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Short Communication

Next-Generation Radiotherapy: Convergence of Physics, Biology, and Real-Time Adaptation

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Abstract
Radiotherapy is undergoing a paradigm shift from a one-size-fits-all approach to biologically individualized and dynamically adaptive treatment. Recent advances presented at major conferences and in peer-reviewed literature demonstrate the rapid clinical translation of technologies that integrate real-time imaging, dose accumulation, and biological targeting. This communication highlightskey innovations including online dose-adaptive radiotherapy, biology-guided radiotherapy with PET tracking, proton and heavy ion lattice therapy, and FLASH ultra-high dose rate techniques. These approaches share a common goal: maximizing tumor control while minimizing collateral damage to healthy tissues through precision delivery and biological optimization

Introduction
For decades, radiotherapy treatment planning has relied on static images acquired days before treatment delivery, with margins added to account for geometric uncertainties. The past year has witnessed transformative advances that challenge this paradigm. From MRI-guided linear accelerators that adapt plans daily to PET-guided systems that track tumours in real time using biological signals, the field is moving toward truly personalized medicine.

Online Dose-Adaptive Radiotherapy

Conventional online adaptive radiotherapy (OART) reduces geometric uncertainties by replanning based on daily anatomy. However, a significant innovation reported by Schröder and colleagues takes this concept further with online dose-adaptive radiotherapy (DART), which incorporates accumulated dose from previous fractions into daily plan optimization.

Biology-Guided Radiotherapy

Perhaps the most conceptually radical advance is the clinical implementation of biology-guided radiotherapy (BgRT), with Stanford Medicine leading the world in adopting the RefleXion platform. This technology integrates positron emission tomography (PET) imaging with radiotherapy delivery, using radioactive tracers that are preferentially absorbed by cancer cells to create a "biological beacon" for real-time tumor tracking

Particle Therapy Innovations

Proton and heavy ion therapy continue to evolve with innovations that exploit the physical Bragg peak while adding biological dimensions. A comprehensive review by Yan and colleaguesexamines advances in dual-energy computed tomography, proton CT, and in-vivo range verification that address fundamental uncertainty limitations in particle therapy

Challenges and Future Directions

Despite these advances, significant challenges remain. Yan and colleagues emphasize the need for rigorous multicenter validation, standardized quality assurance protocols, and integration of multi-omics with functional imaging. The rapid evolution of AI-enhanced image generation and automated treatment planning requires continuous performance monitoring and workforce training. Equitable access across diverse patient populations remains a concern as technologies become increasingly sophisticated and costly.

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