Machine Learning Approaches for PPG-based Blood Pressure Monitoring: Validation against Invasive Arterial Line Measurements

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Arterial blood pressure is a physiological parameter of major importance to medical applications. CSEM has developed pioneering techniques for blood pressure estimation based on optical signals such as photoplethysmographic pulse wave analysis (known as oBPM®), which enable continuous non-occlusive blood pressure monitoring. Recently, CSEM explored data-driven approaches using machine learning to enhance the performance of these techniques. The novel methods were tested in the clinical setting and found to outperform previous approaches by up to 15%.

Photoplethysmography (PPG) could provide a novel approach for continuous, non-obtrusive blood pressure (BP) monitoring, comfortably integrated in wearables and smartphones. CSEM has conducted extensive work in this domain, developing the oBPM® technology for PPG-based BP monitoring [1]. As part of our continued efforts to boost the accuracy, robustness, and applicability of oBPM®, we have explored machine learning (ML) techniques in this framework, motivated by the increasing availability of labeled PPG datasets for supervised learning.

In this work, we developed a novel hybrid approach that pre-processes PPG signals and extracts physiological features using our well-established and clinically validated oBPM® library, and then performs BP estimation via data-based ML models (Figure 1). ML methods capable of automatic feature selection were used to identify the most meaningful features. The selected feature sets were then used to develop higher-accuracy estimation models. For this work, the estimation was focused on systolic (Sys) BP.

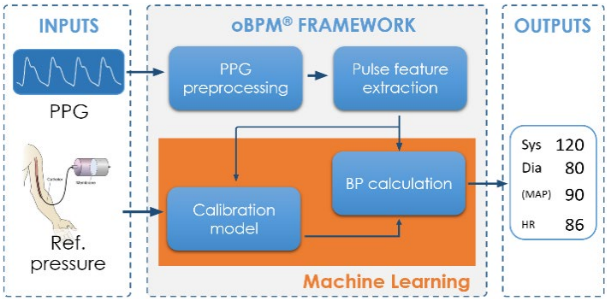

Figure 1: Outline of the novel hybrid approach explored in this work, combining modules from CSEM's oBPM® with novel ML models.

The method was explored on PPG data collected from clinical patients undergoing general anesthesia induction, which caused strong variations in BP over time[2]. Concurrent traces of Sys BP were obtained invasively (catheter) and served as reference.

The PPG data were segmented in 20-second segments, which were grouped in pairs to model a situation where a calibration measurement was previously made (PPG + gold-standard reference), and a second, PPG-only measurement is performed for which Sys BP is to be estimated (Figure 2). The patient group was split into a training and test sets, with each patient contributing to only one set. Three ML models were explored: LASSO regression, Gaussian process regression (GPR), and support vector regression (SVR). A Control model was also included where the Sys BP estimate is equal to the reference Sys BP of the calibration segment, thus assuming no BP variations.

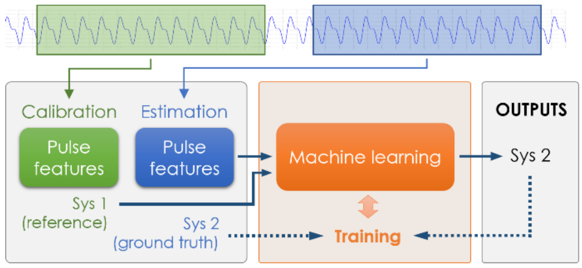

Figure 2: Learning approach to estimate systolic (Sys) BP at a given time (blue) in the presence of calibration information (green).

After training, all models performed substantially better than the Control, and the ML models were found to outperform oBPM® as well, reducing the standard deviation of the estimation error by approximately 9–15% in the test set (Figure 3). This indicates a very favorable performance in this clinical setting, with the potential to expand oBPM®'s accuracy under AAMI standards to a larger range of applicability [2]. Moreover, models like LASSO presented comparable computational costs to oBPM®, and are therefore well suited for embedded estimation as well.

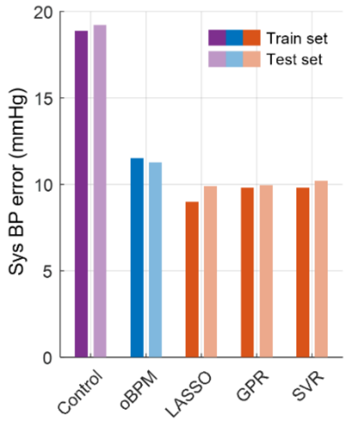

Figure 3: Sys BP estimation performance for different Sys BP estimation models. The Control model is a simple approach where the value of the reference BP in the calibration is used directly as the estimate.

Overall, these results suggest that ML techniques, namely LASSO, GPR, and SVR, are highly promising for non-obtrusive BP monitoring, leveraging CSEM's previous experience in model-based BP estimation with new predictors learned directly from the data. These insights may prove extremely valuable to pursue the challenging goal of BP monitoring using wearable technology and measured in different points of the body.

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[1] M. Proença, J. Solà, M. Lemay, C. Verjus, "Method, apparatus and computer program for determining a blood pressure value," Patent Application WO 2016/138965 A1, Sep. 2016.

[2] M. Proença, Y. Ghamri, G. Hofmann, *et al.*, "Automated Pulse Oximeter Waveform Analysis to Track Changes in Blood Pressure during Anesthesia Induction: A Proof-of-Concept Study," Anesth Analg, 2020, 130(5).