diagnostic marker of peripheral vascular diseases

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***Abstract*— In this work, we report the results of a project, devoted to the development of a real time analysis for non-invasive monitoring of pulse transit time values on people affected by peripheral vascular diseases. Pulse transit time was computed as the time difference between every R-peak of the electrocardiographic signal and the following photopletysmographic peak. Both types of signals were acquired from 12 volunteers and real time signal analysis was performed in LabVIEW. Pathological conditions were simulated on every individual by means of an external cuff pressure applied on their arm. As expected, a PTT increase for increasing values of applied pressure was observed for all the volunteers. The proposed real time analysis could be suggested as a new, non-invasive optical method for real time monitoring of pulse transit time on patients affected by peripheral vascular diseases.**

Keywords—Photopletysmograpy; Pulse Transit Time; Non invasive monitoring.

I. INTRODUCTION

According to its definition, the Peripheral Vascular Disease, or PVD, is considered a disease of blood vessels outside the heart. It affects the peripheral circulation and it comprises diseases of both peripheral arteries and peripheral veins, affecting the compliance of all these vessels. The Pulse Transit Time, or PTT, represents the time the pulse wave requires to travel between two different arterial sites [1]. Photoplethysmography is a technique widely used to estimate PTT parameter [2]. It represents a non-invasive optical technique mainly based on the absorption properties of the vascular tissues when transilluminated by light [3]. Many other parameters can be estimated by means of photoplethysmography, such as arterial blood oxygen saturation (SpO_2) [4], heart rate, blood pressure.

The speed at which the arterial pressure wave travels is inversely proportional to the vascular compliance. This relationship is very important and the PTT value could become a significant marker, since the vascular stiffness (inversely proportional to compliance) is intimately related to the age and to the presence of a cardiovascular disease [5].

For this study, twelve healthy volunteers were involved and asked for consent. PPG and ECG signals of every volunteer were acquired, in order to have a timing reference for each PPG trace. The experiments were carried out by gradually increasing the cuff pressure, while acquiring and recording both signals for 120 s at each value of pressure. In this way, a change in vascular compliance was induced and the corresponding PTT values were computed in real time. The PTT trend was then analyzed as a function of the increment of the external applied pressure. This analysis could thus become a non-invasive and powerful diagnostic method for Peripheral Vascular Diseases.

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II. COMPONENTS AND METHODS

For the acquisition of the biological signals required for the PPT calculation, PPG and ECG systems were used. In particular, a multi-wavelength (λ=525-660-940 nm) PPG system was used, exploiting only the infrared channel obtained with an LED source with central emission wavelength at λ=940 nm, pumped with a current of 40 mA, and providing an optical power of 44 mW. The PPG waveform was detected by a transmittance finger probe. An isolated 3-Lead ECG channel was used during the experiments for the acquisition of the ECG signal. Three electrodes were placed on the body of each volunteer to sense the ECG signals that were fed to an instrumentation amplifier first. Once acquired, both the ECG and PPG signals were then transmitted to processing systems connected with a Data Acquisition Card, as shown in Fig. 1.

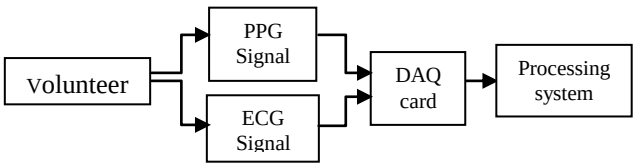

Fig. 1. Scheme of acquisition, transmission and process of the acquired data.

Data acquisition, signal analyses and system interface were implemented by means of LabVIEW. Initially, an offline analysis (Fig. 2) was realized as reference tool for data processing. A graph was positioned on the top part of the interface in order to visualize both signals and their peaks. The peak analysis was facilitate by parameters on the left part that could be optimized by the user. The PTT analysis and its trend were shown on the bottom part of the interface, with the heart rate value as well.

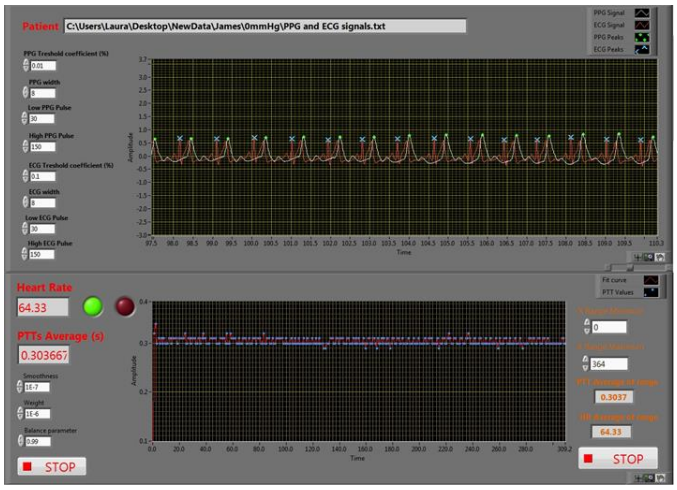

Fig. 2. Interface of the offline system for signal processing.

In a second phase, the real time analysis was also implemented (Fig. 3). On the bottom part of its interface, a chart showed the aquired signals in real time, while the results obtained by the peak detection algorithm were shown and updated every 5 s by the graph on the top. So, every PTT value calculated by the system was referred to the last 5 s of recording. It was also possible to modify specific controls on the right part of the interface in order to improve PPG and ECG signals analysis. All the detected peak locations were then displayed for both signals. Next to the chart, PTT and Heart Rate value related to the last 5 s of recording were displayed.

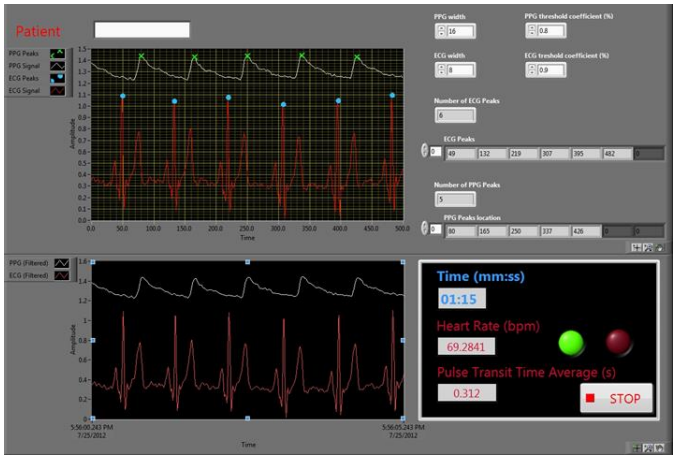

Fig. 3. Interface of the real time system for signal processing.

The experiments consisted in performing physiological measurements on healthy volunteers. For this purpose, twelve volunteers from the City University London were involved and they were all asked for consent. Every volunteer was asked to lie on a crib, relax and rest for five minutes before proceeding with the signal acquisition. The ECG electrodes were positioned on their right and left wristles and on their left ankle. The PPG probe was applied on the finger of the same arm where also the cuff pressure was applied. Each volunteer was asked to remain still during the experiment to reduce motion artifact. Table I briefly summarizes the main information of the involved subjects.

TABLE I. HEALTHY VOLUNTEERS INFORMATION

Volunteer	Age	Height (m)	Sex	Smoke	DBP (mmHg)	SBP (mmHg)	Distance Heart-Finger (m)
Vol 1	27	1,7	M	No	82	130	0,85
Vol 2	29	1,65	F	No	68	111	0,825
Vol 3	32	1,54	F	No	70	105	0,7
Vol 4	23	1,71	M	No	73	120	0,855
Vol 5	26	1,66	F	No	66	118	0,83
Vol 6	26	1,67	F	No	58	105	0,835
Vol 7	25	1,64	F	Yes	83	109	0,82
Vol 8	28	1,72	F	No	62	108	0,86
Vol 9	35	1,75	M	No	62	140	0,875
Vol 10	29	1,73	M	No	61	140	0,865
Vol 11	26	1,88	M	No	73	120	0,94
Vol 12	42	1,78	M	No	73	118	0,89

Since pulse transit time is not an absolute value and can vary from subject to subject, a reference recording was carried on for five minutes and without any applied pressure, in order to have a well defined and reliable PTT value referred to the subject's normal conditions. The external pressure was then applied on the right arm of each subject: after reaching the target value of pressure, the signals were recorded for 120 consecutive seconds, after which the application of pressure was interrupted for a couple of minutes. In this way, the volunteer had time to restore blood circulation, and vessel compliance was allowed to get back to its normal condition. When the volunteer was ready, a new recording was carried out for other two consecutive minutes, by applying a higher cuff pressure on the arm. Pressure was applied at increasing steps of 15 mmHg for every recording, till the PPG signal was still detectable (almost at the systolic pressure of each person).

IV. SIGNAL ACQUISITION AND PROCESSING

Once acquired, both the PPG and ECG signals were first filtered by a bandpass filter realized with a LabVIEW algorithm, setting the sampling frequency at 100 Hz, the high cutoff frequency at 10 Hz and the low one at 0.4 Hz. The implemented peak detection phase and its controls allowed any fake peak on both signals to be deleted. The heart rate and PTT values were thus computed and displayed together with the ECG and PPG real time chart and graph. A real time sytem for PTT computation was also realized and results obtained by the offline and the real time systems were compared by means of MATLAB software.

V. RESULTS AND DATA ANALYSES

For significative data comparison among all the volunteers, who had different systolic pressures, PTT mean values were computed for every subject at the following values of pressure: 0 mmHg, 15 mmHg, 30 mmHg, 45 mmHg,

60 mmHg, 75 mmHg, 90 mmHg and 105 mmHg. The PTT trend obtained with the real time system is shown in Fig. 4. As it is evident, the PTT trend turned out to be a function of the increment of the external applied pressure. As expected, on the base of data reported in the literature, a PTT increase for increasing values of applied pressure was observed for all the volunteers.

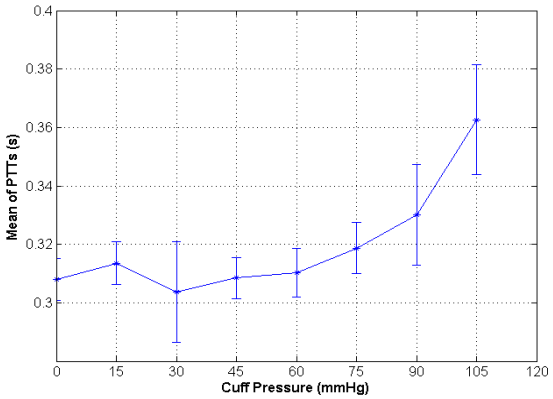

Fig. 4. PTT values as a function of the applied pressure variations.

The increasing PTT trend detected in real time was then compared with the reference trend obtained by running the offline analysis. As reported in Fig. 5, there was no statistically significative difference between PTT values obtained by the two processing systems, as also demonstrated by the t-student test later carried out, which could not reject the null hypothesis, showing all the p-values over 0.05.

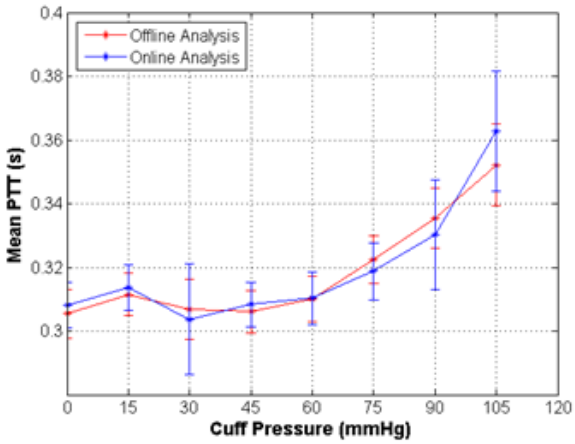

Fig. 5. Comparison between the offline and real time systems.

A further correlation analysis was also carried out to compare the two sets of data: by considering the offline analysis as reference, data obtained by the real time system turned out to be quite reliable. The slight differences between the two sets of data, which are still visible in Fig. 6, could be mainly originated by the following factors:

- Low capability of the real time system to reject movement artefacts: even though every volunteer was asked to remain still, the respiration artefact was sometimes influencing the shape of the signals;
- Presence of some fake data recorded despite the presence of a suitable signal threshold for peak detection: at the beginning of every recording phase, in fact, a suitable threshold from the interface of the real time acquisition system was inserted in order to allow the identification of the necessary peaks;
- Smaller size of the online data set: this was due to the occasional missing of PPG peaks at higher pressures.

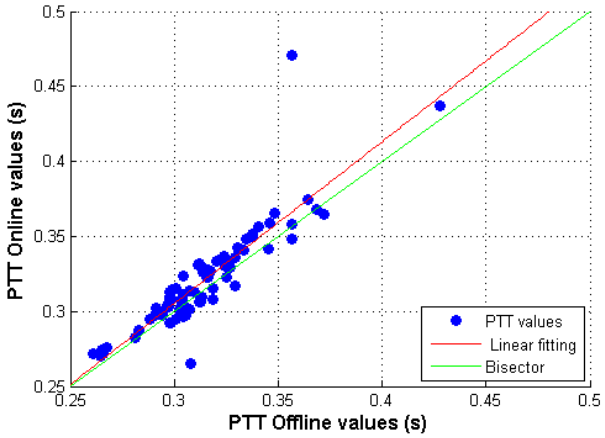

Fig. 6. Cross correlation between PTT values obtained by the real time and the offline analysis.

The cross correlation coefficients were computed taking into account ECG and PPG signals referred to the same subject. This coefficient is generally calculated by normalising the cross-correlation with the power of the two signals i.e. by setting m = 0:

$$c_{xy}[m] = \frac{\Phi_{xy}[m]}{[\Phi_{xx}[0] \cdot \Phi_{yy}[0]]^{1/2}}$$

In particular, this analysis was carried out considering signals recorded at 0 mmHg, 45 mmHg and 90 mmHg. The blue trace in Fig. 7 represents the cross correlation between ECG and PPG referred to Volunteer 9 at 0 mmHg, while the red and yellow traces are referred to the signals respectively recorded at 45 mmHg and 90 mmHg. It is evident that the blue trace is characterized by a wider lag range: this was simply due to a longer recording time interval considered at 0 mmHg (5 minutes which correspond to 300 s). All traces show well defined peaks, all close to lag = 0 s. Moreover, cross correlation peaks referred to the three pressure values turned out to be very different from each other: the higher the applied pressure, the lower the correlation between the signals. This phenomenon was probably due to the gradual decrease in PPG signal amplitude while increasing the pressure.

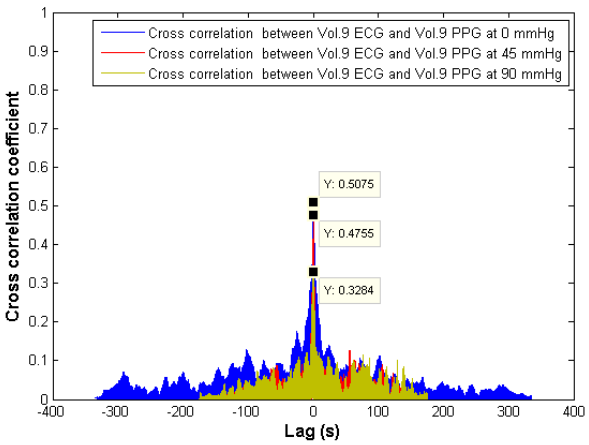

Fig. 7. Cross correlation between ECG and PPG signals of Volunteer 9 at different values of applied pressure.

VI. CONCLUSIONS

In agreement with results found in the literature [6], the increasing applied pressure turned out to really affect the PTT values. In particular, above 45 mmHg the t-test comparing the PTT values recorded at different pressures revealed a p-value lower than 0.05. Moreover, the increasing PTT trend obtained by the offline analysis was demonstrated not statistically different from the one obtained in real time. This comparison allowed to confirm the good reliability of our online analysis.

Differences between offline and online data set observed at higher pressures were mainly due to a limited capability of the online analysis in detecting all the PPG peaks on reduced amplitude signals, yielding higher PTT values. In fact, by increasing the external applied pressure, the PPG signal amplitude became lower and lower, till it disappeared at the systolic pressure of the subject. However, these differences between the two system outcomes could be still considered not significant if taking into account α=0.05. The demonstrated algorithm, eventually improved with minor additions, could thus be suggested as a new, non-invasive optical method for real time PTT monitoring on patients affected by peripheral vascular diseases.

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