

# Towards quantitative precision for ECG analysis: Leveraging state space models, self-supervision and patient metadata

Temesgen Mehari and Nils Strodthoff

**Abstract**—Deep learning has emerged as the preferred modeling approach for automatic ECG analysis. In this study, we investigate three elements aimed at improving the quantitative accuracy of such systems. These components consistently enhance performance beyond the existing state-of-the-art, which is predominantly based on convolutional models. Firstly, we explore more expressive architectures by exploiting structured state space models (SSMs). These models have shown promise in capturing long-term dependencies in time series data. By incorporating SSMs into our approach, we not only achieve better performance, but also gain insights into long-standing questions in the field. Specifically, for standard diagnostic tasks, we find no advantage in using higher sampling rates such as 500Hz compared to 100Hz. Similarly, extending the input size of the model beyond 3 seconds does not lead to significant improvements. Secondly, we demonstrate that self-supervised learning using contrastive predictive coding can further improve the performance of SSMs. By leveraging self-supervision, we enable the model to learn more robust and representative features, leading to improved analysis accuracy. Lastly, we depart from synthetic benchmarking scenarios and incorporate basic demographic metadata alongside the ECG signal as input. This inclusion of patient metadata departs from the conventional practice of relying solely on the signal itself. Remarkably, this addition consistently yields positive effects on predictive performance. We firmly believe that all three components should be considered when developing next-generation ECG analysis algorithms.

**Index Terms**—Decision support systems, Electrocardiography, Machine learning algorithms

## I. INTRODUCTION

Machine learning for ECG analysis Machine learning, in particular deep learning, has the potential to transform the entire field of healthcare. The electrocardiogram (ECG) is particularly well-suited to lead this development because of its widespread use (in the US, an ECG was ordered or provided at about 5% of office visits [1]). While it only requires basic recording equipment, it holds enormous diagnostic potential

that we only gradually start to uncover with the help of machine learning [2]–[5].

**Model architectures** On the algorithmic side, the analysis of ECGs based on raw sensor data is still largely dominated by convolutional neural networks [3], [6]–[8]. This default choice is slowly being challenged by the rise of transformer-based architectures or combinations of convolutional architectures with attention elements, as exemplified by the winning solutions of the two past editions of the Computing in Cardiology Challenge [9], [10]. In this work, we explore a novel algorithmic approach, *Structured State Space Sequence (S4) models* [11], which learn a continuous representation of time series data and are particularly suited for modeling long-term dependencies. S4 models have demonstrated exceptional performance in modeling and analyzing long-term time series data in various domains. By leveraging the inherent sequential dependencies within ECG signals, we anticipate that the application of S4 models to the ECG domain can significantly enhance the performance of existing prediction models. By capturing complex temporal dynamics and long-term dependencies, S4 models have the potential to unlock new insights and achieve more accurate ECG analysis outcomes. We demonstrate consistent improvements in quantitative accuracy through three components: (1) the use of S4 models as internal model architecture, (2) leveraging self-supervised pretraining, and (3) the inclusion of demographic metadata, see also Figure 1 for a visual summary of the achieved results. We discuss all three components in the following paragraphs:

**1) More expressive architectures: SSMs** We thoroughly evaluate the model using a well-established benchmarking procedure [6] on the *PTB-XL* [12]–[14] and *Chapman* [15] datasets and show consistent improvements over the existing (convolutional as well as attention-based) state-of-the-art. Our main insight is methodological in nature. As a consequence, we deliberately focus on comprehensive ECG classification tasks rather than specific clinical prediction tasks, even though we also envision that data-driven methods will eventually supplement current rule-based decision support systems in ECG devices, see also [16].

Furthermore, we use the model’s capability to capture long-term dependencies to systematically investigate long-standing questions in the field, i.e. how long-ranged are the interactions in ECG data that need to be explicitly captured and do models actually profit from input data with a higher sampling frequency of 500 Hz as compared to 100 Hz.

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