Unsupervised Photoplethysmography Signal Quality Assessment using Contrastive Learning and Persistent Homology

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Aims: Photoplethysmography (PPG) is vital for monitoring, but motion artifacts and low perfusion limit its clinical accuracy, silently corrupting estimates like Heart Rate(HR), Heart Rate Variability(HRV), and oxygen saturation. Traditional Signal Quality Indices(SQIs) rely on subjective, hand-crafted heuristics or supervised classifiers. We propose an unsupervised signal quality assessment framework combining a learned geometric approach with data manifold topological properties.

Methods: Our self-supervised pipeline contained 61,363 unlabeled 8-second PPG segments from 120 subjects under resting and stress conditions (resampled to 125 hz). First, a SimCLR framework with a 1D-ResNet encoder is trained using tailored data augmentations to simulate artifacts and preserve rhythm-aware structure. Concurrently, a topological signature is extracted using sliding-window delay embeddings and persistent homology to characterize rhythmicity. Finally, the deep contrastive representations and topological signatures are concatenated to define a unified quality manifold using Hierarchical Density Based Spatial Clustering (HDBSCAN) (Fig1).

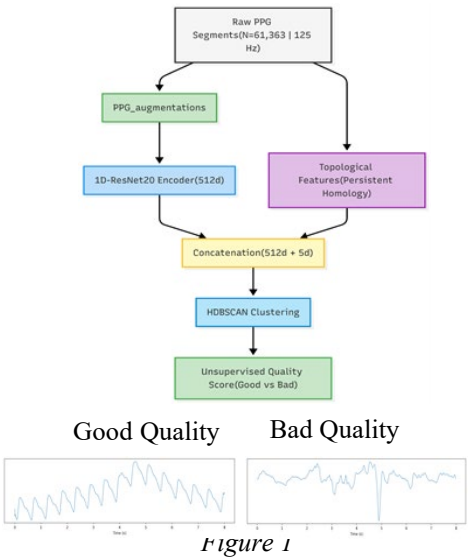

Figure 1

Results: To validate the unsupervised quality assessment, HR was computed for both the PPG and simultaneously recorded ECG for each 8-second segment. The median HR error in segments assigned to the high-quality cluster was 0.86 BPM, indicating close agreement with the ECG reference. In contrast, segments assigned to the low-quality clusters exhibited a median HR error of 55.35 BPM.