PPG-based Methods for Non Invasive and Continuous Blood Pressure Measurement: an Overview and Development Issues in Body Sensor Networks

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***Abstract*—Non invasive and continuous measurement of blood pressure can enable an effective 24/7 monitoring of hypertensive patients to timely prevent cardiovascular problems and precisely regulate anti-hypertension cures. Unfortunately, to date, blood pressure can be only measured through either cuff-based or invasive instruments that cannot be continuously used due to their characteristics. This paper proposes an overview of techniques and approaches based on the photoplethysmographic (PPG) signal for non invasive and continuous measurement of blood pressure. In particular, the PPG signal can be easily acquired from an optical sensor applied on the epidermis and used, alone or integrated with the ECG signal, to estimate the blood pressure. On the basis of such methods new instruments and sensor-based systems can be developed and integrated with computer-based health care systems that aim at supporting continuous and remote monitoring of assisted livings.**

Keywords-PPG signal, blood pressure measurement, sensors, digital signal processing, body sensor networks

I. INTRODUCTION

The number of persons suffering of cardiovascular problems is very high and is increasing particularly in the most developed countries. In particular, the arterial hypertension is also know as the "silent killer" because it does not cause immediate symptoms but it can provoke harms to the cardiovascular system over medium/long-term periods of the human life bringing to ictuses or heartbreaks. According to the World Heart Organization (WHO), 600 millions of worldwide people suffer of hypertension which causes 7 millions of deaths a year [1]. The diagnosis of hypertension is often complicated due to rapid and dynamic variations of the Blood Pressure (BP) of the individual under-examination (or patient) and the currently available measurement methods (cuff-based or invasive) which limit the quality of life of the patients and cannot be used 24 hours a day. In the last decade the interest in computer-based health care systems has grown, particular for its enormous potential to support continuous monitoring of the vital signs of patients both at the hospital and at home [2].

To date, several methods have been defined as basis for the development of instruments and systems for continuous and non invasive BP measurements. In particular methods based on the processing of the photoplethysmographic (PPG) signal [3, 4, 5, 6, 7, 8, 9] have been widely explored in the scientific community. Moreover, in the context of measurement methods for monitoring human BP, the recent establishment of a subcommittee of the IEEE Medical and Biological Measurements technical committee (TC-25) focused on *blood pressure measurement* [10] witnesses the great emerging relevance of the research area in which the proposal of this paper is contextualized.

In this paper we therefore describe and compare techniques and approaches based on the PPG signal for non invasive and continuous measurement of blood pressure. Moreover, we provide technological insights on the development of such methods into advanced health care systems based on wireless body sensor networks [11, 12, 13]

The rest of the paper is organized in three main sections. Section II introduces background about BP measurement. Section III describes PPG-based methods for BP estimation. In Section IV discusses emerging wireless sensor technology enabling the development of systems for the remote monitoring of BP. Finally conclusion summarizes the paper proposal and briefly anticipates on-going work.

II. BLOOD PRESSURE MEASUREMENT

Blood Pressure (BP) is the pressure exerted by circulating blood on the walls of blood vessels, and is one of the principal vital signs [BPwik]. During each heartbeat, BP varies between a maximum BP (or systolic BP – SBP) and a minimum BP (or diastolic – DBP). BP is measured in millimeters of mercury (mmHg) and reported in the form SBP[mmHg]/DBP[mmHg].
SBP and DBP are not static but undergo natural (sometimes large) variations from one heartbeat to another and throughout the day (in a circadian rhythm). They also change in response to stress, nutritional factors, drugs, disease, exercise, and momentarily from standing up. Hypertension refers to arterial

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pressure being abnormally high, as opposed to hypotension, when it is abnormally low (see Table 1).

Hypertension is a chronic medical condition in which the blood pressure is elevated. Persistent hypertension is one of the risk factors for strokes, heart attacks, heart failure and arterial aneurysm, and is a leading cause of chronic renal failure. Even moderate elevation of BP leads to shortened life expectancy. At severely high pressures, defined as mean arterial pressures 50% or more above average, a person can expect to live no more than a few years unless appropriately treated.

TABLE I. CLASSIFICATION OF BP FOR ADULTS

Category	SBP [mmHg]	DBP [mmHg]
Hypotension	< 90	< 60
Normal	**90 – 119**	**and 60 – 79**
Prehypertension	120 – 139	or 80 – 89
Stage 1 Hypertension	140 – 159	or 90 – 99
Stage 2 Hypertension	≥ 160	or ≥ 100

The only way to provide a diagnosis of hypertension is through systematic and cyclic BP measurements which are therefore the most commonly measured physiological parameters along with body temperature, respiratory rate, and pulse rate. After a diagnosis of hypertension patients not only have to assume regularly specific medicines but also their BP has to be regularly monitored. To be fully effective the BP monitoring should be continuous and non-invasive. Table II reports a classification of BP measurement methods. Conventional BP measurement methods are those invasive and non-invasive cuff-based which are not suitable for continuous and non-invasive monitoring. While the invasive methods require the implantation of an arterial line (i.e. a thin catheter inserted into an artery), which can be done by any licensed doctor or a respiratory therapist, and soon after very close supervision, as there is a danger of severe bleeding if the line becomes disconnected, the non-invasive cuff-based methods can be used directly by the patient. However they require the total or partial occlusion of artery due to the cuff pressure so making them not suitable for long period or continuous monitoring.

TABLE II. CLASSIFICATION OF BP MEASUREMENT METHODS

Category	
Invasive	Invasive blood pressure catheter
Non Invasive	*Cuff-based*
	Auscultatory, Oscillometric, Tonometric, Value clamp or Vascular unloading, Ultrasonic, Electronic palpation
	Cuff-less
	Photoplethysmographic

Methods based on the Photoplethysmographic (PPG) approach [3] have the potential to provide continuous BP monitoring. In particular, such approach is based on the analysis of the PPG signal which is a rich source of cardiovascular information such as blood oxygenation, heart rate, blood volume variation, artery stiffness, and information useful to estimate the BP. The PPG signal can be obtained by simple optical sensors composed of an infrared LED and an associated photodetector: the former illuminates the surface of the epidermis (usually at fingers, ear lobes, or foreheads) while the latter measures the quantity of light reflected by (reflexive mode) or transmitted through (transmissive mode) the epidermis. The fundamental concept on which the PPG method is based is that blood absorbs the infrared light much more than the other tissues and the epidermis mostly contains little arteries, veins, and capillaries. The typical waveform of a PPG signal is shown in Figure 1.

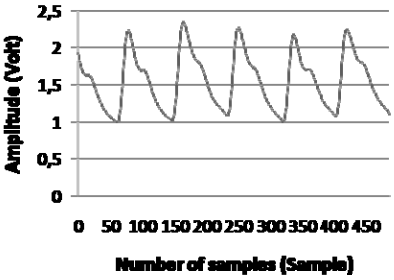

Figure 1. Waveform of the PPG signal.

III. AN OVERVIEW OF PPG-BASED METHODS FOR BP MEASUREMENT

Several methods for the estimation of BP based on the PPG signal have been proposed. In the following, some of the most significant ones are described and then compared. They can be categorized into pure PPG-based methods [5, 4] and hybrid PPG and ECG based methods [6, 7, 8, 9].

McCombie et al [5] have proposed a method for the estimation of the pulse wave velocity (PWV) using a circulatory waveform signal measured from two PPG sensors located at a known distance: the leading sensor applied to the wrist on the ulnar artery and the lagging sensors to the little finger on the digital artery (see Figure 2). BP can be derived from the estimation of the PWV. In particular, the mapping between PWV and BP is based on the relationship that each of them shares with arterial vessel elasticity (Moens-Korteweg equation). A calibration procedure has been defined to individually calibrate the measured PWV to peripheral BP using hydrostatic pressure variation. Finally a non real-time PC-based system has been developed to validate the approach. However, the obtained error with respect to references BP measurement instruments is not shown.

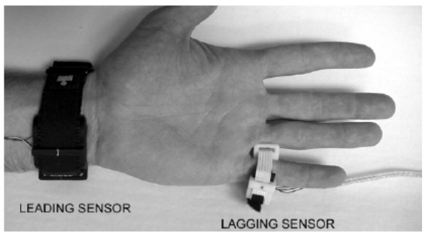

Figure 2. PPG sensor positioning to measure the PWV.

Zhang et al [6] have exploited the linear relationship between the pulse wave transfer time (PWTT) and BP (i.e. when the PWTT increases, the BP decreases, and vice versa). Usually PWTT is defined between two characteristic points: the R peak of the ECG signal and the minimum point of the PPG waveform (see Figure 3). The ECG signal is measured by positioning the electrodes at the wrist whereas the PPG signal is acquired from a photodetector applied to the finger-tip. Although the distance wrist-finger is negligible, the method should be carefully calibrated to have an ampler generality.

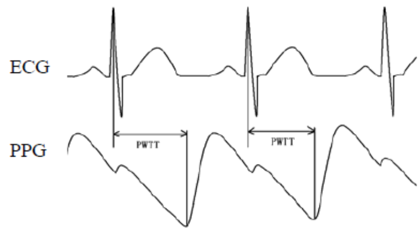

Figure 3. The definition of PWTT.

Fung et al [7] have presented a model which relates PWTT (or simply PTT) with BP more complex than the linear relation used by the previous described approach. The model simplifies the body structure and relates BP to PTT by fundamental physics, particularly the conservation of energy.

Poon and Zhang [8] uses the Moens-Korteweg's formula which expresses the PWV in terms of artery dimension, blood density and artery wall elasticity; PTT is computed as in [6]. EGC and PPG sensors are placed at the fingertips.

Jeong et al [9] calculate the PTT similarly to [6] for the purpose of individually estimating the BP. However the positions of PPG sensor and ECG electrodes are different. The former is positioned at the earlobe whereas the electrodes at the chest. Although an earlobe is a suitable place to measure PPG signal without the restraint in daily work, PTT is sensible to changes of relative vertical position of PPG sensor for the heart that brings the change of PWTT.

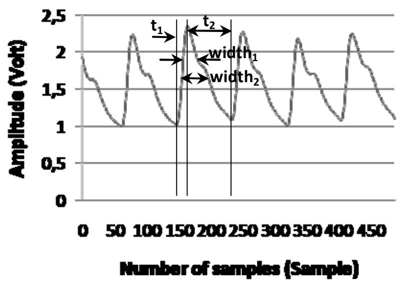

Figure 4. Waveform of the PPG signal with the temporal characteristics.

Teng and Zhang [4] have analyzed the relationships existing among BP and the characteristics of the PPG signal (see Figure 4). BP estimation can be carried out by purposely processing the PPG signal; in particular, the proposed approach is based on the extractions of specific temporal characteristics of the PPG signal and a subsequent BP estimation based on a linear model containing such characteristics as parameters. The considered characteristics are those reported in Figure 4:

- *Width1*, is the width of the signal at 2/3 of the amplitude peak-to-peak;
- *Width2*, is the width of the signal at 1/2 of the amplitude peak-to-peak;
- *T1*, is the Sistolic time defined as the ascending time of the signal from its minimum to its maximum;
- *T2*, is the Diastolic time, defined as the descendent time of the signal from its maximum to its minimum.

On the basis of tests carried out under different load conditions (rest, step-climbing, rest after step-climbing), the diastolic time (T2) is more correlated to BP than the other characteristics. The main issue of such approach is that cardiovascular parameters and the PPG signal are different in different subjects and this variation can affect the estimation of the parameter under measurement. In particular, the followed operational approach consists in the acquisition of the PPG signal from the forefinger and the exclusive use of T2 for BP estimation. T2 can be computed through a peak detection algorithm by determining the time instants in which first the maximum peak and then the minimum peak are detected. The identification can be done through a minimum square method applied to the real values of BP and to the corresponding values of the characteristic T2. The functions to be estimated are two (one for the DBP and the other for SBP):

$$\begin{cases} SBP = a_{SBP} \cdot T2 + b_{SBP} \\ DBP = a_{DBP} \cdot T2 + b_{DBP} \end{cases} \quad (1)$$

The identification of the coefficients of each function should be independently determined. Once identified the model, DBM and SBP can be obtained by computing T2.

TABLE III. ERROR COMPARISON BETWEEN THE DESCRIBED TECHNIQUES AND THE MOST COMMON CUFF-BASED TEQUINIQUES

BP	**Cuff-based**			**Cuff-less**		
	Auscultation method*	Oscillometric method*	Palpation method*	Pulse Transit Time method* [FDR04]	PPG feature -based approach* [TZ03]	Pulse Transit Time method [PZ05]*
SBP	4,6±7,7	3,1±9,0	-0,8±4,6	-0.31±6.64	0.21±7.52	0.6±9.8
DBP	0,0±5,1	-3,9±6,8	-1,5±5,0	-0.36±5.21	0.02±4.39	0.9±5.6

*mean error±std dev [mmHg]

Table III reports the error obtained by the application of three of the discussed methods and by the exploitation of cuff-based traditional methods. While the first three columns of the table reports the accuracy of the traditional methods, the columns 4-6 report the accuracy of the methods proposed in [7], [4] and [8], respectively. Although, the results obtained by the new methods are referred to experimentations carried out on subjects with specific physical characteristics, results are encouraging due to the provided accuracy in terms of mean error and standard deviation.

IV. TOWARDS BP REMOTE MONITORING SYSTEMS BASED ON BODY SENSOR NETWORKS

Current and emerging developments in wireless communications integrated with developments in wearable biomedical sensor technologies will have a radical impact on future health-care delivery systems [2]. New remote continuous cardiac monitoring systems can be thus designed not only in confined contexts such as hospitals and homes but also ubiquitously. In any case the fundamental basis of such systems are the body sensor networks (BSNs) [13], star-based wireless networks composed of small wearable sensors, which are able to sense physiological signals (e.g. ECG, PPG, acceleration, temperature), pre-elaborate and transmit them to a base station or gateways (e.g. a smartphone, PDA, or PC) capable of more powerful computation and direct access to Internet, WiFi and 3G networks (see Figure 5).

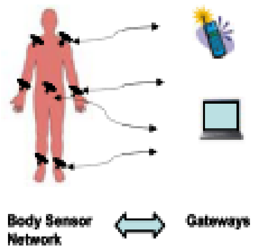

Figure 5. BSN reference architecture.

The main issues in developing BSNs for BP monitoring are essentially associated to the development of wearable sensor nodes characterized by: (i) *small dimensions*, to enhance wearability; (ii) *optimal placement*, to avoid patient annoyance; (iii) *low energy consumption*, to allow a prolonged battery life; and (iv) *in-node processing*, to save bandwidth by avoiding to transmit raw data to the base station and transmit only significant features or even the final high-level measurement computed on windows of raw sensed data [11].

In particular, the development of wearable BP measurement sensors is challenging not only from a technological point of view (see the aforementioned required features) but also from a standardized measurement perspective. In [12], the authors experimentally point out that new cuff-less measurement techniques (such as those described in section III) integrated into BSN nodes require new validating protocols and standards different from those (BHS and AAMI) established for cuff-based BP measurement instruments [14]. From a technological perspective, the development of a single sensor node able to measure the BP would be of great impact. The methods described in section III, apart from the one presented in [4], are all based on two sensors placed in different body locations. In particular, the methods based on ECG and PPG, not only require two sensors in two different positions but also the computation of the BP estimation on the basis of the two signals. This would require the transmission of the raw data (related to PPG and ECG) to the base station where BP can be estimated (see [12, 8] for an example system). Conversely, the method proposed in [4] could enable the development of a self-contained sensor which can be placed at a given body location (finger, wrist, earlobe) and can compute the BP in-node at a programmed rate and then transmit it either continuously or if BP is out of the normal range (see Table I).

V. CONCLUSION

This paper has proposed an overview of approaches based on PPG signal for non invasive and continuous blood pressure measurement. The described methods can be categorized in pure PPG-based through which the BP estimation is carried out only on the basis of the elaboration of the PPG signal, and hybrid methods which relies on the elaboration of the ECG and PPG signals. The development of such techniques into wireless wearable sensors would enable the development of pervasive and continuous BP monitoring systems. Such systems would greatly enhance the prevention and the cure of cardiac diseases caused by BP disturbs such as hypertension. However, there are several issues to work out associated to sensor technology and measurement standards.

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