

MEIT: Multimodal Electrocardiogram Instruction Tuning on Large Language Models for Report Generation

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<https://github.com/AIoT-MLSys-Lab/MEIT>

Abstract

Electrocardiogram (ECG) is the primary non-invasive diagnostic tool for monitoring cardiac conditions and is crucial in assisting clinicians. Recent studies have concentrated on classifying cardiac conditions using ECG data but have overlooked ECG report generation, which is time-consuming and requires clinical expertise. To automate ECG report generation and ensure its versatility, we propose the Multimodal ECG Instruction Tuning (MEIT) framework, the first attempt to tackle ECG report generation with LLMs and multimodal instructions. To facilitate future research, we establish a benchmark to evaluate MEIT with various LLMs backbones across two large-scale ECG datasets. Our approach uniquely aligns the representations of the ECG signal and the report, and we conduct extensive experiments to benchmark MEIT with nine open-source LLMs using more than 800,000 ECG reports. MEIT's results underscore the superior performance of instruction-tuned LLMs, showcasing their proficiency in quality report generation, zero-shot capabilities, resilience to signal perturbation, and alignment with human expert evaluation. These findings emphasize the efficacy of MEIT and its potential for real-world clinical application. Our code is released at <https://github.com/AIoT-MLSys-Lab/MEIT>.

1 Introduction

Electrocardiogram (ECG) is the primary tool for heart disease diagnosis. In standard practice, cardiologists examine these ECG recordings and manually generate detailed diagnostic reports, which is a complex and time-consuming process. Recently, AI models have been developed to streamline ECG data analysis for the classification task (Hu et al., 2023; Liu et al., 2023a, 2024a), yet the automatic generation of reports from ECG recordings remains relatively underexplored.

Unlike image-based medical report generation tasks (e.g., radiology reports), ECG report gener-

ation faces unique challenges due to the concise, keyword-centric content of ECG reports, which contrasts with the more extensive anatomical descriptions in radiology. Directly transferring methods from radiology is hindered by the distinct nature of ECG signals and the limited semantic overlap with imaging data. Furthermore, there is still a lack of comprehensive benchmarks for evaluating the performance of ECG report generation.

Drawing on the versatility of LLMs and multimodal LLMs (MLLMs) (Achiam et al., 2023; Touvron et al., 2023b; Wan et al., 2023b; Wang et al., 2024a; Zhu et al., 2024b; Wang et al., 2024b; Zhang et al., 2025a; Zhu et al., 2025) in various language tasks, in this work, we introduce MEIT, a Multimodal ECG Instruction Tuning framework that extends the capability of large language models (LLMs) for the task of ECG report generation. By aligning ECG recordings with human instructions, MEIT produces clinically relevant reports and demonstrates zero-shot performance when transferring across different continents and data collection devices. Concretely, we construct a multimodal instruction dataset from publicly available ECG recordings and propose an efficient attention-based fusion method that incorporates ECG signals into the latent space of LLMs without adding new parameters.

We also introduce a comprehensive benchmark to evaluate ECG report generation across two large-scale datasets (with 20K and 800K ECG-report pairs), covering four tasks: (1) report generation quality, (2) zero-shot transfer across datasets, (3) robustness under signal perturbations, and (4) alignment with expert evaluation. We assess MEIT using ten open-source LLMs, demonstrating: (1) the superior performance of MEIT in ECG report generation and effective ECG representation learning; and (2) the strong transferability of instruction-tuned LLMs across diverse clinical domains.

In summary, our primary contribution is the

MEIT framework, a novel method for automated ECG report generation and evaluation based on LLMs. It features a lightweight, attention-based fusion module for integrating ECG signals and text, along with a newly designed four-task benchmark for ECG report evaluation. Empirical results highlight MEIT’s ability to generate high-quality reports, perform robustly under data perturbations, and align closely with expert assessments, thereby paving the way for improved ECG interpretation and broader innovations in embedding biomedical signals into LLMs.

2 Related Work

Medical Report Generation. Our work is closely related to medical report generation, which has been extensively studied in the context of medical images. Existing methods can be grouped into three main categories: (1) template-based methods, such as HRGR (Li et al., 2018) and CMAS (Jing et al., 2017); (2) data integration and coherence methods, such as PPKED (Liu et al., 2021) and CA (Ma et al., 2021); and (3) cross-modal alignment methods, exemplified by Chen et al. (2022) and Qin and Song (2022). However, these methods are designed for medical images and struggle with ECG signals due to their distinct temporal and waveform characteristics.

Instruction Tuning. Our work is also related to instruction tuning, which improves zero-shot learning in LLMs through task-specific instructions (Zhang et al., 2023; Wang et al., 2023). Models like InstructGPT (Ouyang et al., 2022), FLAN-PaLM (Chung et al., 2022), and Alpaca (Taori et al., 2023) leverage instruction data, including human feedback. Multimodal variants, such as LLaVA (Liu et al., 2023c), MiniGPT-4 (Zhu et al., 2023), and AnyMAL (Moon et al., 2023), extend this to visual tasks. However, these methods focus on natural images and are not directly applicable to ECG signals. To bridge this gap, we introduce a specialized instruction-tuning framework for ECG report generation.

LLMs for ECG. Few studies have explored the use of LLM for the analysis of ECG signals (Liu et al., 2023b; Qiu et al., 2023; Yu et al., 2023). Some of them (Liu et al., 2023b; Yu et al., 2023) convert ECG signals into text features before importing them into LLMs, bypassing crucial modality-specific characteristics. In addition, these works focus on the task of disease classification rather

than report generation. In contrast, our method directly processes ECG signals and focuses on the task of report generation.

3 MEIT

3.1 Preliminaries

Electrocardiogram (ECG) measures the electrical activity of an individual’s heart over time. An 12-lead ECG recording is a multivariate time series. It offers a multi-dimensional view, encompassing both spatial and temporal aspects of cardiac function. The 12 ECG leads include six limb leads (i.e., I, II, III, aVR, aVL, and aVF) that monitor arms and legs, providing frontal plane views, and six precordial leads (i.e., V1, V2, V3, V4, V5, and V6) that monitor chest, showing horizontal plane views.

Formally, let $\mathbf{X}_e \in \mathcal{R}^{M \times T}$ denote an ECG recording, where M represents the number of leads, and T represents the signal length. Each ECG recording is associated with an ECG report \mathbf{X}_t that describes and interprets the ECG recording. Thus, we denote each ECG recording-report pair as $\{\mathbf{X}_e, \mathbf{X}_t\}$.

3.2 Overview of MEIT

Figure 1 (a) illustrates the proposed MEIT framework. In the data curation stage, we construct the ECG instruction tuning data, which includes instruction prompts, ECG recordings and the corresponding ground truth ECG reports. In the instruction tuning stage, the ECG instruction tuning data are fed into the Report Generator for training using an autoregressive approach. During inference, the instruction prompts and the ECG recordings are inputted into the Report Generator to generate the ECG reports. In the following sections, we describe each component in detail.

3.3 Data Curation

Given an ECG recording \mathbf{X}_e , our goal during inference is to generate an ECG report using an instruction prompt such as “*Given the ECG recording, please help me generate a report for this ECG recording.*”. To achieve this goal, we aim to create a set of instruction tuning data to generate a response $\hat{\mathbf{X}}_t$ that semantically aligns with the ground truth \mathbf{X}_t . Since we cannot predict the exact instruction prompt that users will use, we need to ensure that our report generation process is robust enough to handle different prompts. To do so, we manually design a small set of prompt samples, and

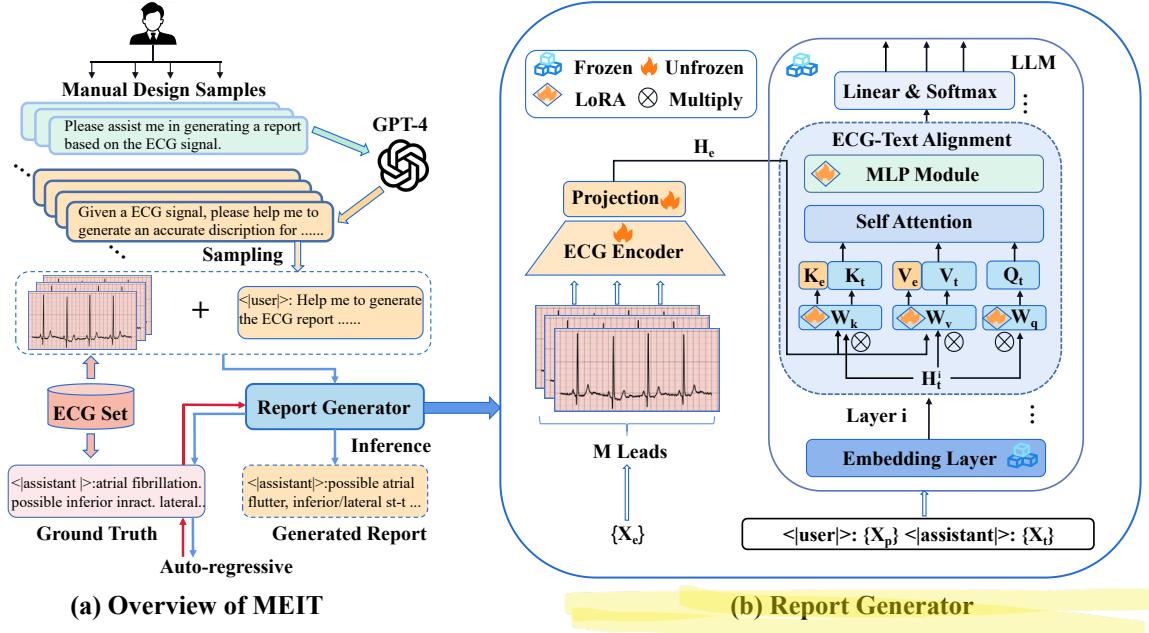


Figure 1: (a) Overview of MEIT; (b) Illustration of the architecture of Report Generator.

then utilize GPT-4 (Achiam et al., 2023) to generate a larger prompt set by rephrasing, as shown in Figure 1 (a). For each ECG recording-report pair as $\{\mathbf{X}_e, \mathbf{X}_t\}$, we randomly select one instruction prompt \mathbf{X}_p from the larger prompt set and create an instruction tuning template: $<\text{user}>: \{\mathbf{X}_p, \mathbf{X}_e\} <\text{assistant}>: \{\mathbf{X}_t\} </s>$, where $<\text{user}>$ and $<\text{assistant}>$ are added special tokens for tokenizer, and $</s>$ is a stop sign for each response. This approach ensures that the generated response conveys the same meaning as the ground truth and remains adaptable to different instruction prompts. Following this strategy, we construct the ECG instruction tuning data using the PTB-XL (Wagner et al., 2020) dataset and the MIMIC-IV-ECG (Gow et al.) dataset. Some examples of ECG instruction tuning data are included in Appendix A.8.

3.4 Report Generation

Figure 1 (b) illustrates the architecture of the Report Generator. As shown, the Report Generator utilizes an ECG encoder to encode \mathbf{X}_e into ECG embeddings and integrates them with the language embeddings extracted from the corresponding instruction tuning template through an ECG-text alignment module to autoregressively generate the ECG report. In this section, we describe the key components of the Report Generator in detail.

ECG Encoder. Since the ECG recording is high resolution in the time domain, it is vital to efficiently extract temporal features per lead before

interaction with semantic embeddings inside the LLM backbone. Our default ECG encoder $\mathcal{F}_e(\cdot)$ consists of temporal convolution blocks to encode the ECG recordings into embeddings. Specifically, each temporal convolution block comprises several 1-D convolution layers, batch normalization layers, and ReLU activation layers, followed by average pooling. This design allows us to effectively capture temporal dependencies and reduce the complexity of the signal representations, ensuring that the model can quickly learn important temporal features efficiently. To further align the output dimension with the head dimension of the LLM backbone $\mathcal{F}_l(\cdot)$, we employ a non-linear projection layer $\mathcal{P}_e(\cdot)$ to generate the ECG embeddings:

$$\mathbf{H}_e = \mathcal{P}_e(\mathcal{F}_e(\mathbf{X}_e)), \quad (1)$$

where $\mathbf{H}_e \in \mathcal{R}^{D_h}$, D_h has the same dimension as the multi-head attention layers of LLMs. Note that our default ECG encoder is lightweight and is able to learn temporal patterns of ECG recordings without a long training period. More details about the ECG encoder are included in Appendix A.3.

ECG-Text Alignment. Given the ECG and the text embeddings, we introduce an ECG-text alignment strategy to guide the LLM in aligning the ECG embeddings with the text embeddings. As shown in Figure 1 (b), given the ECG embeddings \mathbf{H}_e , the ECG-text alignment strategy incorporates \mathbf{H}_e with the current hidden state \mathbf{H}_t^i generated from the previous $(i - 1)$ th layer of the LLM backbone

$\mathcal{F}_l(\cdot)$ for next-token prediction task. Here \mathbf{H}_t^i is defined as:

$$\mathbf{H}_t^i = \mathcal{F}_l^{i-1}([\mathbf{X}_p, \mathbf{X}_t]), \quad (2)$$

where i is the current layer index.

Traditional gated-attention fusion methods like Flamingo (Alayrac et al., 2022), Memorizing Transformer (Wu et al., 2022), G-MAP (Wan et al., 2022), and Q-former in BLIP-2 (Li et al., 2023) require additional trainable parameters and are designed for complex multi-stage alignment of rich semantic information (e.g., images). Different from them, our method provides a lightweight concatenation-based alignment strategy tailored to the ECG embeddings, enabling efficient learning of ECG semantic features via directly injecting the ECG embeddings with language context in the self-attention, while preventing potential catastrophic forgetting of general knowledge in LLMs.

In our approach, each attention layer combines \mathbf{H}_e , generated from the ECG encoder and projector as a prefix condition, with \mathbf{H}_t^i , derived from the preceding layer. The fusion process is as follows:

$$\text{Self-Attn}(\mathbf{H}_e, \mathbf{H}_t^i) = [\text{head}_1, \dots, \text{head}_k] \mathbf{W}_o, \quad (3)$$

where k represents the number of attention heads, and \mathbf{W}_o , a matrix in $\mathcal{R}^{kD_h \times D_m}$, serves as the projection matrix with D_m denoting the hidden size of the LLM backbone. We replicate \mathbf{H}_e for each head k times, merging the ECG and language features in the sequence dimension. This is achieved through a shared projection of keys and values for each pattern. The fusion is then articulated as:

$$\mathbf{K}_{m,j} = [\mathbf{K}_{e,j}, \mathbf{K}_{t,j}]^\top, \mathbf{V}_{m,j} = [\mathbf{V}_{e,j}, \mathbf{V}_{t,j}], \quad (4)$$

$$\text{head}_j = \text{Softmax}\left(\frac{\mathbf{Q}_{t,j} \mathbf{K}_{m,j}}{\sqrt{D_h}}\right) \mathbf{V}_{m,j}, \quad (5)$$

where $\mathbf{Q}_{t,j} = \mathbf{H}_{t,j}^i \mathbf{W}_{q,j}$, $\mathbf{K}_{e,j} = \mathbf{H}_e \mathbf{W}_{k,j}$, and $\mathbf{K}_{t,j} = \mathbf{H}_{t,j}^i \mathbf{W}_{k,j}$, with a similar notation for $\mathbf{V}_{e,j} = \mathbf{H}_e \mathbf{W}_{v,j}$ and $\mathbf{V}_{t,j} = \mathbf{H}_t^i \mathbf{W}_{v,j}$. Concatenation is denoted by $[\cdot]$, and $\mathbf{K}_{m,j}$ and $\mathbf{V}_{m,j}$ symbolize the amalgamated features of query and key. $\mathbf{W}_{q,j}$, $\mathbf{W}_{k,j}$, and $\mathbf{W}_{v,j}$ in $\mathcal{R}^{D_h \times D_h}$ represent the projection matrices for query, key, and value for each head j , respectively. Such design allows for the efficient fusion of two modalities through causal attention, facilitating conditional generation without the need for additional parameter updates to align the ECG modality with the text modality.

Ablation studies comparing with other fusion methods demonstrate the effectiveness and efficiency of our proposed lightweight alignment strategy. More comparisons about ECG-text alignment and other fusion approaches are included in Table 5.

3.5 Instruction Tuning

During instruction tuning, we follow the instruction tuning template: $<|\text{user}|>: \{\mathbf{X}_p, \mathbf{X}_e\} <|\text{assistant}|>: \{\mathbf{X}_t\} </s>$ and compute the autoregressive loss only on tokens after response tokens $<\text{assistant}>$, and use label loss masking to finetune the model, where we mask all tokens belonging to \mathbf{X}_p and \mathbf{X}_e . To save computational resources and accelerate the convergence of instruction tuning, we use LoRA (Hu et al., 2021) adapters for all linear layers of the LLM backbone \mathcal{F}_l and freeze its backbone. Subsequently, given a sequence of ECG instruction data, we compute the probability of the target response \mathbf{X}_t as an autoregressive function:

$$p(\mathbf{X}_t | \mathbf{X}_p, \mathbf{X}_e) = \prod_{i=j}^L p_\theta(\mathbf{x}_{t,i} | \mathbf{X}_p, \mathbf{X}_e, \mathbf{X}_{t,<i}), \quad (6)$$

where j is the start index after $<\text{assistant}>$, θ is the trainable parameters of LoRA and ECG encoder \mathcal{F}_e , and $\mathbf{X}_{t,<i}$ is the response tokens before the current generation $\mathbf{x}_{t,i}$.

4 ECG Report Generation Benchmark

4.1 Datasets

MIMIC-IV-ECG. MIMIC-IV-ECG (Gow et al.) is the largest publicly available 12-lead ECG dataset. MIMIC-IV-ECG contains 800,035 samples from 161,352 subjects. Similar to PTB-XL, each sample includes a raw ECG recording and its report, sampled at 500Hz for 10 seconds. The dataset is split into training, validation, and test sets at a ratio of 80%:10%:10% respectively.

PTB-XL. We also use the PTB-XL dataset (Wagner et al., 2020), which contains 21,837 clinical 12-lead ECG recordings collected from 18,885 patients. Each ECG recording is 10 seconds long sampled at 500Hz and has a corresponding report. We divide PTB-XL into training, validation, and test sets at a ratio of 70%:10%:20%, respectively.

4.2 Models

We use two smaller language models and ten LLMs based on the PEFT¹ library, which directly supports LoRA (Hu et al., 2021) to construct the multimodal ECG report generation model described in Section 3.4. The two smaller language models are GPT2-Medium and GPT-Large (Radford et al., 2019). The ten LLMs are GPT-Neo (Black et al., 2021), GPT-NeoX (Black et al., 2022), GPT-J (Wang and Komatsuzaki, 2021), BLOOM (Workshop et al., 2022), OPT (Zhang et al., 2022), LLaMA-1 (Touvron et al., 2023a), LLaMA-2-Instruct (Touvron et al., 2023b), LLaMA-3-Instruct (Touvron et al., 2023b), Mistral (Jiang et al., 2023), and Mistral-Instruct.

4.3 Evaluation Metrics

We evaluate the performance using ten metrics: BLEU 1-4 (Papineni et al., 2002), METEOR (Banerjee and Lavie, 2005), ROUGE 1, 2 and L (Lin, 2004), CIDEr-D (Vedantam et al., 2015), and BERTScore (Zhang et al., 2019). Specifically, BLEU 1-4 and METEOR assess machine translation quality, focusing on accuracy and fluency. ROUGE-L measures sentence fluency and structure, while ROUGE-1 and ROUGE-2 examine uni-gram and bi-gram overlaps. CIDEr-D evaluates the relevance and uniqueness of the generated ECG reports against a candidate set. Lastly, BERTScore assesses semantic similarity to the ground truth.

4.4 Tasks

Task #1: Quality of the Generated Reports. In our first task, we aim to assess the quality of the generated ECG reports using 10% of PTB-XL and MIMIC-IV-ECG datasets as the test set. Specifically, this task examines how closely the generated reports match the ground truth reports in terms of structure and semantic meaning under various instructions and ECG recordings.

Task #2: Zero-shot Generalizability. As the second task, to explore the generalizability of LLMs in domain transfer scenarios following ECG instruction tuning, we trained the models on 70% of the instruction data from MIMIC-IV-ECG. Following this, we evaluated the models' zero-shot capabilities on the PTB-XL test set. It is important to note that the PTB-XL and MIMIC-IV-ECG datasets originate from different continents, Europe, and the

United States, respectively, utilizing different devices and from different hospitals, across different time periods. Therefore, we consider these datasets to represent two separate domains. This distinction allows us to use the PTB-XL dataset to gauge our model's performance in zero-shot domain transfer effectively. We used the metrics BLEU-4, METEOR, ROUGE-L, and CIDEr-D because of limited space and calculated their average for model evaluation.

Task #3: Signal Perturbation Robustness. In real-world clinical settings, ECG signals often contain some degree of noise. To evaluate the robustness of MEIT against such noisy interference, we selected 10% of the ECG samples from the MIMIC-IV-ECG test dataset. We then added Gaussian noise to these samples during the models' instruction-based inference process. For this evaluation, we used BLEU-4, METEOR, ROUGE-L, and CIDEr-D as metrics.

Task #4: Evaluation of Alignment with Human Expert Annotations. Lastly, to evaluate the differences between the reports generated by MEIT and human expert annotations, we established specific evaluation criteria and utilized closed-source LLMs to conduct a professional assessment of both the generated reports and expert annotations.

5 Experiments and Analysis

5.1 Experimental Setup

We utilized PyTorch 2.1, transformers (Wolf et al., 2020), and accelerated on A100 GPUs with LLMs from Hugging Face (Wolf et al., 2019) ranging from 2.7 to 70 billion parameters. For larger models, we used DeepSpeed². The training covered 5 epochs on MIMIC-IV-ECG and PTB-XL with a 2e-5 learning rate and 64 batch size, employing a linear optimizer with a 0.03 warm-up ratio. For text preprocessing, we initially remove all instances of the 'nan' string and sentences that consist solely of numerical values. Subsequently, we discard any samples whose reports contain fewer than 5 tokens. For ECG encoder, we adopt random initialization. Additionally, the default number of generated prompts from GPT-4 is 256.

5.2 Quality Evaluation

Performance on MIMIC-IV-ECG. Table 1 and 3 present the results of various types of language

¹<https://github.com/huggingface/peft>

²<https://github.com/microsoft/DeepSpeed>

Table 1: Natural language generation metric on **MIMIC-IV-ECG**. For model size, 'M' denotes the million level, and 'B' denotes the billion level. All checkpoints are downloaded from Hugging Face website. And all models have been fine-tuned using ECG instructions. The light teal color indicates the second highest results, and heavy teal color indicates the highest results.

MODELS	SIZE	BLEU-1	BLEU-2	BLEU-3	BLEU-4	METEOR	ROUGE-L	ROUGE-1	ROUGE-2	CIDEr-D
GPT2-Medium	345M	0.576	0.527	0.456	0.425	0.551	0.523	0.544	0.512	3.70
GPT2-Large	774M	0.614	0.563	0.490	0.476	0.595	0.571	0.585	0.538	4.21
GPT-Neo	2.7B	0.631	0.579	0.534	0.489	0.727	0.689	0.715	0.592	4.81
GPT-NeoX	20B	0.645	0.588	0.539	0.523	0.719	0.701	0.712	0.622	4.92
GPT-J	6B	0.676	0.628	0.584	0.542	0.756	0.721	0.744	0.632	5.23
BLOOM	7B	0.669	0.624	0.591	0.550	0.758	0.725	0.745	0.639	5.19
OPT	6.7B	0.673	0.616	0.598	0.532	0.755	0.732	0.743	0.631	5.32
LLaMA-1	7B	0.685	0.648	0.615	0.543	0.761	0.724	0.742	0.642	5.26
Mistral	7B	0.697	0.659	0.611	0.571	0.763	0.740	0.765	0.658	5.48
LLaMA-2-Instruct	7B	0.706	0.662	0.622	0.581	0.775	0.745	0.768	0.664	5.55
Mistral-Instruct	7B	0.714	0.665	0.619	0.576	0.768	0.751	0.762	0.667	5.62
LLaMA-3-Instruct	8B	0.733	0.686	0.648	0.610	0.799	0.773	0.795	0.686	5.78

Table 2: Natural language generation metric on **PTB-XL**. The light teal color indicates the second highest results, and heavy teal color indicates the highest results.

MODELS	SIZE	BLEU-1	BLEU-2	BLEU-3	BLEU-4	METEOR	ROUGE-L	ROUGE-1	ROUGE-2	CIDEr-D
GPT2-Medium	345M	0.329	0.278	0.254	0.232	0.441	0.391	0.561	0.433	2.12
GPT2-Large	774M	0.437	0.395	0.355	0.320	0.575	0.481	0.652	0.527	3.25
GPT-Neo	2.7B	0.474	0.449	0.398	0.373	0.602	0.486	0.674	0.595	3.70
GPT-NeoX	20B	0.469	0.453	0.417	0.399	0.620	0.553	0.688	0.622	3.58
GPT-J	6B	0.485	0.452	0.428	0.405	0.656	0.550	0.662	0.613	3.72
BLOOM	7B	0.491	0.462	0.427	0.415	0.665	0.580	0.678	0.605	3.80
OPT	6.7B	0.502	0.477	0.431	0.418	0.662	0.568	0.669	0.624	3.94
LLaMA-1	7B	0.514	0.485	0.465	0.430	0.678	0.588	0.682	0.613	3.97
Mistral	7B	0.486	0.475	0.446	0.421	0.673	0.591	0.697	0.634	3.98
LLaMA-2-Instruct	7B	0.515	0.484	0.469	0.439	0.675	0.594	0.698	0.624	4.05
Mistral-Instruct	7B	0.501	0.481	0.457	0.425	0.664	0.592	0.700	0.641	4.01
LLaMA-3-Instruct	8B	0.539	0.513	0.494	0.467	0.698	0.615	0.725	0.646	4.45

Table 3: Semantic similarity between the generated ECG reports and ground truths is measured using BERTScore, denoted as P for Precision, R for Recall, and F-1 for the F-1 Score.

MODELS	MIMIC-IV-ECG			PTB-XL		
	P	R	F-1	P	R	F-1
GPT2-Medium	0.562	0.453	0.502	0.534	0.465	0.497
GPT2-Large	0.657	0.574	0.613	0.625	0.553	0.586
GPT-Neo	0.723	0.633	0.675	0.675	0.588	0.628
GPT-NeoX	0.719	0.638	0.676	0.654	0.579	0.614
GPT-J	0.725	0.655	0.688	0.689	0.622	0.654
BLOOM	0.734	0.684	0.708	0.701	0.645	0.672
OPT	0.713	0.667	0.689	0.712	0.648	0.678
LLaMA-1	0.752	0.697	0.723	0.725	0.657	0.689
Mistral	0.761	0.732	0.746	0.711	0.664	0.687
LLaMA-2-Instruct	0.764	0.725	0.744	0.721	0.668	0.693
Mistral-Instruct	0.773	0.722	0.747	0.730	0.661	0.694
LLaMA-3-Instruct	0.798	0.745	0.771	0.745	0.682	0.712

encoders $\mathcal{F}_l(\cdot)$ on MIMIC-IV-ECG. The results show that all ten LLMs perform better than the two smaller language models (GPT2-Medium and GPT2-Large) across all evaluation metrics. Notably, from GPT-Neo to Mistral-Instruct, LLM-based backbones achieve a significant margin over

SLMs in all metrics. For instance, compared to GPT2-Large, the METEOR score increases in the range of 0.132 to 0.18 from GPT-Neo to LLaMA-2, and Mistral-Instruct outperforms GPT2-Large with an improvement of 0.18 in the ROUGE-L score and 0.134 in the F-1 of BERTScore. The observed performance underscores the adeptness of LLMs in generalizing from ECG data showcasing enhanced proficiency in aligning ECG data representations with corresponding textual information. This highlights the significant potential of LLMs in ECG-to-text generation. Particularly, LLaMA-2-Instruct, Mistral-Instruct, and LLaMA-3-Instruct surpass their counterparts in most evaluative metrics, suggesting that models pre-tuned with general instructions are more adept at learning ECG-text alignment.

Performance on PTB-XL. As shown in Table 2, the models exhibit reduced performance on PTB-XL compared to MIMIC-IV-ECG, which is attributable to the smaller scale of the instruction data in PTB-XL. This underscores the im-

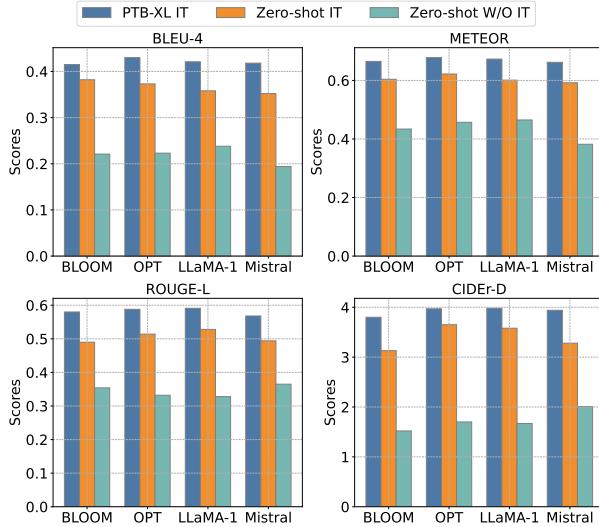


Figure 2: Zero-shot performance on PTB-XL dataset. “IT” denotes instruction tuning.

portance of data scale in enhancing instruction-based ECG report generation. Moreover, similar to the MIMIC-IV-ECG results, all LLM-based models show significant improvement over SLMs. Specifically, LLaMA-2 surpasses GPT2-Large by 0.134 in the BLEU-3 metric, while LLaMA-1 achieves a 0.103 improvement in the METEOR score. The overall experimental results also reveal that **Mistral-Instruct**, **LLaMA-2-Instruct**, and **LLaMA-3-Instruct** are consistently the top two performers across most metrics because of their strong general instruction-following capabilities.

5.3 Zero-shot Evaluation in Domain Transfer

Although both PTB-XL and MIMIC-IV-ECG datasets are time-series data, they differ significantly in several aspects, including population (European vs. American), diverse collection devices, continents (Europe vs. US), protocols, and hospitals. These differences introduce substantial medical domain gaps (Bilheimer and Klein, 2010; Ross et al., 2020). In Figure 2, we present the evaluation of the zero-shot learning capabilities of various LLMs, which is trained on the MIMIC-IV-ECG dataset and then tested on PTB-XL (unseen dataset). The assessed models include BLOOM, OPT, LLaMA-1, and Mistral. Firstly, all selected LLMs undergo instruction tuning on the MIMIC-IV-ECG train set, followed by zero-shot testing on the PTB-XL test set verified by human experts, denoted as **ZERO-SHOT IT**. We also measure the performance of each model in report generation without prior ECG-specific instruction tuning, denoted

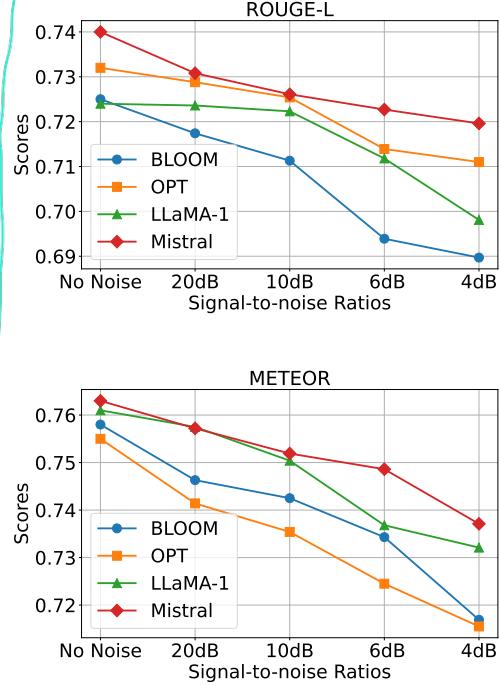


Figure 3: Signal perturbation robustness analysis on various LLMs.

as **ZERO-SHOT W/O IT**. **PTB-XL IT** represents training on the PTB-XL train set and then evaluated on the PTB-XL test set. Notably, although **ZERO-SHOT IT** shows a slight degradation compared to **PTB-XL IT**, the results still indicate a variance in the model’s ability to generalize to an unseen dataset with instruction tuning (IT), compared to **ZERO-SHOT W/O IT**. The involvement of **ECG instruction tuning on MIMIC-IV-ECG** enables the models to achieve superior zero-shot performance on the unseen **PTB-XL** dataset, indicating the necessity of instruction tuning in enhancing the models’ zero-shot ability on unseen datasets in ECG report generation.

5.4 Robust Analysis with Perturbed ECG Recordings

In a noise stress evaluation (Wang et al., 2019), we added Gaussian noise to ECG signals at signal-to-noise ratios (SNRs) of 0.05, 0.1, 0.15, and 0.2 during testing to assess model robustness. Our experiments utilized four LLM architectures: BLOOM, OPT, LLaMA-1, and Mistral, each trained on clean ECG signals from the MIMIC-IV-ECG training set and tested on corresponding noise-added signals from its test set. The results, illustrated in Figure 3, show a performance decline in all LLMs as SNR decreased, highlighting the significant interference of ECG noise. Furthermore, as shown in Table 1,

Table 4: Evaluation results of LLaMA-2-Instruct and LLaMA-3-Instruct against human expert-annotated ground-truth reports. Each dimension is scored on a scale of 1 to 5.

Model	Medical Terminology Accuracy	Logical Consistency	Completeness	Diagnostic Accuracy
LLaMA-2-Instruct	4.25	4.11	3.72	3.60
LLaMA-3-Instruct	4.52	4.38	4.01	3.98

Mistral also excelled in tests on noise-free datasets, suggesting a synergistic effect between clean and noisy test sets. The results demonstrate Mistral’s strong resistance to perturbations. Even with more severe noise, it maintained robustness regarding ROUGE-L and METEOR metrics.

5.5 Evaluation of Alignment with Human Expert Annotations

In Table 4, we conducted an evaluation of model-generated ECG reports from ECG instruction-tuned versions of LLaMA-2 and LLaMA-3 against 500 ground-truth reports, meticulously annotated by human medical experts. These test annotated data were randomly sampled from the PTB-XL dataset, with all selected reports carefully reviewed and validated by human experts. Each model-generated report was compared with these expert-annotated reports using gpt-4o³, which assessed quality across four dimensions: **Medical Terminology Accuracy**, **Logical Consistency**, **Completeness**, and **Diagnostic Accuracy**, on a scale of 1 to 5. To evaluate these reports, we employed the following prompt template, which guided GPT-4o’s scoring process across the defined dimensions, as shown in Table 6 in Appendix. This prompt template ensures that GPT-4o evaluates the reports in a structured and consistent manner, highlighting both strengths and weaknesses of the model-generated reports in comparison to human expert annotations. The results indicate that the LLaMA-3 model, with an average Diagnostic Accuracy score of 3.85, closely matches the quality of the human expert annotations, whereas the LLaMA-2 model scored 3.60. This evaluation underscores the effectiveness of using human expert annotations from the PTB-XL (Wagner et al., 2020) dataset as a rigorous benchmark for assessing the models’ ability to generate clinically reliable ECG reports.

6 Conclusion

In this paper, we introduced MEIT, a framework for generating instruction-following data to train a multimodal LLM that can produce ECG reports based on human instructions. We also proposed an effective method for aligning ECG and report representations across various open-source LLMs, demonstrating strong performance on both the MIMIC-IV-ECG and PTB-XL datasets across multiple tasks. Additionally, we established a comprehensive benchmark for ECG instruction-following in report generation, providing a standardized evaluation for future research. Although this work primarily focuses on ECG signals, it serves as a foundational step in applying instruction-tuning to biomedical signals. For future research, we aim to extend our framework and benchmark to other medical domains, such as EEG, with the hope of driving further progress in developing more capable medical-signal LLMs.

7 Limitations

Our MEIT framework first attempts to address automatic ECG report generation through ECG instruction tuning, establishing the first comprehensive benchmark for this process with mainstream LLMs. In this work, we mainly focus on generating reports from multimodal ECG instructions using LLMs. However, the generated results are not fully explainable or controllable, even though the generation procedure is transparent and trackable. This is because the underlying theory of LLMs remains largely unexplored, necessitating further investigation to ensure the quality and safety of the generated content. In the future, we aim to enable LLMs to utilize external, expert-verified knowledge databases, such as clinical protocols and medical textbooks, to enhance the explainability of the generated ECG reports.

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³<https://platform.openai.com/docs/models/gpt-4o>

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A Appendix.

A.1 Further Analysis of MEIT

Instruction Tuning Visualization. Figure 4 compares the convergence curves of the instruction tuning loss and the METEOR score between GPT-Neo (2.7B), BLOOM (7B), OPT (6.7B), and LLaMA-2 (7B) on the MIMIC-IV-ECG train and validation datasets. We observe that larger models with more parameters can converge to a more minor loss and achieve higher performance on the METEOR score. Notably, an increase in model size correlates with higher performance and lower loss, suggesting that larger models have the potential for better performance.

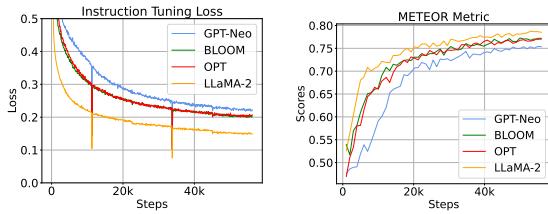


Figure 4: Visualizations of instruction tuning loss and METEOR score.

Analysis of ECG Modality Alignment. To study the effectiveness of our proposed concatenated-fusion method for ECG modality alignment, we compare it with other fusion approaches such as direct input in LLava (Liu et al., 2023c) and additional trainable cross-attention layer in Flamingo (Alayrac et al., 2022). For straightforward input, we follow the design of LLava by directly concatenating the ECG encoder’s output embeddings with the sentence’s embeddings before inputting them into the LLM backbones. For the second comparison method, we follow Flamingo by adding a trainable cross-attention layer within the attention block. From Table 5, we observe that the Concatenated-fusion method outperforms the trainable cross-attention method of Flamingo in most metrics and is consistently superior to the Straightforward input method of LLava. Consequently, the concatenated fusion is more effective for the LLM backbone’s alignment with fine-grained ECG patterns without necessitating additional trainable parameters.

Scalability Analysis. To investigate whether ECG instruction tuning on larger-scale models yields better results, we validated LLaMA-2 models of 7B, 13B, and 70B parameter sizes on both MIMIC-IV-ECG and PTB-XL datasets. As depicted in

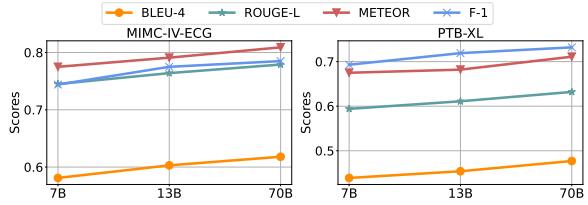


Figure 5: Model scaling performance on MIMIC-IV-ECG and PTB-XL.

Figure 5, an upward trend in all evaluation metrics is observed with a gradual increase in model size.

However, it is noteworthy that the gains in performance associated with increasing model size are not particularly significant. For example, the F-1 score for the 70B model on the PTB-XL dataset exhibits a marginal increase of 0.02 over the 13B model. Similarly, on the MIMIC-IV-ECG dataset, the 70B model’s F-1 score is only 0.01 higher than that of the 13B model. Therefore, we conjecture that enhancing both data scale and model size concurrently is necessary to achieve superior performance (Wei et al., 2022).

Ablation Study on ECG Instruction Tuning. We conducted an ablation study to evaluate instruction tuning’s impact on aligning ECG signals with report representations. Utilizing LLMs such as BLOOM, OPT, LLaMA-1, and Mistral without instruction tuning, we allowed direct learning from ECG signals. The findings, illustrated in Figure 6, indicate a significant performance drop across all metrics without instruction tuning, particularly in Mistral. This underscores instruction tuning’s superiority in enhancing LLMs’ generalization to new tasks/data over direct fine-tuning (Ouyang et al., 2022).

Qualitative Results. In Figure 7, we randomly select two samples generated by MEIT using LLaMA-2 and Mistral-Instruct as the LLM backbones. The consistent key information, highlighted in blue, indicates that both models have successfully learned important patterns from the ECG signals. Overall, the models’ results align with the ground truth, accurately identifying cardiac abnormalities from the ECG signals. Furthermore, both models provide detailed explanations of abnormal ECG signal details, such as ‘ischemia’ from sample 1 and ‘right bundle branch block’ from sample 2. These generated reports demonstrate the efficacy of our method.

Table 5: Performance comparison of the proposed concatenated-fusion method and other mainstream fusion variants. We evaluate these methods on the MIMIC-IV-ECG dataset, using BLEU-4, METEOR, ROUGE-L, and CIDEr-D metrics. We take LLaMA-1 7B as the LLM backbone here. **heavy teal** color indicates the highest results.

FRAMEWORK	METHOD	BLEU-4	METEOR	ROUGE-L	CIDEr-D
LLaVA	Straightforward input	0.529	0.737	0.712	4.99
Flamingo	Trainable cross-attention	0.527	0.768	0.715	5.11
MEIT	Concatenated-fusion	0.543	0.761	0.724	5.26

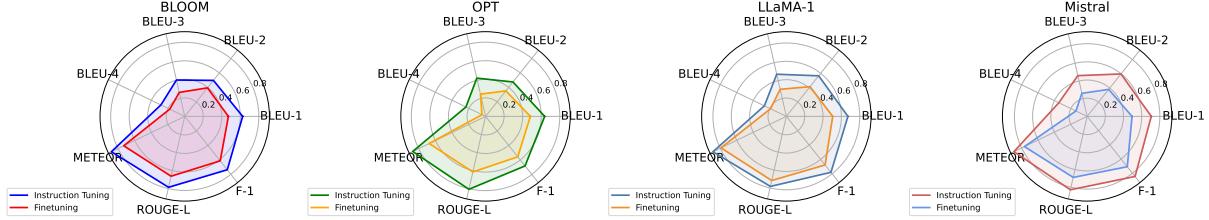


Figure 6: Ablation Study of ECG Instruction Tuning on MIMIC-IV-ECG Dataset.

LLaMA-2
[ECG signal sample 1]
Generated Report: sinus rhythm with 1st degree a-v block. left axis deviation. left ventricular hypertrophy. inferior/lateral st-t changes may be due to hypertrophy and/or ischemia. abnormal ecg.
Ground Truth: sinus rhythm with 1st degree a-v block. left axis deviation. probable normal variant. inferior/lateral st-t changes may be due to myocardial ischemia. abnormal ecg.

Mistral-Instruct
[ECG signal sample 2]
Generated Report: sinus rhythm. right bundle branch block. abnormal ecg.
Ground Truth: sinus rhythm. indeterminate axis. right bundle branch block. abnormal ecg.

Figure 7: Examples of ECG reports generated by LLaMA-2 and Mistral-Instruct. We highlight the consistent information between the generated reports and the ground truths with **blue** color.

A.2 Hyper-parameters of ECG Instruction Tuning

In this study, we implement the Low-Rank Adaptation (LoRA) (Hu et al., 2021) technique for efficient fine-tuning, specifically applied to ECG instruction tuning. As detailed in Table 7 provided, we utilize mixed precision at bf16 for enhanced computational efficiency. Our models undergo instruction tuning over 5 epochs, with LoRA parameters set at an alpha of 64 and a rank of 128, accompanied by a dropout rate of 0.1. The total batch size is 64, with a gradient accumulation factor of 2. The maximum sequence length is constrained to 256 tokens. Additionally, we adopt a learning rate with 2e-5 for GPT-NeoX and 1e-4 for the other models, optimized using the AdamW algorithm. The learning rate follows a linear schedule with a warm-up ratio of 0.03. We set the weight decay to 0.0.

Moreover, as shown in Table 8, we detail the ECG embedding dimensions for various language models, highlighting their approach to ECG data encoding. GPT2-Medium and GPT2-Large feature ECG dimensions 64, while GPT-Neo, BLOOM, OPT, LLaMA-1, Mistral, LLaMA-2, and Mistral-Instruct use a dimension of 128. GPT-NeoX employs a dimension of 96, and GPT-J notably uses the largest dimension of 256. These dimensions, reflecting each model’s head dimension design, illustrate diverse strategies in ECG data processing across different models.

A.3 More Details of ECG Encoder

Projection Layer For the design of the projection layer within the ECG encoder, we adopt a non-linear approach similar to CLIP (Radford et al., 2021) and Med-UniC (Wan et al., 2024a). Specifically, in our experiments, we employ two consecutive linear layers, each followed by BatchNorm1d⁴. Besides, ReLU serves as the activation function between the two linear layers. The default settings for input and hidden layers dimensions are set to 2048 in our experiment.

Parameter Size Analysis To demonstrate the ECG encoder’s lightweight design, we analyzed its trainable parameters during instruction tuning and total parameters during inference, using the LLaMA-1 7B model for illustration (Table 10). The analysis reveals the ECG encoder’s trainable parameters are substantially fewer than those of the LoRA adapter in the LLM backbone during instruction tuning, and its parameter share of the overall framework is

⁴<https://pytorch.org/docs/torch.nn.BatchNorm1d.html>

Table 6: Prompt template used for GPT-4o evaluation. This prompt guided the model’s evaluation of generated ECG reports.

Prompt Template for GPT-4o Evaluation
You are an expert in Electrocardiogram (ECG) text evaluation. Your task is to assess the quality of a generated ECG report by comparing it to a real, expert-annotated ECG report.
Generated ECG Report: {Generated_Report}
Real ECG Report: {Real_Report}
Please evaluate the generated report based on the following criteria:
1. Medical Terminology Accuracy: Does the generated report use correct and appropriate ECG signal terms?
2. Logical Consistency: Is the information presented in a logical and medically sound order?
3. Completeness: Does the report include all necessary details that would be present in a real ECG report, such as heart rhythm, rate, and any abnormalities?
4. Diagnostic Accuracy: Are the diagnoses and interpretations in the generated report accurate and consistent with the expert-annotated report?
Please provide a detailed analysis and score each criterion on a scale of 1 to 5 (1 = Poor, 5 = Expert-Level).

Table 7: Hyper-parameters of ECG instruction tuning for all LLM backbones.

Hyperparameters	
Mixed precision	bf16
Instruction tuning epochs	5
LoRA alpha	64
LoRA rank	128
LoRA dropout	0.1
Total batch size	64
Gradient accumulation	2
Maximum sequence length	256
Learning rate	2e-5, 1e-4
Learning rate Optimizer	AdamW
Schedule	linear
Warm-up ratio	0.03
Weight decay	0.0

minimal for inference, underscoring its efficiency.

Ablation Study of ECG Encoder we conducted additional experiments comparing our default 1-D Temporal Convolution ECG encoder with alternative architectures, including: 1. S4-based Model: Vim-B (Vision Mamba, 98M parameters) (Zhu et al., 2024a). 2. Transformer-based Model: ViT-B/16 (Vision Transformer, 86M parameters) (Dosovitskiy et al., 2020), adapted for 1-D token patching to align with the temporal nature of ECG signals. 3. SSL-Transformer Model: ViT-B/75 initialized with self-supervised learning (SSL) weights specific to ECG signals (Na et al., 2024). We evaluated these models on two tasks: Quality of Generated Reports using the MIMIC-IV-ECG dataset, and Evaluation of Alignment with Human Expert Annotations using the PTB-XL dataset. For fair comparison, we used Meta-Llama-3-8B-Instruct as the LLM back-

MODELS	ECG Dimension
GPT2-Medium	64
GPT2-Large	64
GPT-Neo	128
GPT-NeoX	96
GPT-J	256
BLOOM	128
OPT	128
LLaMA-1	128
Mistral	128
LLaMA-2	128
Mistral-Instruct	128

bone due to its consistent strong performance.

The results, summarized in the table below, show that our 1-D Temporal Convolution ECG encoder, despite having significantly fewer parameters, performs comparably or better across most metrics compared to ViT and ViT-SSL, and comprehensively outperforms the S4-based Vim. Notably, the ViT-SSL encoder demonstrates the benefit of self-supervised pretraining for initial ECG representation learning. However, our default ECG encoder effectively captures the 12-channel ECG temporal patterns while remaining lightweight, making it well-suited for our efficient instruction tuning framework. These findings validate the effectiveness of our 1-D Temporal Conv encoder and also provide valuable insights for future work, including designing more complex ViT-based architectures optimized for ECG time-series data.

Table 9: Comparisons of results with and without supervised manner. We take LLaMA-2-Instruct as the LLM backbone here. **heavy teal** color indicates the highest results.

METHODS	SIZE	MIMC-IV-ECG				PTB-XL			
		BLEU-4	METEOR	ROUGE-L	CIDEr-D	MTA	MTA	LC	DA
Vision Mamba	86M	0.548	0.737	0.715	5.58	3.78	3.88	3.61	3.50
Vision Transformer	98M	0.592	0.815	0.772	5.67	4.33	4.15	4.12	3.78
Vision Transformer (SSL)	98M	0.581	0.822	0.766	5.75	4.42	4.28	3.85	3.85
1-D Temporal Conv (Ours)	20.4M	0.610	0.799	0.773	5.78	4.52	4.38	4.01	3.98

Table 10: Parameter Comparison of ECG encoder and LLM backbone. We use LLaMA-1 7B as an example.

MODULE	Trainable Params	Inference Params
LLM backbone	159M	6.90B
ECG encoder	20.4M	20.4M

A.4 Further Analysis of Generated Prompts

Prompts Number Analysis In the ECG instruction data curation, we manually created 32 prompt examples, as illustrated in Section 3.3. To increase the diversity of our samples, we employed GPT-4 to rephrase these manually designed prompts, generating a larger pool of prompt examples. These generated examples were randomly sampled and paired with ECG-text pairs to compile the ECG instruction dataset. In this section, We compare the experiment’s effects using 128, 256, and 512-generated samples, respectively. Table 11 shows the corresponding results with different dimensions. When the number is 256, it can achieve better results in most experimental settings. Hence, we take 256 generated samples as our default setting during the instruction tuning and inference.

Ablation Study on GPT-4 Prompt Rephrasing We also conducted an ablation study to compare the performance with and without GPT-4 rephrasing prompts, using a fixed prompt for the latter. The results in the following Table 12 indicate that using diverse prompts rephrased by GPT-4 leads to better performance, highlighting the superiority of instruction tuning in enhancing LLMs’ generalization to new tasks and data over direct fine-tuning.

A.5 Comparison with Encoder-Decoder Models

In this section, we conducted additional comparative experiments using two open-source traditional encoder-decoder architectures: BART-Large (406M parameters) (Lewis, 2019) and T5-Large (780M parameters) (Raffel et al., 2020), as shown

in Table 13. In adapting our framework for ECG instruction tuning, we employ the language encoder to process the input instruction, an ECG encoder to handle the input ECG signals, and the language decoder to generate the ECG report based on the output from both language end ECG encoder.

Our findings indicate that the performance of encoder-decoder models is comparable to the small pre-trained language models (GPT2-Medium and GPT-Large) presented in Table 1 and Table 2 of our paper. Moreover, LLM-based backbones (such as LLaMA1-2) consistently achieve a significant margin of improvement over the encoder-decoder architectures across all metrics.

A.6 Analysis of Combining MEIT with a Supervised Manner

In this section, we conduct a new experiment where we trained a CNN (ECG encoder) in a supervised manner on the PTB-XL training set, utilizing all available annotations (approximately 70 patterns), as shown in Table 14. We then transferred the CNN for ECG instruction fine-tuning on both the MIMIC-IV-ECG and PTB-XL datasets. Our findings indicate that performance increased on the PTB-XL dataset in most metrics, likely due to the model’s prior learning of specific annotated patterns. However, performance fluctuated on the MIMIC-IV-ECG dataset, which contains more data and exhibits greater diversity. This suggests that the supervised approach may enhance performance on in-domain data, but it limits generalizability to data from unseen domains.

A.7 Computational Cost Analysis of MEIT

Table 11: Performance comparison of different numbers of generated prompt samples. We evaluate them on the MIMIC-IV-ECG dataset, using BLEU-4, METEOR, ROUGE-L, and CIDEr-D metrics. We take LLaMA-1 7B as the LLM backbone here. heavy teal color indicates the highest results.

PROMPT NUMS	BLEU-4	METEOR	ROUGE-L	CIDEr-D
128	0.541	0.756	0.718	5.15
256	0.543	0.761	0.724	5.26
512	0.538	0.754	0.732	5.03

Table 12: Performance comparison of with and without GPT-4 prompt rephrasing. We take Mistral-Instruct as the LLM backbone here. heavy teal color indicates the highest results.

PROMPT NUMS	BLEU-4	METEOR	ROUGE-L	CIDEr-D
w.o. Rephrasing	0.564	0.745	0.738	5.50
w. Rephrasing (Ours)	0.576	0.768	0.751	5.62

The time cost experiment, detailed in the Table 15, was conducted on the MIMIC-IV-ECG dataset. We found that larger models have longer training and inference times. Thus, we are considering techniques like quantization and other compression methods to improve model efficiency in future work.

A.8 Examples of ECG Instruction Tuning Data and the Corresponding Generated ECG Reports

As illustrated in Figures 8, 9, and 10 we have visualized the report samples generated by LLaMA-1, LLaMA-2, and Mistral-Instruct. The samples are presented in blue font to highlight the key information that aligns with the ground truth. The visualization demonstrates that all three selected models can capture the essential patterns of ECG signals and generate accurate reports. This underscores the efficacy of our proposed **MEIT** framework, which is adaptable to most open-source LLMs. It effectively learns the correct clinical semantics of ECG signals, thereby enabling the generation of corresponding reports.

A.9 Future Works

In this work, we propose an effective and efficient method for generating ECG reports. Since this is a generative task, the content produced may occasionally lead to hallucinations (Zhu et al., 2025). This is particularly pertinent in medical contexts such as ECG report generation, where accuracy is of utmost importance. To mitigate this issue, future iterations of our work could incorporate retrieval-augmented methods (Wan et al., 2022; Li et al.,

2024), information optimized strategies (Xiong et al., 2022; Liang et al., 2020a,b), multi-modal fusion and optimization strategies (Wan et al., 2024c; Xiong et al., 2024a; Liu et al., 2024c; Gong et al., 2024; Wan et al., 2023a; Chen et al., 2025; Luo et al., 2024; Shen et al., 2025b; Wan et al., 2025b; Zhang et al., 2025b; Liu et al., 2024b; Huang et al., 2024; Zhu et al., 2024b; Liu et al., 2025a), Reasoning enhanced methods (Wan et al., 2025a; Liu et al., 2025b; Shen et al., 2025a), efficient ML (Wang et al., 2024b; Tao et al., 2024; Wan et al., 2024b; Liu, 2024; Xin et al., 2024; Shen et al., 2024; Wang et al., 2025; Xiong et al., 2024b, 2025). For instance, by integrating a retrieval mechanism that accesses a database of verified medical or biological knowledge (Zheng et al., 2024) or previous ECG reports, the model could be guided towards generating more accurate and reliable outputs.

Table 13: Comparison with encoder-decoder-based models on MIMIC-IV-ECG. For model size, 'M' denotes the million level, and 'B' denotes the billion level. The light teal color indicates the second highest results, and heavy teal color indicates the highest results.

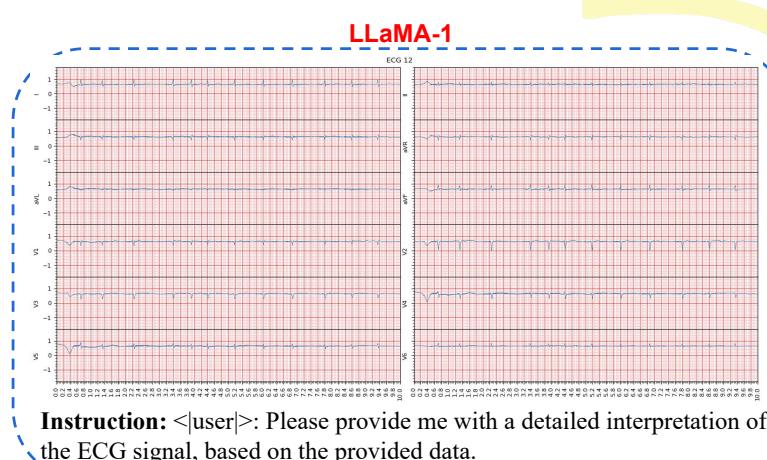
MODELS	SIZE	BLEU-1	BLEU-2	BLEU-3	BLEU-4	METEOR	ROUGE-L	ROUGE-1	ROUGE-2	CIDEr-D
BART-Large	406M	0.525	0.498	0.466	0.388	0.455	0.472	0.5124	0.451	3.15
T5-Large	780M	0.595	0.542	0.465	0.422	0.498	0.456	0.522	0.438	4.08
LLaMA-1	7B	0.685	0.648	0.615	0.543	0.761	0.724	0.742	0.642	5.26
LLaMA-2-Instruct	7B	0.706	0.662	0.622	0.581	0.775	0.745	0.768	0.664	5.55

Table 14: Comparisons of results with and without supervised manner. We take LLaMA-2-Instruct as the LLM backbone here. heavy teal color indicates the highest results.

METHODS	PTB-XL			
	BLEU-4	METEOR	ROUGE-L	CIDEr-D
MEIT	0.439	0.675	0.594	4.05
MEIT + Supervised manner	0.445	0.664	0.612	4.12
MIMIC-IV-ECG				
METHODS	BLEU-4	METEOR	ROUGE-L	CIDEr-D
	0.581	0.775	0.745	5.55
MEIT + Supervised manner	0.578	0.778	0.739	5.47

Table 15: Computational time Analysis of MEIT with various parameters and backbones.

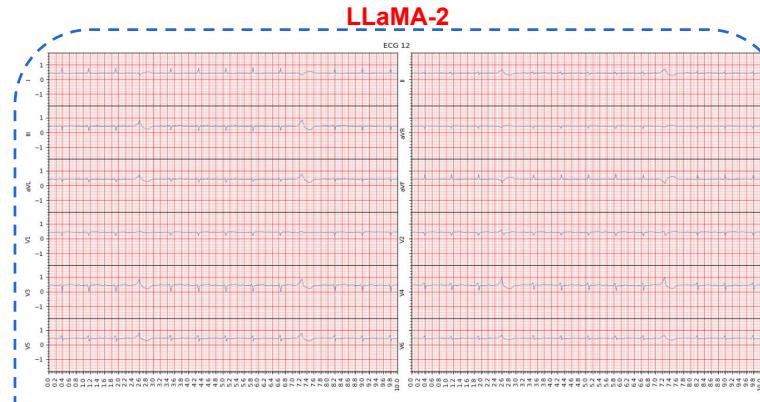
MODEL	SIZE	Training time		Testing time	
		4 A100 and 3 Epochs	1 A100 and 128 Generated Samples		
GPT-2 Large	774M	3.25h		3.125min	
LLaMA-2-Instruct	7B	13.5h		9 min	
LLaMA-2-Instruct (+)	13B	27h		14.125 min	



Generated Report: <|assistant|>: atrial fibrillation. extensive st-t changes may be due to myocardial ischemia. abnormal ecg.</s>

Ground Truth: <|assistant|>: atrial fibrillation. possible inferior infarct - age undetermined. possible anteroseptal infarct - age undetermined. lateral st-t changes may be due to myocardial ischemia. abnormal ecg.</s>

Figure 8: Reports generated by LLaMA-1 following ECG instruction Tuning.

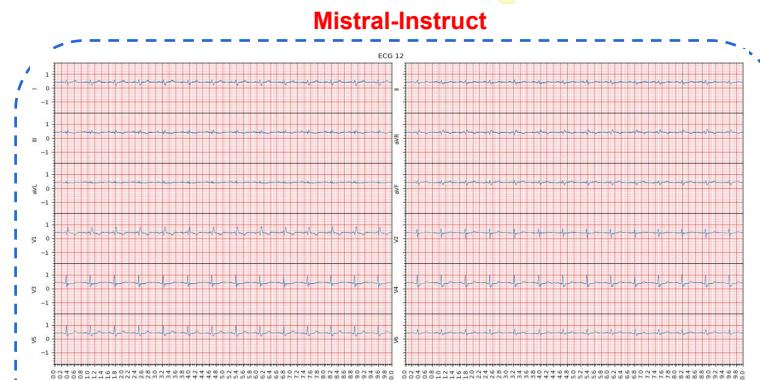


Instruction: <|user|>: Given the ECG signal embeddings, please help me generate an accurate description for this ECG signal embeddings:

Generated Report: <|assistant|>: sinus rhythm with 1st degree a-v block. left axis deviation. left ventricular hypertrophy. inferior/lateral st-t changes may be due to hypertrophy and/or ischemia. abnormal ecg. </s>

Ground Truth: <|assistant|>: sinus rhythm with 1st degree a-v block. left axis deviation. probable normal variant. inferior/lateral st-t changes may be due to myocardial ischemia. abnormal ecg. </s>

Figure 9: Reports generated by LLaMA-2 following ECG instruction Tuning.



Instruction: <|user|>: Please assist me in creating a precise description for the ECG signal:

Generated Report: <|assistant|>: sinus rhythm. right bundle branch block. abnormal ecg </s>

Ground Truth: <|assistant|>: sinus rhythm. indeterminate axis. right bundle branch block. abnormal ecg. </s>

Figure 10: Reports generated by Mistral-Instruct following ECG instruction Tuning.