Application of Deep Hierarchical VAE for ECG Reconstruction

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Clinical Problem: Sleep-Cardiac Monitoring Gap

Established, but not well understood

- **80%** of sleep apnea patients have undiagnosed cardiac arrhythmias
- **45%** increase in cardiac events during specific sleep stages

Current Diagnostic Limitations

- PSG studies lack continuous cardiac monitoring

Treatment Optimization Barriers

- CPAP therapy cardiac impact poorly quantified
- Sleep medication cardiac effects undermonitored
- Individual treatment response highly variable
- No personalized risk stratification tools

Workflow Inefficiencies

- Limited simultaneous PSG-ECG monitoring
- **3x** cost increase for comprehensive assessment

Need: Integrated sleep-cardiac monitoring solution for comprehensive patient assessment

Technical Challenges in Cross-Modal Modeling

Why PSG-to-ECG Reconstruction is Challenging

Signal Processing

- PSG-ECG signals have different temporal dynamics during sleep transitions
- Sleep phenomena span microseconds to hours

Individual Variability

- Physiological Coupling
- Comorbidity Effects
- Medication Interactions
- Demographic Factors

Goal: Develop robust cross-modal models that work across diverse patients and clinical environments

Existing Methods

- Transition from **GAN-based** ECG generators to **Variational Autoencoders (VAEs)**
- **cNVAE-ECG** (Sviridov & Egorov, 2025): conditional *hierarchical* VAE
- Multi-scale latent hierarchy disentangles
  - beat-level morphology (P, QRS, T)
  - pathology-level context
- Explicit likelihood and latent traversals $\Rightarrow$ clinical interpretability & uncertainty quantification
- +2 % AUROC vs. state-of-the-art GANs on PTB-XL

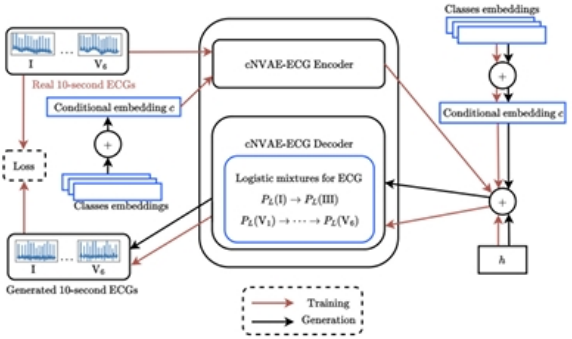


Fig. 1. Proposed cNVAE-ECG architecture.

Dataset & Cross-Modal Framework

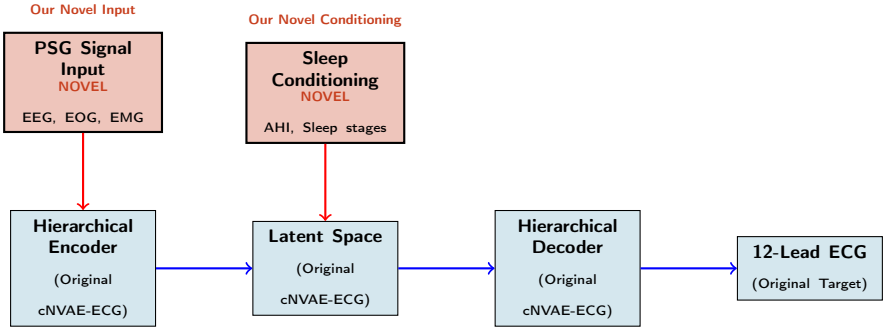
Multi-Modal Sleep Dataset

- **63** 63 sleep study participants (Aug–Oct 2024)
- 103,705 synchronized 30-second **windows**
- 8 channels (EEG, EOG, EMG, respiratory, ECG)
- **Clinical Variables:** 47 sleep architecture & physiological metrics
- **2**56 Hz sampling, SNR $>$ 15 dB preprocessing

Data Splits (Patient-Level)

- **Train:** 56,919 windows (AHI-stratified)

Proposed Architecture: Original cNVAE-ECG + Novel PSG Conditioning



Original cNVAE-ECG Framework

- Hierarchical VAE architecture (Sviridov & Egorov)
- Noise-to-ECG generation with class conditioning
- 12-lead ECG output with cardiac pathology labels
- Proven superior performance vs. GAN methods

Our Novel Contributions

- PSG signal input instead of random noise
- Sleep clinical variable conditioning framework
- Cross-modal PSG-to-ECG reconstruction paradigm
- Feasibility study for sleep-cardiac monitoring

Our Cross-Modal Adaptation Methodology

Mathematical Framework for PSG-to-ECG Reconstruction

Original cNVAE-ECG Model:

$$p(x_{ECG}|c_{pathology}) = \int p(x_{ECG}|z)p(z|c_{pathology})dz \tag{1}$$

Our Adaptation for Cross-Modal Reconstruction:

$$p(x_{ECG}|x_{PSG}, c_{sleep}, s) = \int p(x_{ECG}|z)p(z|x_{PSG}, c_{sleep}, s)dz \tag{2}$$

Novel Loss Function Extension:

$$\mathcal{L}_{our} = \underbrace{\mathcal{L}_{recon}}_{\text{ECG Fidelity (Original)}} + \underbrace{\mathcal{L}_{KL}}_{\text{Regularization (Original)}} + \underbrace{\mathcal{L}_{sleep\text{-}cond}}_{\text{Sleep Conditioning (Novel)}} \tag{3}$$

where $x_{PSG} \in \mathbb{R}^{7\times T}$ (EEG, EOG, EMG, respiratory), $c_{sleep} \in \mathbb{R}^{47}$ (clinical variables), s (sleep stage)

Core Research Questions

Can we successfully replace random noise input with PSG signals in the cNVAE-ECG architecture?

Do basic sleep clinical variables (AHI, sleep stages) improve reconstruction quality over PSG signals alone?

What are the fundamental limitations preventing higher reconstruction quality?

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