Physics-Informed Neural Networks for Robust Multiple Sclerosis Lesion Detection: Integrating Bloch-Based Pre-Training

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Abstract

Background: While the diagnosis of Multiple Sclerosis (MS) requires a combination of clinical history, physical examinations, and spinal tap results, Magnetic Resonance Imaging (MRI) plays a central and indispensable role in this assessment. Conventional MRI (cMRI) provides qualitative intensities varying across scanners, complicating automated detection. While quantitative MRI (qMRI) offers standardized biomarkers such as relaxation times (T_1, T_2), adoption is limited because of long acquisition times. Current state-of-the-art deep learning models often operate as "black boxes", failing to account for the physical principles of signal acquisition. To address these limitations, we proposed a Physics-Informed Neural Network (PINN) implementation. In this study, we benchmark the proposed PINN against current state-of-the-art (SoTA) implementations, such as nnU-Net, LST-AI, 2.5D Tiramisu, and modified Attention U-Nets, using the publicly available ISBI 2015 Longitudinal MS Lesion Challenge and MICCAI MSSEG-2 datasets. *Methods*: The proposed PINN integrates qMRI and cMRI for MS lesion detection through a two-stage 'Sim-to-Real' strategy. First, the network undergoes self-supervised pre-training using a differentiable MRI simulator. By leveraging Bloch-inspired approximations, we employ sequence-parameterized forward models to generate synthetic contrasts from quantitative maps, thereby forcing the encoder to learn robust, anatomy-centric features. Second, the model is fine-tuned for lesion segmentation using combined data with a physics-consistency loss. *Results*: Physics-informed pre-training significantly enhances the detection of subtle lesions that are typically masked by noise. Preliminary findings show gains of up to 8.3% in Dice scores in low-data settings and improved invariance to scanner-induced domain shifts. *Conclusions*: Integrating biophysical modeling with deep learning provides reliable, interpretable MS biomarkers. By enhancing the detection of subtle lesions and maintaining high performance in low-data regimes, this PINN framework offers a highly reliable tool for automated radiological assessment. Future work will aim to correlate these refined imaging biomarkers with clinical disability scores, paving the way to address the 'clinicoradiological paradox' in MS progression.

Keywords: MS (Multiple Sclerosis) lesion; Physics-Informed Neural Network (PINN); Magnetic Resonance Imaging (MRI).