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A Fast and Generic Energy-Shifting Transformer for Hybrid Monte Carlo Radiotherapy Dose Calculation

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We introduce a novel learning framework for accelerated Monte Carlo (MC) dose calculation termed Energy Shifting. This approach leverages deep learning to synthesize complex polyenergetic dose distributions directly from simple monoenergetic inputs under identical beam configurations. Unlike conventional approaches such as denoising or GenAI techniques, our method achieves superior cross-domain generalization on unseen datasets by integrating high-fidelity anatomical textures and source-specific beam similarity directly into the model's input space. Furthermore, we propose a novel 3D architecture termed TransUNetSE3D, featuring Transformer blocks for global context and Residual Squeeze-and-Excitation modules for adaptive channel-wise feature recalibration. Hierarchical representations of these blocks are fused into the network's latent space alongside the primary dose-map parameters, allowing physics-aware reconstruction. This hybrid design outperforms existing U-Net and Transformer-based benchmarks in both spatial precision and structural preservation, while maintaining the execution speed necessary for real-time use. Our proposed pipeline achieves a Gamma Passing Rate exceeding 98% (3%/3mm) compared to the MC reference, evaluated within the framework of a treatment planning system using 6MV TrueBeam Linear Accelerator for prostate radiotherapy. These results offer a robust solution for fast volumetric dosimetry in adaptive radiotherapy.

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