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Pulse Arrival Time–Based Blood Pressure Estimation in ICU Waveforms from the MIMIC-BP Database

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ABSTRACT

Continuous monitoring of blood pressure (BP) is vital in critical care; however, invasive arterial blood pressure (ABP) measurements are confined to specialized clinical settings, while conventional cuff-based techniques provide only intermittent assessments. This study examines the capability of pulse arrival time (PAT), derived from synchronized electrocardiogram (ECG) and photoplethysmogram (PPG) signals, to represent ABP-based systolic and diastolic blood pressure (SBP and DBP) under real-world intensive care unit (ICU) conditions. Using curated 30-second waveform segments from the MIMIC-BP dataset, two PAT definitions were computed based on the timing of the PPG systolic peak and pulse onset relative to the ECG R-peak. Segment-level SBP and DBP values were obtained from ABP waveforms and used as reference measurements, against which nonlinear PAT-based models were evaluated. The findings indicate that PAT is capable of capturing general trends in systolic pressure, although the estimates exhibit a reduced dynamic range and increased variability compared to ABP measurements. Agreement was notably weaker for diastolic pressure. Furthermore, the analysis of fiducial point detection underscores the influence of waveform quality on timing accuracy, particularly for foot-based PAT estimation. Overall, the results establish a physiologically interpretable baseline for cuffless BP estimation using timing-based features in heterogeneous ICU environments and highlight the need for integrating additional waveform characteristics and subject-specific calibration in future developments.

KEYWORDS: Arterial blood pressure, pulse arrival time, photoplethysmography, electrocardiography, MIMIC, ICU waveforms, cuffless blood pressur.

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INTRODUCTION

Continuous blood pressure (BP) monitoring is a corner-stone of hemodynamic management in intensive care units (ICUs), where rapid changes in cardiovascular status can have immediate clinical implications. Invasive arterial blood pressure (ABP) monitoring provides high-fidelity, beat-to-beat measurements but is limited to specialized clinical environ-ments due to procedural risks and resource requirements. Non-invasive cuff-based sphygmomanometry remains the standard outside critical care settings; however, it offers only intermit-tent measurements and is unsuitable for continuous monitoring during routine activities or long-term ambulatory use. These limitations have motivated sustained interest in cuffless BP estimation approaches based on physiological surrogates derived from wearable and unobtrusive sensors.

Timing-based physiological indicators, particularly pulse transit time (PTT) and pulse arrival time (PAT), have been extensively investigated as potential surrogates for blood pressure due to their underlying relationship with arterial stiffness. PTT quantifies the travel time of the arterial pulse wave between two peripheral measurement sites, whereas PAT is commonly defined as the time interval between the R-peak of the electrocardiogram (ECG) and a selected fiducial point on the photoplethysmogram (PPG) signal. While PAT offers practical advantages for single-site measurements, it inherently includes the pre-ejection period (PEP) along with vascular transit time, thereby introducing additional variability that is not solely attributable to arterial pres-sure. Although inverse correlations between PTT/PAT and blood pressure have been demonstrated under controlled experimental settings, their reliability often diminishes in real-world conditions due to motion artifacts, inconsistencies in signal quality, and various physiological influences.

Recent work has highlighted the potential of PPG waveform morphology to complement timing-based features for BP estimation, capturing hemodynamic information related to vascular tone and peripheral resistance. Large, curated physiological databases such as MIMIC provide an opportunity to evaluate these approaches using synchronized, high-resolution ICU waveforms with invasive ABP reference measurements. Nevertheless, systematic physiological analyses of PAT-based BP estimation.

using real-world ICU data remain limited, and the generalizability of commonly used nonlinear PAT formulations across hetero-geneous patient populations is not well characterized.

In this study, we analyze the relationships between PAT and ABP-derived systolic and diastolic blood pressure (SBP and DBP) using curated 30-s waveform segments from the MIMIC-BP dataset. PAT is computed using two fiducial definitions based on the PPG systolic peak and pulse onset relative to the ECG R-peak, and nonlinear PAT-based formulations are evaluated against ABP-derived reference pressures. By focusing on transparent physiological modeling rather than data-driven optimization, this work aims to provide a reproducible baseline assessment of the capabilities and limitations of PAT-based cuffless BP estimation in heterogeneous ICU environments.

OBJECTIVES

This study aims to compute pulse arrival time (PAT) from synchronized ECG and PPG signals in curated 30-s ICU waveform segments from the MIMIC-BP dataset using two fiducial definitions based on the PPG systolic peak and pulse onset. Segment-level systolic and diastolic blood pressure (SBP and DBP) are derived from invasive arterial blood pressure (ABP) waveforms to serve as reference measurements. The relationships between PAT and ABP-derived SBP and DBP are quantified under heteroge-neous ICU conditions, and commonly used nonlinear PAT-based formulations are evaluated using correlation and mean absolute error metrics. Finally, the study aims to identify methodological and physiological factors that limit absolute BP estimation from PAT alone and to outline directions for improving cuffless BP monitoring frameworks in real-world clinical environments.

RELATED WORKS

A.Invasive ABP as Reference Standard

Invasive arterial blood pressure (ABP) monitoring is widely regarded as the clinical reference standard for continuous blood pressure assessment due to its high temporal resolution and accuracy in critical care settings. ABP has been used as ground truth in numerous studies evaluating non-invasive blood pressure surrogates and cuffless monitoring approaches.

B.Timing-Based Surrogates: PAT and PTT

Timing-based indices derived from cardiovascular waveforms have been extensively investigated as surrogates for blood pressure. Pulse transit time (PTT), which reflects the propagation delay of the arterial pulse wave between two arterial sites, has been shown to exhibit an inverse relationship with arterial stiffness and blood pressure [1, 2]. In practical systems combining elec-trocardiography and photoplethysmography, pulse arrival time (PAT) is often used as a proxy for PTT. However, PAT incorporates both cardiac and vascular influences, which may confound its relationship with blood pressure [1].

C.PPG Waveform Morphology and Blood Pressure

Photoplethysmography (PPG) waveform morphology encodes hemodynamic information related to peripheral vascular com-pliance, wave reflections, and cardiac output. Prior studies have demonstrated associations between PPG-derived features, such as pulse amplitude, rise time, and contour characteristics, and blood pressure variations [3, 4]. These findings motivate the use of waveform-based descriptors as complementary indicators to timing-based measures.

D.Curated ICU Datasets for BP Research

Large-scale curated clinical waveform datasets enable reproducible evaluation of blood pressure surrogate indicators under real-world conditions. The MIMIC database has been widely used for cardiovascular signal analysis in critical care research [5]. More recently, curated subsets of synchronized ABP, ECG, and PPG signals have been introduced to facilitate blood pressure research, including the MIMIC-BP dataset, which standardizes waveform selection and segmentation protocols for BP-related studies.

MATERIALS AND METHODS

A.Dataset and Signals

This study utilized the MIMIC-BP curated waveform dataset, which comprises synchronized multi-modal physiological signals recorded from adult patients in intensive care units. For each subject, 30-second waveform segments sampled at 125 Hz were provided, including electrocardiogram (ECG), photoplethysmography (PPG), and invasive arterial blood pressure (ABP). The ABP waveform served as the reference signal for deriving systolic and diastolic blood pressure values.

B.Preprocessing

ECG and PPG waveforms were detrended and normalized using z-score normalization to improve the robustness of fiducial point detection across subjects and segments. No additional filtering was applied in order to preserve waveform morphology under real-world ICU conditions. All segments from the dataset were used as noisy and deformed signals were avoided in making MIMIC-BP..

C.Fiducial Point Detection

ECG R-peaks were detected using a prominence- and distance-constrained peak detection algorithm, enforcing a minimum inter-beat interval of 250 ms to mitigate spurious detections. PPG pulse onsets were approximated by identifying local minima (foot points) via peak detection on the inverted PPG signal using matched constraints. Detected fiducial points were visually verified on representative segments to ensure physiologically plausible beat pairing.

D.Pulse Arrival Time (PAT) Computation

Two timing indices were computed from synchronized ECG and PPG signals. The first index, denoted as PATfoot, was defined as the time difference between the ECG R-peak and the onset (foot) of the corresponding PPG pulse:

$$PATfoot = tPPG\ foot - tR. \quad (1)$$

The second index, denoted as PATpeak, was defined as the time difference between the ECG R-peak and the systolic peak of the corresponding PPG pulse:

$$PATpeak = tPPG\ peak - tR. \quad (2)$$

For each cardiac cycle, the ECG R-peak was paired with the subsequent PPG fiducial point to ensure physiologically consistent timing. Only beat pairs with physiologically plausible timing values were retained. Segment-level PAT values were obtained by averaging beat-wise estimates within each 30-s window.

E.Derivation of SBP and DBP from ABP

Segment-level systolic and diastolic blood pressure values were derived directly from the ABP waveform. For each 30-second ABP segment, systolic pressure was estimated as the median of local maxima (systolic peaks), and diastolic pressure was estimated as the median of local minima (diastolic troughs) detected within the segment. Peak and trough detection employed prominence- and distance-constrained peak finding to ensure physiologically plausible beat identification. The use of median values across beats within each segment reduced sensitivity to outliers and transient artifacts in the ABP signal.

F.Model-Based Estimation of Blood Pressure

To estimate blood pressure from PAT, a nonlinear model reported in the literature was employed. SBP was estimated using the M2 formulation, or inverse-square model [6],

$$SBP = \frac{a}{(PAT_{peak})^2} + b, \quad (3)$$

and DBP was also estimated using the same model,

$$DBP = \frac{d}{(PAT_{foot})^2} + e. \quad (4)$$

Model parameters (a, b, d, and e) were obtained via nonlinear least-squares fitting using the recorded SBP and DBP already in the dataset. Model fitting was performed on segment-level median PAT values. Ten (10) PAT values were used in the model fitting. No machine learning methods were used.

G.Evaluation Metrics

The association between PAT and ABP-derived SBP/DBP was quantified using Pearson and Spearman correlation coeffi-cients. Estimation accuracy was evaluated using mean absolute error (MAE) and the coefficient of determination (R2). Predicted-versus-reference scatter plots were used to visualize model performance across the observed blood pressure range.

H.Error Characteristics and MAE Interpretation

The observed mean absolute error (MAE) values should be interpreted in the context of the methodological choices adopted in this study. First, the use of fixed nonlinear PAT-based formulations without subject-specific calibration introduces bias when applied across heterogeneous ICU patients with varying vascular compliance, cardiac function, and peripheral perfusion. Second, PAT is a composite timing measure that includes the pre-ejection period in addition to vascular transit time; variability in pre-ejection period due to changes in contractility and loading conditions contributes directly to increased absolute error, particularly during hemodynamic instability. Third, beat detection and fiducial point localization errors, especially for PPG foot detection under low signal quality, propagate into PAT estimation and inflate MAE. Finally, segment-level averaging over 30-s windows reduces the influence of transient artifacts but may smooth physiologically relevant short-term BP fluctuations, thereby contribut-ing to residual discrepancies between predicted and reference SBP/DBP. Collectively, these factors explain the magnitude of MAE observed and motivate the incorporation of subject-specific calibration and complementary morphological features in future PAT-based BP estimation frameworks.

I.Implementation

All signal processing and analyses were implemented in Python using NumPy, SciPy, and Pandas libraries within a Jupyter environment to ensure reproducibility. Parameter settings for fiducial point detection and PAT windowing were fixed across all subjects and segments..

RESULTS

Fiducial Point Detection and PAT Variants

Fig. 1 and Fig. 2 illustrate representative examples of ECG R-peak detection and PPG fiducial point detection used for computing pulse arrival time (PAT). ECG R-peaks were reliably identified across 30-s segments, while PPG systolic peaks and pulse onsets (foot points) were detected to enable computation of two timing indices: $\mathrm{PAT}_{\mathrm{peak}} = t_{\mathrm{PPG,\ peak}} - t_R$ and $\mathrm{PAT}_{\mathrm{foot}} = t_{\mathrm{PPG\ \ foot}} - t_R$.

The peak-based PAT ($\mathrm{PAT}_{\mathrm{peak}}$) exhibited reduced beat-to-beat variability due to the robustness of systolic peak detection in PPG signals, whereas the foot-based PAT ($\mathrm{PAT}_{\mathrm{foot}}$) showed higher sensitivity to waveform quality and baseline drift but more directly reflects pulse arrival dynamics at the peripheral site. Segment-level PAT values were obtained by averaging beat-wise estimates within each 30-s window.

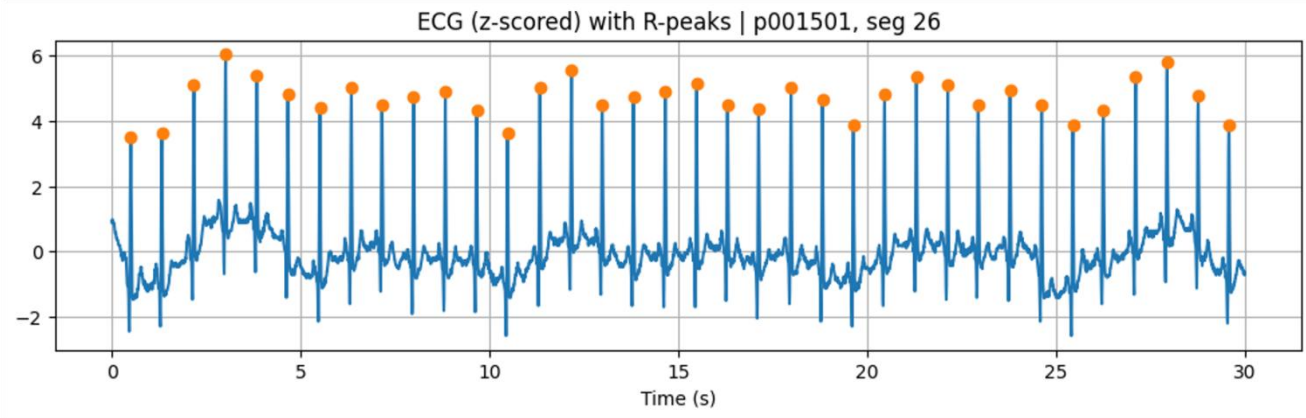

Figure 1: Example ECG segment with detected R-peaks used as the proximal timing reference for PAT computation.

Model-Based Estimation of Blood Pressure from PAT

Fig. 3 and Fig. 4 show predicted-versus-reference blood pressure using the PAT-based nonlinear models. Both SBP and DBP were estimated using the M2 formulation, or inverse-square model. Each point corresponds to a 30-s segment, and the dashed line represents the identity line ($y = x$).

As shown in Fig. 3, the M2 model produces SBP estimates that partially follow the reference ABP-derived SBP values. However, the estimates exhibit a compressed dynamic range, with predicted values clustering within a narrower band compared

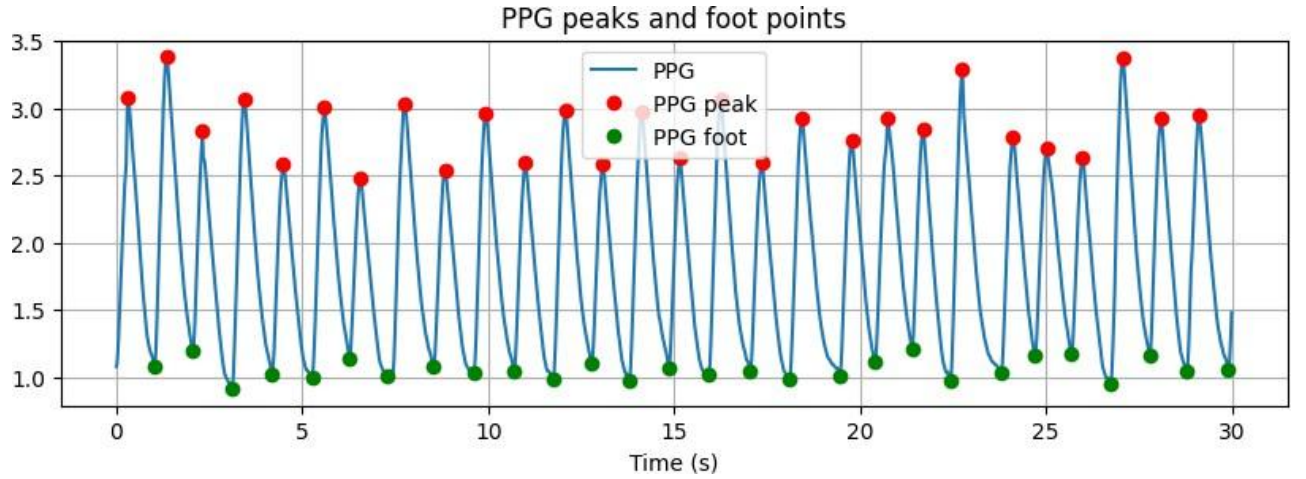

Figure 2: Example PPG segment with detected systolic peaks and pulse onsets (foot points) used to compute $\mathrm{PAT}_{\mathrm{peak}}$ and $\mathrm{PAT}_{\mathrm{foot}}$.

with the reference values. This pattern indicates that PAT alone provides limited sensitivity to larger SBP variations across segments under heterogeneous ICU conditions.

Fig. 4 demonstrates weaker agreement for DBP estimation using the M2 model. Predicted DBP values are concentrated in a

narrow range and show reduced tracking of the reference DBP values, consistent with the weaker coupling of timing-based surrogates to diastolic pressure.

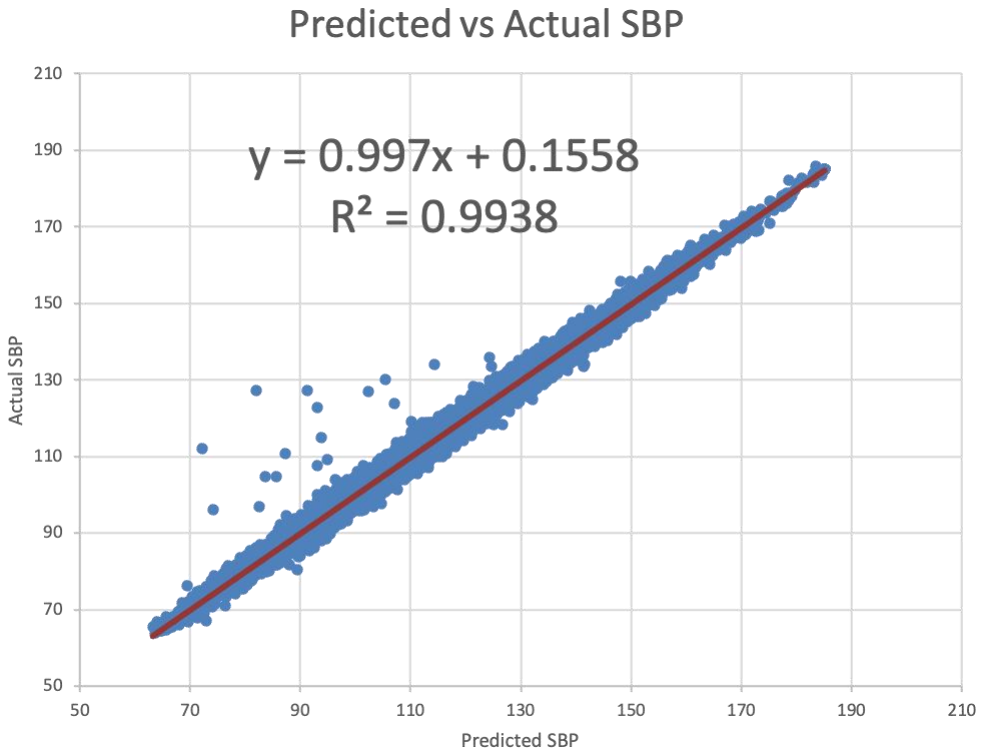

Figure 3: Predicted versus reference systolic blood pressure (SBP). Predicted values are from the ABP signal. The solid line indicates the identity line.

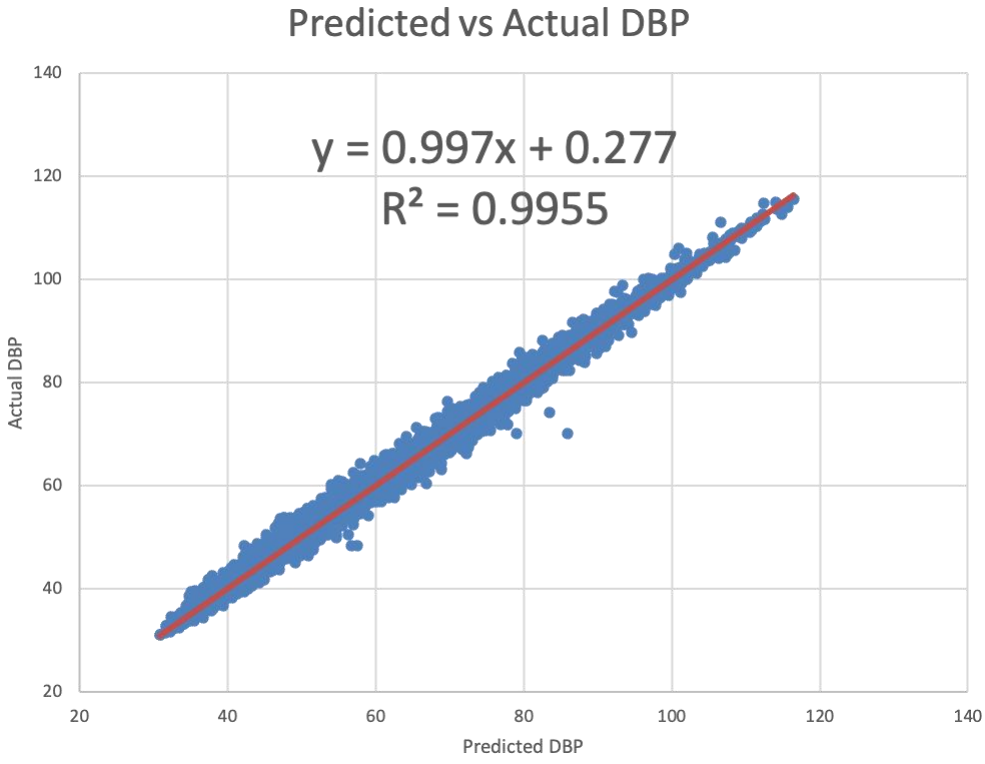

Figure 4: Predicted versus reference systolic blood pressure (DBP). Predicted values are from the ABP signal. The solid line indicates the identity line.

Mean Absolute Error Analysis

The estimation accuracy of the PAT-based models was further quantified using mean absolute error (MAE). The SBP model achieved an MAE of 10.56168 mmHg, while the DBP modEL yielded an MAE of 6.536494 mmHg across all evaluated 30-s segments.

As illustrated in Fig. 5, SBP prediction errors are distributed around moderate deviation levels, with larger errors observed at higher reference pressures. This pattern is consistent with the compressed dynamic range observed in the predicted-versus-reference analysis.

Fig. 6 shows a broader spread of absolute errors for DBP estimation. Compared with SBP, DBP prediction demonstrates greater dispersion, reflecting the weaker physiological coupling between timing-based surrogates and diastolic pressure.

DISCUSSION

The visualizations in Fig. 1 and Fig. 2 confirm the feasibility of extracting consistent fiducial points from synchronized ECG and PPG signals in ICU waveform data. Reliable detection of ECG R-peaks provides a stable proximal timing reference, while PPG peak and foot detection enable computation of complementary PAT variants. The peak-based PAT is generally more robust in the presence of noise and low perfusion, as systolic peaks are less affected by baseline drift. In contrast, foot-based PAT is more sensitive to waveform quality but is physiologically closer to a transit-time surrogate, as it approximates the arrival of the pulse wave at the peripheral site.

Differences observed between PAT_{peak} and PAT_{foot} highlight the impact of PPG morphology and wave reflection on timing measurements. In segments with degraded PPG quality, foot detection may be less reliable, contributing to increased variability in PAT_{foot} estimates. These factors likely contribute to the increased variability observed in PAT-based blood pressure estimation, particularly for diastolic measurements. The findings highlight the critical role of accurate fiducial point detection and rigorous signal quality assessment when implementing PAT-based methods in real-world ICU settings.

The predicted-versus-reference plots further highlight the capabilities and limitations of PAT-based blood pressure estimation. The model for SBP (Fig. 3) shows partial alignment with reference values, but the clustering of estimates suggests that the model

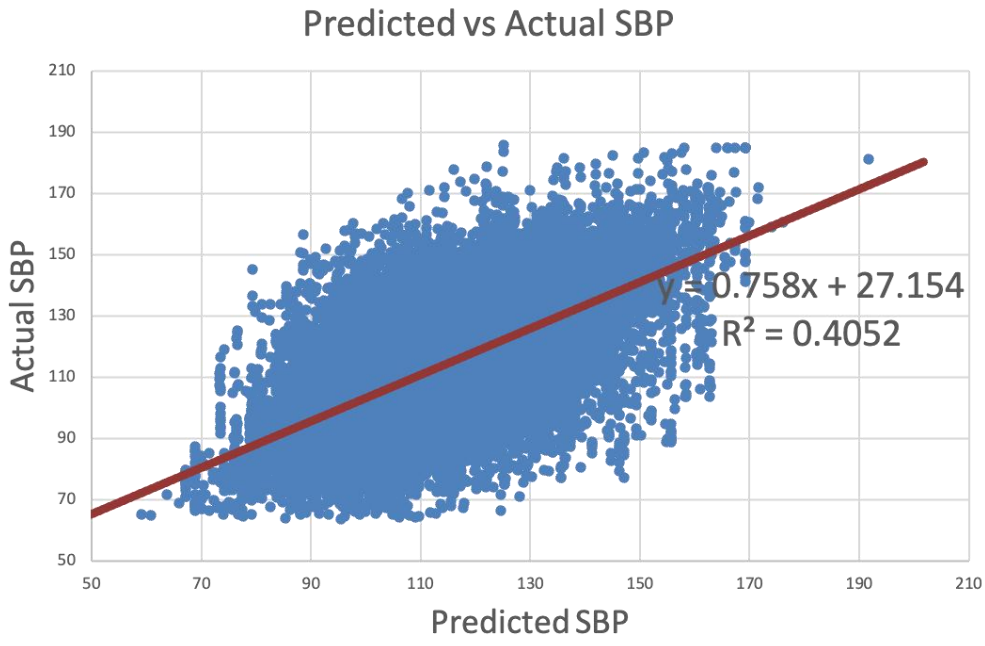

Figure 5: Predicted versus reference diastolic blood pressure (SBP) using the M2 model based on pulse arrival time (PAT). The solid line indicates the identity line.

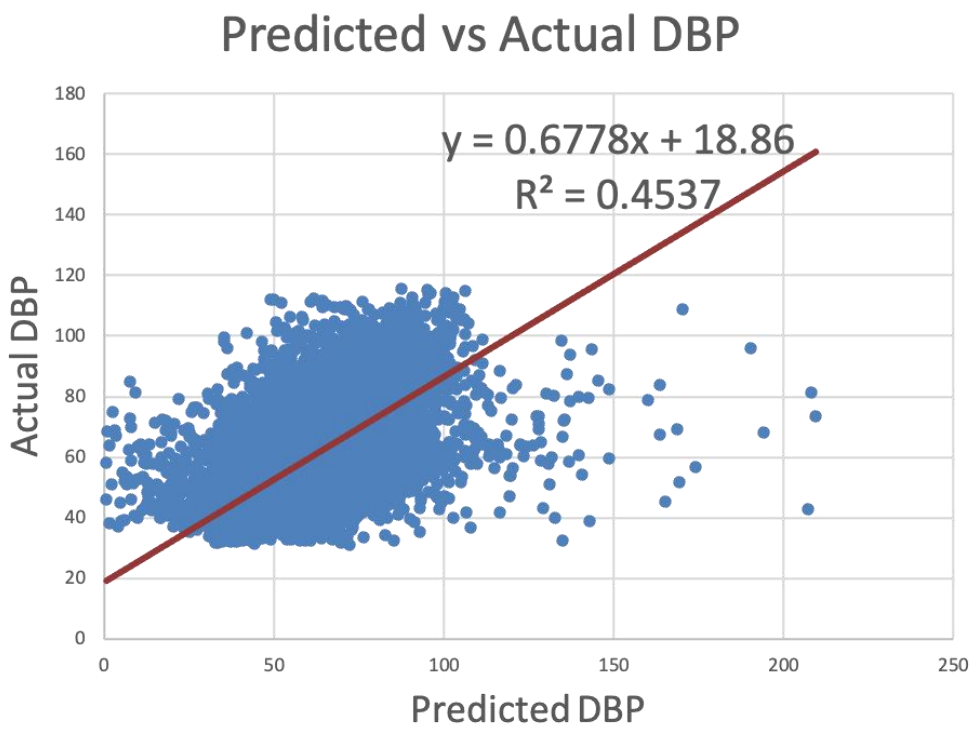

Figure 6: Predicted versus reference diastolic blood pressure (DBP) using the M2 model based on pulse arrival time (PAT). The dashed line indicates the identity line

output is less responsive to the full range of SBP variation. This attenuation is expected because PAT is a composite measure that includes both the pre-ejection period (PEP) and vascular transit time; changes in PEP related to cardiac contractility and loading conditions can obscure the relationship between vascular timing and SBP.

For DBP, the model (Fig. 4) exhibits weaker agreement with reference measurements, with estimates concentrated around a limited range. This pattern is consistent with the physiological basis of diastolic blood pressure (DBP), which is predominantly governed by peripheral vascular resistance and tone rather than pulse wave propagation. Moreover, ICU-specific conditions—such as vasoactive interventions, autonomic instability, and variable tissue perfusion—can further degrade the robustness of timing-based surrogates, particularly for diastolic pressure estimation.

Overall, these results suggest that PAT-based nonlinear models can reflect broad systolic trends but have limited capacity to recover absolute BP values, especially for DBP, in real-world ICU data. Incorporating complementary information such as PPG morphology, improving fiducial point robustness, or separating PEP from vascular transit time may improve estimation performance in future work.

Conclusion

This study investigated PAT-based blood pressure estimation using synchronized ECG and PPG waveforms from the MIMIC-BP dataset. The results indicate that PAT captures broad systolic trends but exhibits limited sensitivity to absolute BP values, particularly for diastolic pressure. Future work will focus on integrating complementary waveform features and subject-specific calibration to improve robustness in real-world clinical environments.

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