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# Spatial dependency of the PPG morphology at right carotid common artery

S Bonnet, M Lubin, M Doron, G Blanquer, M Perriollat, R Prada, P Blandin, and R Gerbelot

**Abstract—** PhotoPlethysmoGraphy (PPG) is ubiquitously employed in wearable devices for health monitoring. Photodiode signal inversion is observed in rare occasions, most of the time when the sensor is pressed against the skin. We report in this article such observations made at the right common carotid artery site. Indeed we have systematically observed a photodiode signal inversion when the PPG sensor is placed where the pulse is the best felt at the carotid. In addition to be inverted, the pulse is steeper during the systolic phase. Such inversion has implications in terms of pulse arrival time (PAT) measurements. In our experiments, this causes a difference of 20 ms in the carotid PAT when measured at the absolute maximum slope. The mechanical and optical properties of tissues must be better accounted to explain the PPG signal morphology.

**Clinical Relevance—** Understanding the role of mechanical tissue properties seems relevant in order to obtain more reproducible results in PPG signal analysis.

## I. INTRODUCTION

PhotoPlethysmoGraphy (PPG) is ubiquitously employed in wearable devices for health [1]. It is a relatively simple technique which consists on the one hand in emitting light into tissue and on the other hand in recording either transmitted light (transmittance PPG) or backscattered light (reflectance PPG). Furthermore, it is well known that the PPG signal (i.e. the current collected by the photodiode) has one slowly varying DC component and one pulsatile component, termed AC, with a frequency related to heart rhythm. This optical measurement technique gives a very effective way to determine heart rate (HR) and its variability at different body locations. Many medical applications have been foreseen using such technology ranging from pulse oximetry to blood pressure [1].

In a PPG photodiode signal, a period is usually characterized by a steep decrease followed by a slower increase in time. A widespread assumption is that blood volume in the artery under the PPG sensor will increase during systole because of the artery compliance and such blood volume increase will cause the photodiode signal to decrease because of a larger light absorption by the tissues. However we must be aware that skin tissue organization is rather complex with several plexus and also that the light diffusion is a rather complex phenomenon [2]. Indeed it is hard to tell how much each skin layer/compartement contribute to the photodiode signal.

PPG using green light ( $\lambda=574$  nm) is often used because the AC component has a good signal to noise ratio making it easy to estimate heart rate (HR) from it. But at such wavelength, light merely reaches capillaries that are supposed not to be pulsatile. So the above theory for the origin of the PPG signal may somewhat be too simple relatively to the complexity of the skin and the underlying physiology. The group from Kamshilin proposed in 2017 that in addition to optical properties, mechanical properties of the skin should also be considered to fully understand the origin of the PPG signal [3]. They postulate that pulse propagation will also cause mechanical tissue deformation under the sensor that can for instance modify the local density of capillaries. This is both the change of (spatial) capillaries density and the optical properties of tissue that could be the *true* origin of the pulsatile PPG signal.

Another evidence that the blood volume theory is sometimes inadequate to explain measurements is the occurrence of ‘inverted’ photodiode signals. In some cases, it has been observed that photodiode signal corresponds to the opposite pattern as described before with now a steep *increase* during systole followed by a slower diastolic decrease. The blood volume theory could not easily account for such phenomenon. Kashmilin has performed such observation at wrist with remote imaging photoplethysmography [3] using green light. They also noticed that close spatial regions at wrist can give rise to counter-phase PPG signals. Identical observations have been made by Amelard at the carotid using remote PPG [4].

Similar observations has been made using wrist reflectance PPG with sensors directly located on the skin [5]. In a current project, we have also been confronted with such inversions at common carotid artery with PPG sensor pressed onto the skin. The goal of this paper is to report these observations, analyze the pulse morphology and discuss the implications of such an inversion in terms of pulse arrival time (PAT) measurements.

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## II. MATERIAL AND METHODS

### A. Material

The system used in this work has been described in detail in [6]. It consists of a versatile physiological monitoring platform (PMP) with different synchronized modalities. For this study, we will mostly use one-lead ECG sensor and two reflectance PPG sensors placed at the right common carotid artery (CCA) and at the radial artery.

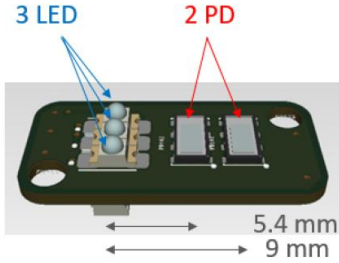


Figure 1. Geometry of the multi-PPG sensor.

Each PPG sensor has up to three LEDs and two photodiodes with source-detector distances respectively equal to 5.4 and 9 mm. Data are obtained with a sampling frequency equal to 1 kHz. Only one LED will be used in this study with a wavelength equal to 855 nm in the near-infrared spectrum.

### B. Sensor placement

Two different placements have been considered at the carotid site in this paper with 1) natural positioning and 2) US-guided positioning. In the first case, the PPG sensor is placed at the location where the pulse is ‘naturally’ felt. This will be the ideal location in case of applanation tonometry where the measurement directly depends on the amplitude of the force caused by pulse propagation [7]. This location will be referred to as TONO position. In a second phase, we use the ULITE ultrasound imaging system (Sonoscanner, France) to place our PPG sensor at the closest distance from the CCA. This position will be preferred in PPG measurement since we may hope that in this case artery may contribute the most to the photodiode signal. This sensor location will be referred to as US position.

These two configurations are illustrated in Fig. 2. Note that the sensors are pressed using a clip from COMPLIOR (Alam Medical, France) where a mechanical piece has been designed to easily integrate our sensor in this medical device.

As a reference, a second sensor is placed at the wrist location above the radial artery. It is kept unchanged whenever it is a US or TONO acquisition at carotid.

### C. Experimental protocol

Our experimental protocol is rather simple with two sequential measurements performed at US and TONO positions. The subject is at rest in a vertical sitting posture. The protocol has been tested on 4 healthy volunteers, aged from 25 to 47 years and with systolic BP from 117 to 135 mmHg. Approval for this study by the research ethics committee of CEA-Leti organization and informed written consent for all subjects were obtained. Each experiment lasts about two

minutes and measurements are achieved sequentially at the two positions.

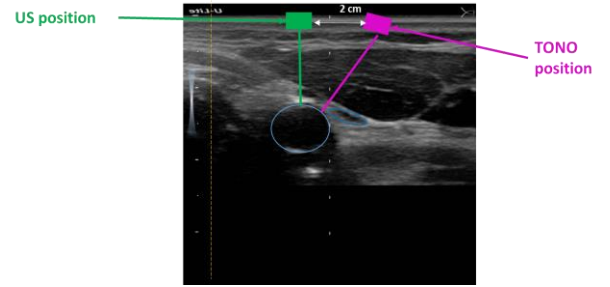


Figure 2. The right common carotid artery (CCA) is identified as the central blue ellipse. The green rectangle indicates the sensor position in US configuration favorable for PPG measurement while the pink rectangle indicates the TONO sensor position in configuration favorable for tonometry measurement.

### C. Methods

An ECG-informed approach is used to analyze PPG signals. First ECG R-peaks are detected on the ECG signal using a filter-threshold approach. Let us denote by  $t_{ECG}[n]$  the time/index of the  $n$ -th detected R-peak. We may easily deduce the interbeat interval (IBI) by time difference and we can also exclude detected beats that present an IBI that is too far from the median IBI of the sequence.

The PPG signal is epoched based on the detected ECG R-peaks to obtain PPG pulse templates. To account for IBI variability, each PPG pulse is resampled at 100 equidistant samples (rescaling in time) and normalized in amplitude. The median PPG can then easily be computed from the different normalized pulse epochs.

The pulse arrival time (PAT) is computed on the median pulse by determining the maximum slope index  $idx_{sm}$ . Because of the time normalization that has been made beforehand, we estimate the PAT by multiplying by the median IBI.

$$PAT = \frac{idx_{sm}}{100} \langle IBI \rangle \quad (1)$$

## III. RESULTS

We show in the next figure two PPG signals acquired at the right CCA. The top figure shows the case where the photodiode has a steep increase during systole while the bottom figure shows the opposite situation. The former situation will be termed ‘inverted’ PPG form since it is not easily explained by the standard blood volume theory. Note that the usual presentation of PPG signal is the opposite of the photodiode.

In all 5 subjects, a PPG inversion was observed for the TONO position and only for that position. Wrist PPG was similar in morphology between the US and TONO positions which is coherent since the sensor remains unchanged.

The radial artery diameter is 1.91-2.54 mm with a depth to surface equal to 3.58-4.41 mm. The carotid artery is much larger with a diameter of 5.87-7.24 mm and it is much deeper, typically 17.75-20.88 mm. For the given PPG geometry, cf. Fig. 1, the photodiode signal is not directly sensitive to carotid pulse distensions.

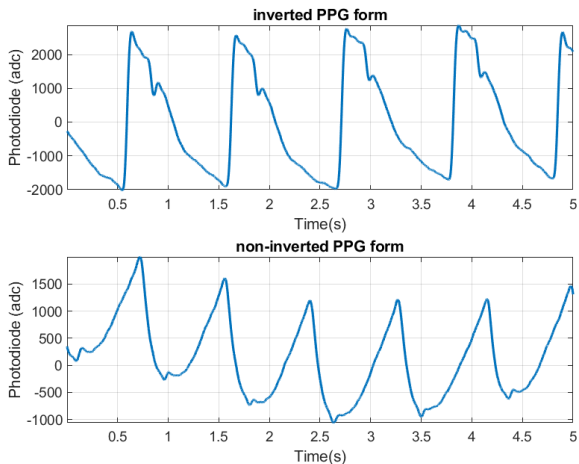


Figure 3. Top: Inverted PPG signal during systole (obtained at TONO position). Bottom: ‘Normal’ PPG photodiode signal during systole (obtained at US position).

For one volunteer, about 140 beats are obtained for each sensor placement. Median IBI is about 838.5 ms (inverted case) and 870.5 ms (non-inverted case). This effectively demonstrates that heart activity is captured in both configuration in the AC signal.

Using the methodology described in previous section, median pulse beats are given for one subject in Fig. 4 for wrist and carotid locations and for the two photodiode signals. The same pattern is observed for every subject. As it can be observed, the wrist PPG is almost identical in both acquisitions since this sensor has not been displaced between the two configurations. The PPG signals at carotid are without exception inverted when the PPG sensor is located where the pulse is felt (TONO position). Simply flipping the sign of the pulse as for instance done in [5] is not sufficient to recover exactly the same shape.

We have computed the PAT from these median pulse templates and results are reported in table 1.

TABLE I. PAT MEASUREMENTS : MEDIAN (STANDARD DEVIATION)

	US/ PHD1	TONO/ PHD1	US/ PHD2	TONO/ PHD2
$PAT_{wrist} (ms)$	229.98 (44.6)	222.96 (30.39)	234.32 (40.59)	229.68 (38.04)
$PAT_{carotid} (ms)$	165.84 (35.71)	142.01 (15.98)	167.24 (26.81)	142.01 (23.44)

As it can be observed from table 1, the carotid PAT is strongly affected by the sensor position and is considerably slower (about 20 ms) in the non-inverted situation. However a statistical test (paired-sample t-test, 5 participants) indicates that this difference (between US and TONO) is only significant for carotid PHD2 (short source-detector distance).

Pulse morphologies can be clearly investigated in Fig. 4. Note here that we are computing the PAT at the absolute slope maximum (because of the inversion).

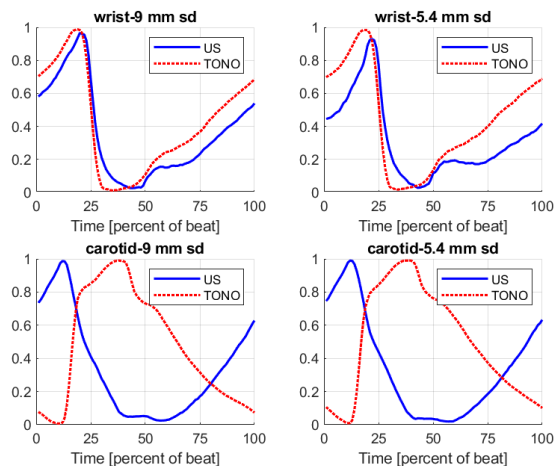


Figure 4. Normalized photodiode signal for one subject. Top row corresponds to wrist, bottom row corresponds to right common carotid artery location. Left column corresponds to **longest source-detector** (sd) distance (9 mm) Right column corresponds to **smallest sd distance** (5.4 mm). The blue curves (solid linestyle) are obtained for the US acquisition while the red curves (dotted linestyle) are obtained for the TONO position.

We also observe in Fig. 4 that both photodiodes give identical results at carotid but some discrepancies exist at wrist. This can be explained by the fact that for the given geometry, photodiodes are probing the same tissue at carotid without any arteries (because of the depth of the right CCA). This situation is more contrasted at wrist and it maybe the case that radial artery contributes directly to the photodiode signal with the longest source-detector distance.

#### IV. DISCUSSION

Since pulse arrival time is based on the detection of certain fiducial points, such inversion observed at carotid site will inevitably cause a problem. We have observed at this measurement site a high sensitivity of the PPG morphology to sensor localization. Positions are just two-centimeter apart.

Kasmilin observed such undesirable effects at wrist with remote PPG [3]. Again PPG signals may be in counter-phase if the sensor is displaced from a few centimeters. We may also hypothesize that PPG signal may be a combination of these two opposite phenomena which may compromise the reproducibility of the method to compute reliable PATs.

To better understand this situation, we have started to acquire remote PPG (R-PPG) image to identify these areas at wrist which is our long-term wearable target position. The image shown in Fig. 5 was obtained thanks to a CCD camera under a green LED lighting after phase analysis. The phase image highlights specific areas where the phase is spatially alternating. Such remote PPG phase image can be used as a guideline to position PPG sensors and better apprehend the sensitivity of the photodiode signal to spatial location. Further work based on R-PPG phase image and PPG sensor signals correlation will be investigated.

The contact pressure that is applied by the COMPLIOR clip must also be better controlled and future work will consist in changing the applied pressure and see if the morphology inversion still holds. There may be an optimal contact pressure where the mechanical skin effects are negligible so that the usual blood volume variation theory dominates the origin of the PPG signal.

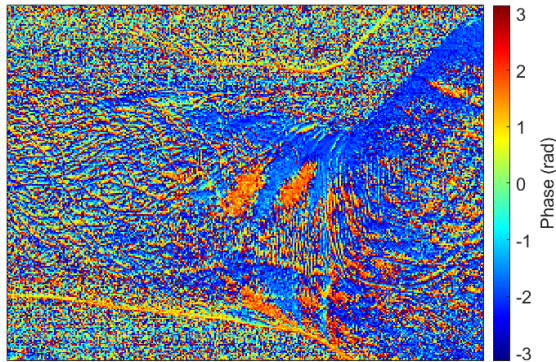


Figure 5. Phase image of a left wrist acquisition with CCD camera under green LED lighting. The orange areas display counter-phase patterns with respect to the blue surroundings.

## V. CONCLUSION

This paper investigated the inversion of the photodiode signal when PPG is measured at the right common carotid artery using a clip sensor. Mechanical skin properties maybe the dominant effect in the PPG signal in this configuration. Because morphology is altered and unpredictable, pulse arrival time measurements will be strongly affected when measured at right CCA. Inverted PPG signal occurs when PPG sensors are placed at the exact same location than tonometry does (where the pulse is felt). Non-inverted PPG signal occurs when PPG sensors are placed thanks to US imaging at the vertical of carotid artery. Further understanding in the mechanism of the PPG formation is still needed. Similar investigations will be performed at wrist in future studies.

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