Feasibility of Non-invasive Blood Pressure Estimation Based on Pulse Arrival Time: a MIMIC Database Study

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Abstract

The purpose of the present study was to evaluate the feasibility of blood pressure (BP) estimation by means of pulse arrival time (PAT) from data records of ICU patients available at the MIMIC public database. Datasets consisting of ECG, PPG and arterial BP waveforms from 8 subjects were used for the analysis and the relationship of PAT with systolic, diastolic and mean blood pressure was assessed through a linear regression fit. The analysis was carried out on datasets of short (20 min) and long (60 min) duration in order to evaluate the temporal changes on the linear relationship. The results showed high correlation between BP and PAT for both the short-term and the long-term analyses. The mean absolute error found between the true and estimated systolic BP values was close to 5mmHg; however, the error noticeably increased on the long-term dataset for all subjects.

1. Introduction

Elevated Blood Pressure (BP) is a human-specific illness affecting a quarter of the worldwide population. Clinically known as hypertension, elevated BP is considered the major risk factor for cardiovascular disease: the most common cause of death in developed countries. Consequently, detecting, treating and controlling hypertension are major goals of modern medicine [1]. The most accurate way to monitor someone's BP is by using invasive techniques; however, this is neither practical nor desirable in many cases [2]. On the other hand, non-invasive cuff-based methods have several disadvantages such as the inability to detect short-term changes in BP and the alterations in the measurement caused by the inflation of the cuff itself.

A novel technique for continuous non-invasive BP estimation based on PAT (Pulse Arrival Time) has raised the attention of the research community over the last 15 years due to its suitability and convenience for either ambulatory or clinical implementation. PAT is defined as the time interval that takes the pulse wave to reach a specific point in the periphery from its onset on the left ventricle in the same cardiac cycle. The theoretical framework that outlines the relationship between PTT (Pulse Transit Time) and BP is well-known by the Moens-Korteweg equation, which connects the pulse wave velocity with dimensions of the vessel and the distensibility of the vessel wall [3]. Although several authors have found a strong correlation between PAT/PTT and BP, there are still problems to be addressed in order to overcome the current limitations of the measurement.

Currently in the market, there is no device capable of continuously and noninvasively tracking blood pressure in a reliable way by means of the PTT technique [4]. The global demands on healthcare improvement require more sophisticated, reliable and easy-to-use technologies as well as solutions that do not interfere with patient's daily activities. The mentioned challenges have been stimulating the research on the promising PTT technique for blood pressure measurement owing its simplicity and availability of ECG and PPG sensors on ambulatory and clinical scenarios; nevertheless, there are still problems to be addressed in order to overcome the current limitations of the measurement.

This paper study the feasibility of non-invasive blood pressure estimation based on PAT over a public database called MIMIC from Physionet [8], which contains a collection of ECG, PPG and invasive arterial BP waveforms from ICU patients.

2. Materials

The MIMIC Database includes data recorded from over 90 ICU patients. The data in each case include signals and periodic measurements obtained from a bedside monitor as well as clinical data obtained from the patient's medical record. The recordings vary in length; almost all of them are at least 20 hours, and many are 40 hours or more [8].

In order to obtain a clean data subset for the study, certain inclusion and exclusion criteria were imposed to the patients. Firstly, only patient's records that have all three waveforms of interest available (ABP, ECG, PPG) were included. It is important to note that if any of the waveforms were missing even during a short period of time, the entire record was excluded. Patients that were admitted to the ICU with initial diagnoses related to heart or vascular diseases were also excluded. At last, waveforms with excessive motion artifact noise were also dropped from the dataset since clean records are required for the purpose of the study. After applying the mentioned filters to the whole database, 8 patients were found to be available. Table 1 presents a brief description of the patients selected.

Table 1. Age and gender of the patients selected from the MIMIC database.

Patient	Age	Gender
1	67	M
2	67	F
3	21	M
4	68	M
5	75	F
6	75	F
7	76	F
8	60	M

ECG signals are available at a sample rate of 500Hz whereas the PPG and the ABP at 125Hz. The waveforms were accessed using the WFDB Toolbox for Matlab, which is freely distributed by Physionet.

From the 24-hour waveform records available for each subject in average, a segment of an hour was selected based on the largest change in arterial BP. This data was further partitioned into two datasets: a long term dataset of 60 minutes of waveforms and a short term dataset of 20 minutes.

3. Methods

PAT was calculated beat-to-beat as the time interval between the R-peak on the ECG and two characteristic points on the PPG waveform: the point of maximum amplitude (PAT_p2p) and the point of the steepest slope on the rising edge (PAT_p2s) (see figure 1).

The relationship between systolic, diastolic and mean blood pressure with PAT was assessed through a linear regression fit of the following form:

$$BP = a * PAT + b$$

50 data-pairs where randomly obtained from both the short term and the long term dataset for every patient and each analysis was performed separately. To assess the relationship between the PAT and BP, the correlation coefficient and the mean squared error were calculated for all the setups mentioned.

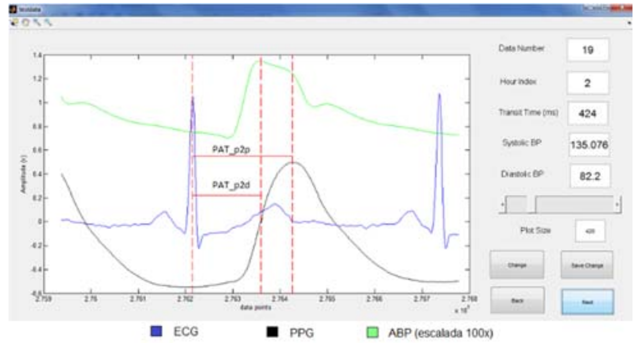

Figure 1. Two different ways of PAT estimation, PAT_p2p (peak to peak) and PAT_p2d (peak to maximum slope)

4. Results

Table 2 shows the variation for both the systolic and diastolic blood pressure within the hour of signals selected for each patient.

Table 2. Range of variation for systolic and diastolic BP for all subjects.

Patient	*Systolic Min*	*Systolic Max*	*Diastolic Min*	*Diastolic Max*
1	120	207	47	69
2	120	147	63	76
3	132	176	70	120
4	120	189	63	91
5	80	135	36	65
6	112	161	60	68
7	75	121	25	42
8	90	149	54	76

The average change in systolic BP (Systolic max – Systolic min) was 55mmHg while the average change in diastolic was 24mmHg. The correlation coefficients found in the linear regression for each of the setups are shown in Table 3. The values on the table represent the average across all subjects.

Table 3. Correlation coefficient for the linear regression between PAT and BP (systolic, diastolic and mean) for the short term and long term datasets. Values represent the average over the eight subjects.

BP	**Correlation Coefficient**			
	20 min Dataset		60 min Dataset	
	PAT_p2p	PAT_p2s	PAT_p2p	PAT_p2s
Systolic	-0.85	-0.89	-0.81	-0.89
Diastolic	-0.85	-0.83	-0.79	-0.84
Mean	-0.86	-0.88	-0.81	-0.88

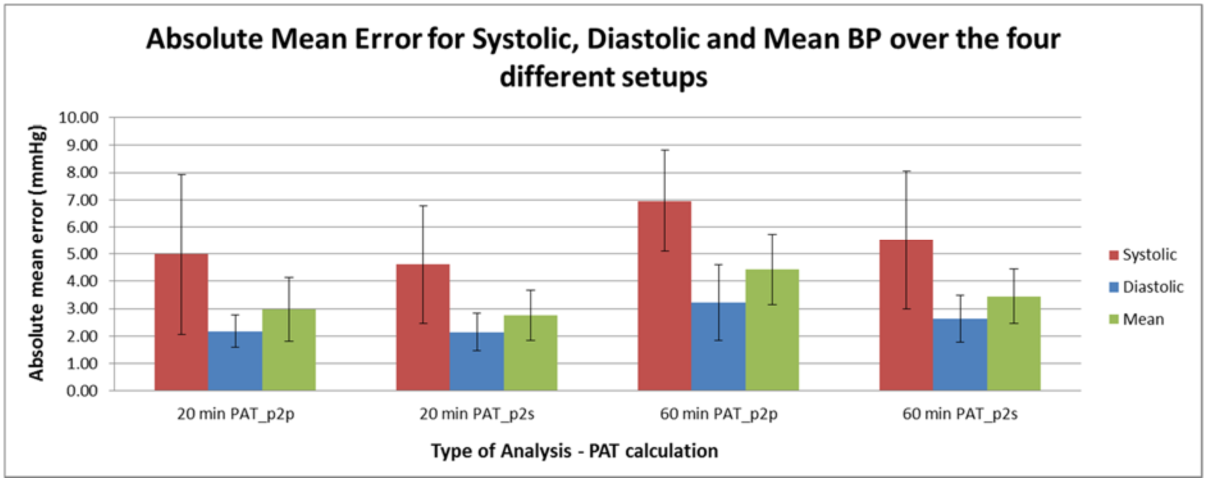

Figure 2. Average absolute mean error for the linear regression for all subjects in the four different setups.

The values obtained in the linear regression show a strong correlation between PAT_p2p and PAT_p2d with all three different blood pressure readings. In terms of the datasets of short and long duration, there is no remarkable difference across them. The average absolute mean error for the linear regression in all four different setups is shown in Figure 2. As expected, the systolic blood pressure presented the largest error reaching a maximum at 7mmHg for the PAT_p2p in the long term analysis.

5. Discussion and conclusion

The purpose of this paper was to evaluate the feasibility of blood pressure estimation based on pulse arrival time through a subset of patient's waveforms available on the MIMIC public database. The procedure implemented for subject selection reduced the number of data available for the study since just eight of the subjects met with the proposed criteria. One can possibly argue that a dataset of waveforms of this size is not enough to give a conclusion about the feasibility of this novel technique, however, our primarily interest was to perform the analysis on a homogeneous population avoiding the influence of external factors, challenging clinical conditions and noise as much as possible.

Since during an ICU stay the blood pressure of a subject could remain stable for long periods of time, the proposed analyses were performed separately on a segment of data of about an hour duration in where maximum variation of the BP was observed per subject. It is important to notice that the information about the medications provided to each subject during their stay in ICU was not taken into account for this study. In this scenario, large variations of systolic and diastolic could have been caused by the effects of any of this drugs, however, its influence or presence was not studied.

Two different methods for PAT calculation were evaluated (PAT_p2p and PAT_p2d). Although their performed similar in terms of the absolute mean error and the correlation coefficient on the linear regression fit, PAT_p2d exhibited a slightly better outcome. Several authors have widely discussed which specific point in the PPG waveform used as a stop marker for PAT calculation yields the best results in terms of the correlation with BP. The foot of the PPG waveform can also be found on the literature and good results have been achieved, however, this technique is prone to non-trivial error due to common artifact in the waveforms and wave reflection interference [5]. This study did not evaluate the performance of the PPG's foot for PAT calculation but it is being considered for a future work.

The temporal variation of the PAT-BP relationship is also a matter of discussion. Our results showed that the absolute mean error of the measurement increased in the 60 minutes subset of data for systolic, diastolic and mean blood pressure. This phenomenon has been previously studied by [2], [6] and some recalibration procedures have been implemented in order to tackle this problem. The purpose of this study was not to propose a solution to this issue but to provide more evidence to the hypothesis that the PAT-BP relationship is not static over the time.

It is widely accepted that there is a strong correlation between BP and PAT/PTT/PWV. Many research papers as well as our own findings have contributed to prove this assertion. The Moens-Korteweg equation has provided the mathematical foundation that fuels the research towards this direction, however, the practical use of this equation implies several assumptions that might not be valid for the complex behavior and regulation of the arterial tree involved. Some authors have concluded that vascular smooth muscle tone changes have non negligible influence on the BP-PWV relationship, evidencing that the assumption of a constant thickness to radius ratio from the equation might not be valid [3], [7] . It is also important to notice that the arterial segment involved on the PWV estimation is formed for both elastic and muscular arteries and it is well known that their biomechanical properties differ from each other. An interesting phenomenon called vasomotion has also been reported as a major source of error that blur the BP-PWV relationship [3] [5]. However, the understanding of this phenomenon is still in development and its influence on the BP-PWV has to be further investigated.

It is concluded that PAT could be potentially used for non-invasive BP estimation on ICU patients under certain limitations; nonetheless, further investigation needs to be addressed on the temporal degradation of the BP-PAT relationship in order to improve the technique reliability and accuracy.

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