Blood Pressure Tracking Capabilities of Pulse Transit Times in Different Arterial Segments: A Clinical Evaluation

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Abstract

In recent decades many research effort has been expended in the field of noninvasive, continuous blood pressure (BP) estimation by cardiovascular surrogate parameters, mainly the pulse transit time (PTT). Due to differences in the measurement setup and in the consideration of important physiological aspects, however, there is a multitude of inconsistent statements about the BP tracking capabilities of the parameter PTT in literature. For the purpose of comparing the PTTs on different arterial segments regarding their suitability for central BP estimation – with or without the influence of important physiological aspects – an appropriate clinical trial has been conducted, whereas significant differences could be observed.

1. Introduction

The development of arterial calcifications – as the main risk factor for cardiac infarction and apoplectic stroke (the most common death causes in industrialized countries) – is well-known promoted by the presence of a chronic hypertension. Blood pressure, for this reason, represents an essential hemodynamic parameter for the assessment of a patients' cardiovascular status in clinical practice as well as in ambulant personal health scenarios. The recording of a continuous blood pressure profile throughout the whole day (for the purpose of final hypertension diagnosis or therapy adjustment) is thereby often recommended by hypertension experts, due to the limited significance of conventional cuff-based methods for the discrete measurement of BP values (e.g. in 30-minute intervals).

In this context, a profound literature survey on noninvasive and continuous blood pressure estimation approaches has been carried out [1]. The determination of surrogate parameters – basically pulse transit time – thereby has shown to be realized in various different ways by measurement settings often disregarding important physiological aspects like e.g. (i) the variable pre-ejection period (PEP) of the heart – the time from maximum excitation of the left ventricle to the very ejection of blood in the aortic arch – in ECG-based PTT calculation settings, (ii) the gradually changing elastic properties of arteries along the arterial tree leading to a distorted PTT calculation on the basis of an averaged pulse wave velocity profile, and (iii) the autoregulatory effects in microcirculatory vessels affecting the non-central part of the pulse transit time since responding to local changes in temperature or in the local need for oxygen.

Against the background of these findings, an appropriate clinical trial has been conducted in cooperation with the clinic of anesthesiology at the University Hospital in Erlangen. By measuring an electrocardiogram and the local pulse wave signals of four sequential arterial sites, five observation points (see Fig. 1) and a total of 10 resulting (cardio-)vascular segments (see Fig. 3) can be derived. As intended, this kind of measurement setup enables the comparison of pulse transit times between the different arterial sites with respect to their suitability for central BP estimation – particularly with or without the influence of the above mentioned physiological aspects.

2. Methods

2.1. Measurement setup

Within the scope of vital data acquisition an electrocardiogram (ECG @ 100 Hz), a photoplethysmogram of the finger (PPG @ 100 Hz) and the invasive (arterial line) blood pressure signal (IBP @ 50 Hz) in the radial artery have been measured by an Infinity Delta Monitor (Dräger medical GmbH, Lübeck, Germany) [2] in 22 sedated ICU patients. Furthermore, the cardiovascular monitor Niccomo (medis. Medizinische Messtechnik GmbH, Ilmenau, Germany) [3] has been applied for the recording of a bioimpedance cardiogram (ICG @ 200 Hz), a bioimpedance plethysmogram at the forearm (IPG @ 200 Hz) and an

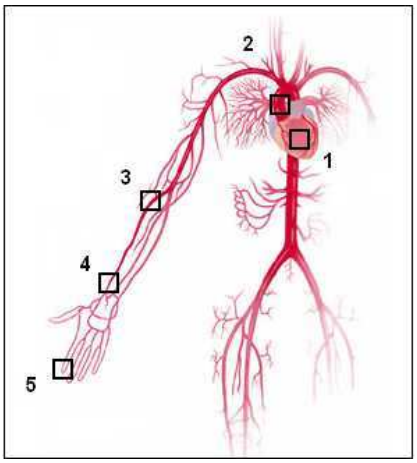

Figure 1. Scheme of the five sequential arterial observation points between the heart and the periphery with (1) ECG, (2) ICG, (3) IPG, (4) IBP, and (5) PPG

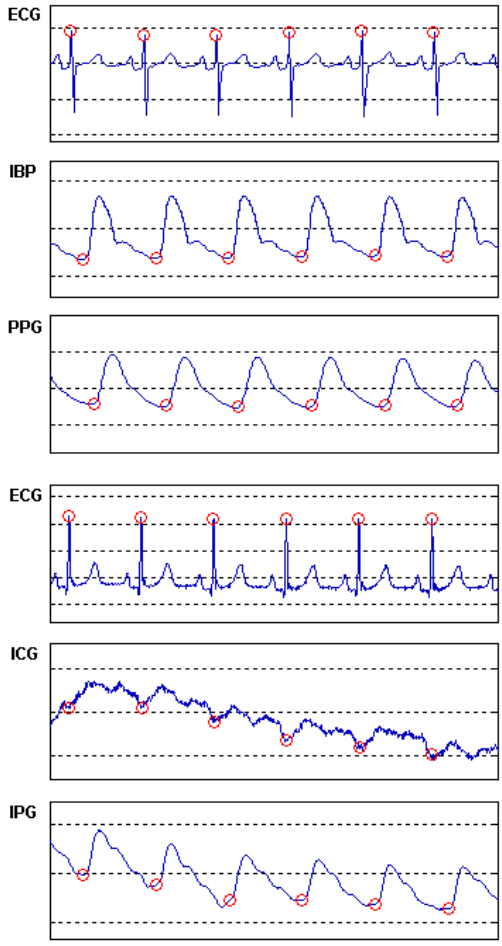

Figure 2. Exemplary signal segments from Infinity Delta (upper three) and Niccomo Monitor (lower three) with detected R-peak and pulse wave foot point indexes

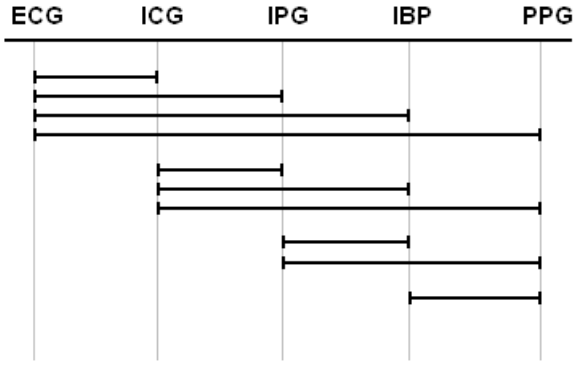

Figure 3. Ten cardiovascular segments resulting from the five sequential arterial observation points by paired combination

additional electrocardiogram (ECG @ 200 Hz) for later synchronization of both signal sources. The measurement sites of the ECG and the four pulse wave signals thereby are located on a common arterial segment between the heart and the periphery as depicted in figure 1.

2.2. Vital parameter processing

After measurement the acquired vital signals have been imported into Matlab (The MathWorks Inc., Natick, USA) [4] for further offline processing. Basing on the first of all detected indexes of ECG R-peaks and pulse wave foot points (see Fig. 2), the reference parameters systolic, diastolic and mean BP, and the pulse transit times on a total of 10 different (cardio-)vascular segments (see Fig. 3) have been calculated for every heart cycle and stored in discrete time series. The Infinity and Niccomo indexes time series thereby have been synchronized in advance by means of both corresponding RR interval time series for the reasonable calculation of signal source spanning pulse transit times. Subsequent to the vital parameter determination and signal source synchronization, the time series' indexes (represented by the intervals inbetween) and values have been evaluated for plausibility in due consideration of the associated RR interval time series and with regard to their adjacent values, respectively. Thus, invalid indexes and values not featuring a minimum plausibility, e.g. maldetections or outliers, could be removed.

2.3. Statistical analysis

For quantification of the relationships between the different pulse transit times and the systolic, diastolic and mean BP, the correlation coefficient and the standard BP estimation error by linear regression have been applied.

The 30 possible BP-PTT time series combinations of each measurement by this means have been analyzed in terms of a successive time window (with a width of 1000 heart cycles and a 50 percent overlap) focusing on short-term interdependencies. According to vital signal quality and measurement duration, only 14 out of the overall 22 measurements in ICU patients have been found successful and consequently have been considered for analysis. In so doing, a data pool containing about 240 hours of measured vital signals and approximately 920.000 analyzed heart cycles has been acquired.

3. Results

In the course of statistical data analysis, the calculated linear regression features of each BP-PTT combination have been averaged over the corresponding time windows in the total of all measurements. The resulting (measurement spanning) mean correlation coefficients of the 30 possible BP-PTT combinations thereby range in absolute values from virtually no correlation (R = 0.18) to a medium linear relationship (R = 0.47) (see Fig. 4 and Tab. 1). The mean standard BP estimation errors however are in the interval 6.7 – 8.8 mmHg for the systolic, in 5.6 – 7.2 mmHg for the mean, and in 4.9 – 6.6 mmHg for the diastolic BP-PTT combinations (see Tab. 2).

4. Discussion and conclusions

In the present paper, the design and the conduct of a clinical trial for the comparison of pulse transit times on different arterial segments with respect to their suitability for (systolic, diastolic and mean) BP estimation have been presented. The results of the corresponding statistical data analysis thereby indeed have shown significant differences in this context due to the influence and the consideration of the physiological aspects identified.

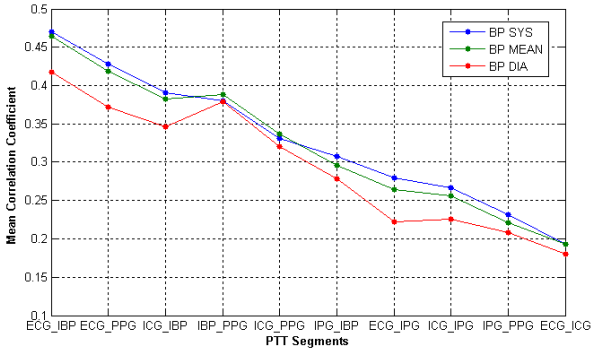

Figure 4. The mean correlation coefficients belonging to the combinations of systolic (blue), mean (green), diastolic (red) BP and pulse transit times on the different arterial segments (in descending order w.r.t. systolic BP)

The pre-ejection period (PEP) of the heart (here stated as PTT_ECG_ICG), for instance, being the least suitable by itself, obviously has positive effect on the BP estimation performance when combined to its adjacent arterial segments, since PTT_ECG_X is featuring a higher correlation coefficient than the respective PTT_ICG_X. For the most peripheral segment (here represented by PTT_IBP_PPG) including microcirculatory vessels (→ arterioles) for the (non-central) regulation of local perfusion, on the contrary, the inverse observation has been made. Though featuring a comparatively strong

PTT Segment	Mean Correlation Coefficient		
	BP_SYS	BP_MEAN	BP_DIA
ECG_IBP	0.47	0.46	0.42
ECG_PPG	0.43	0.42	0.37
IBP_PPG	0.41	0.42	0.41
ICG_IBP	0.39	0.38	0.35
ICG_PPG	0.33	0.33	0.32
IPG_IBP	0.31	0.29	0.28
ECG_IPG	0.28	0.26	0.22
ICG_IPG	0.27	0.26	0.23
IPG_PPG	0.23	0.22	0.21
ECG_ICG	0.19	0.19	0.18

Table 1. The mean correlation coefficients belonging to the combinations of systolic, mean, diastolic BP and pulse transit times on the different arterial segments (in descending order w.r.t. systolic BP)

PTT Segment	Mean Standard Error [mmHg]		
	BP_SYS	BP_MEAN	BP_DIA
ECG_IBP	7.13	5.63	4.91
ECG_PPG	6.73	5.62	5.28
IBP_PPG	7.59	5.85	4.90
ICG_IBP	7.61	5.87	4.90
ICG_PPG	7.93	6.44	5.81
IPG_IBP	8.74	6.54	5.63
ECG_IPG	8.01	6.62	6.11
ICG_IPG	8.81	7.19	6.59
IPG_PPG	8.30	6.73	5.96
ECG_ICG	8.74	7.15	6.50

Table 2. The mean standard BP estimation errors (in mmHg) belonging to the combinations of systolic, mean, diastolic BP and pulse transit times on the different arterial segments (in the same order as in table 1)

correlation with BP by itself, it contributes to a lowering of the BP estimation performance when combined to its adjacent arterial segments, since PTT_X_PPG yields a worse correlation coefficient than the respective PTT_X_IBP. The hypothesis of a negative effect on PTT determination accuracy by averaging over a non-homogenous pulse wave velocity profile along the arterial tree (especially in longer arterial segments) could not be confirmed. By contrast, better results in general have been achieved on the basis of longer PTT segments, whereas inaccuracies in pulse wave foot point detection, due to the limited temporal resolution of the acquired vital signals, and mainly affecting the pulse transit times of short arterial segments, might be an explanation. By reason of the highest dynamics, the systolic BP (in comparison with the mean and diastolic BP) has shown to correlate best with the available pulse transit times, though featuring the greatest standard estimation errors (for the same reason).

Apart from the findings concerning the consideration of physiological aspects in the determination of pulse transit time, the linear mapping approach has not proven to be suitable for an accurate BP estimation – not even in short-term applications – but is at best applicable for coarse BP trend indications. An improvement of BP estimation performance thereby might be achieved by the analysis and consideration of further vital parameters like e.g. heart rate (HR) and heart rate variability (HRV) introducing the frequency-dependence of the arterial vessel compliance and the influence of the autonomic nervous system on vascular tone, respectively.

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