

From Minutes to Seconds: Hybrid AI–Monte Carlo Dose Calculation for Real-Time Radiotherapy

Artificial Intelligence in Radiotherapy Symposium
CAP Congress – Ottawa, Canada (June 2026)

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University Health Network (UHN)

- #1 research hospital in Canada (since 2011)
- ~\$599M annual research spending
- UHN hospitals include #2 ranked hospital worldwide (2026)
- ~24,000+ staff and 2,000+ physicians



https://www.uhn.ca/corporate/AboutUHN/Pages/uhn_at_a_glance.aspx

<https://www.uhnresearch.ca/news/12-04-2025/uhn-is-canadas-1-research-hospital>



Princess Margaret Cancer Centre (PM)

- Top 10 globally in oncology (Newsweek World's Best Specialized Hospitals 2026)
- #1 cancer centre in Canada
- ~20,000 new cancer patients/year
- ~279,000 clinic & virtual visits/year
- ~\$298M annual research funding

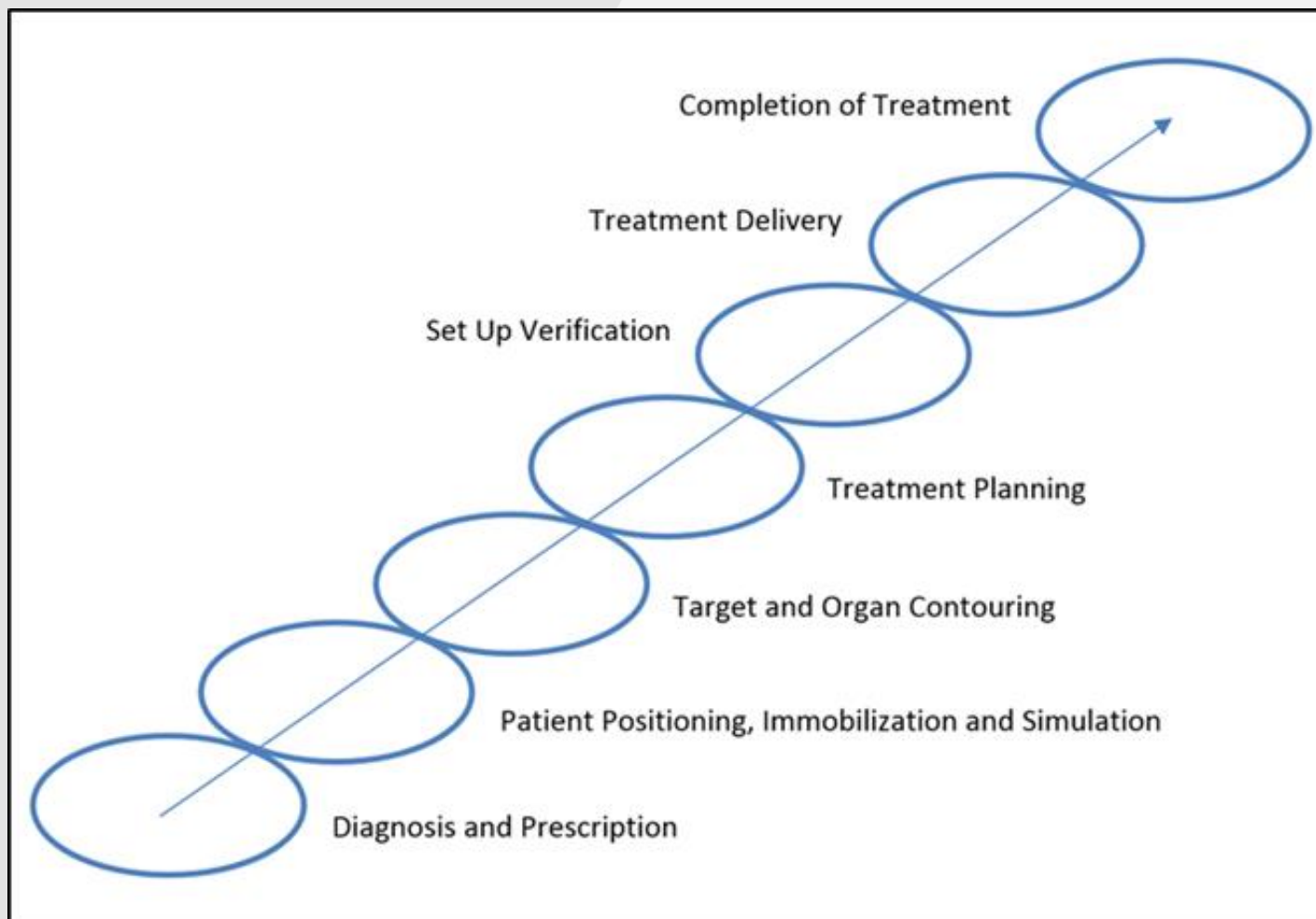


<https://www.uhn.ca/corporate/News/PressReleases/Pages/canadian-hospital-now-ranked-2-in-the-world.aspx>

<https://www.uhnresearch.ca/news/12-04-2025/uhn-is-canadas-1-research-hospital>



Radiotherapy Chain

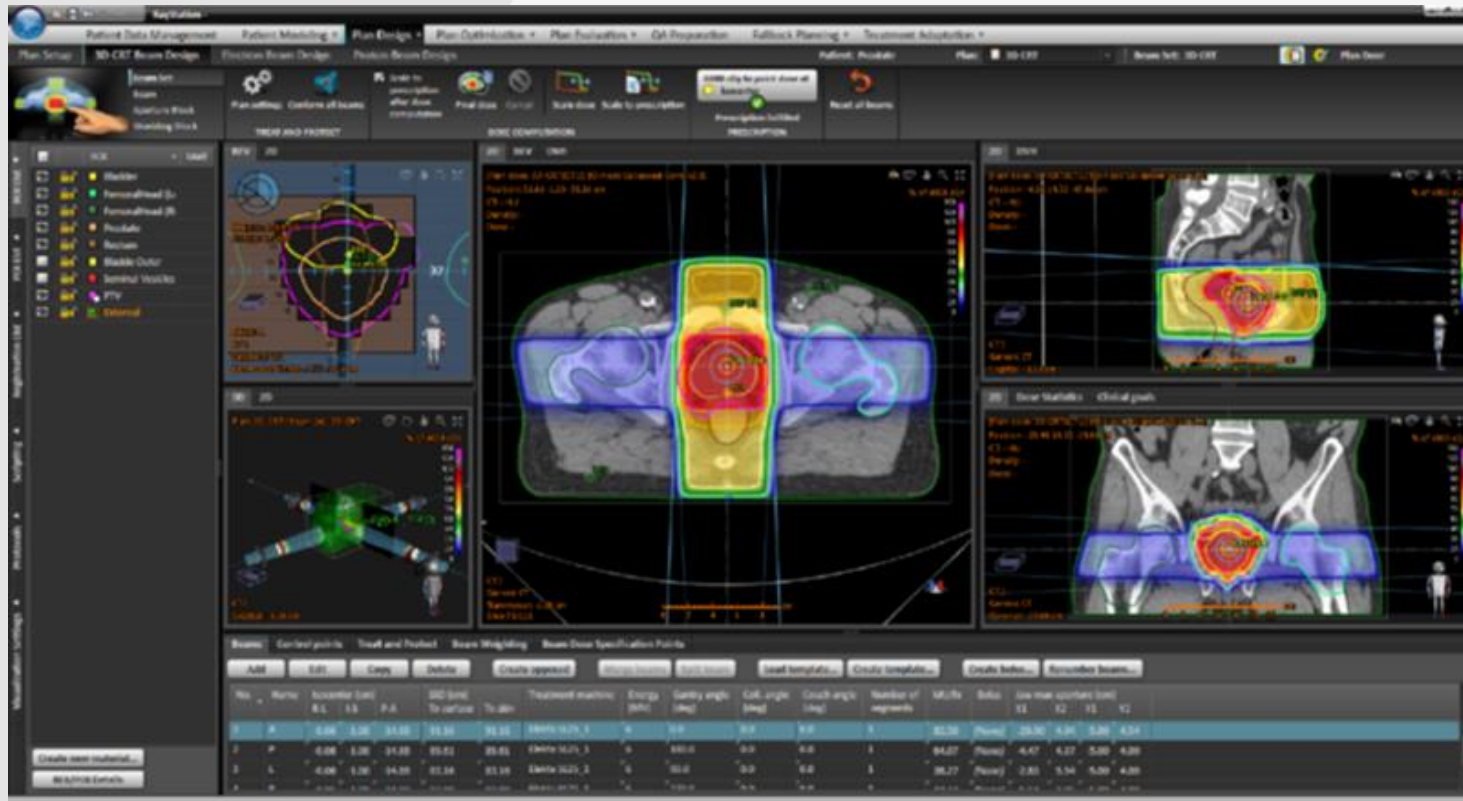


Chow JCL. Recent Progress of Gold Nanomaterials in Cancer Therapy. In *Handbook of Nanomaterials and Nanocomposites for Energy and Environmental Applications*. Springer Nature, Cham, pp. 1-30. 2020. DOI https://doi.org/10.1007/978-3-030-11155-7_2-1.

A radiotherapy chain showing different steps in the radiation treatment process.

Radiation Treatment Planning

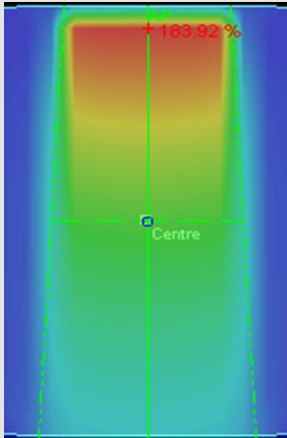
In radiotherapy, radiation treatment planning is the process in which a team of Radiation Oncologists, Radiation Therapists, Medical Physicists and Medical Dosimetrists plan the appropriate external beam radiotherapy or internal brachytherapy technique for a cancer patient.



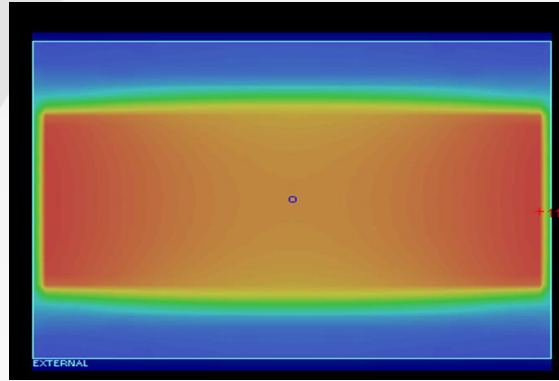
https://en.wikipedia.org/wiki/Radiation_treatment_planning



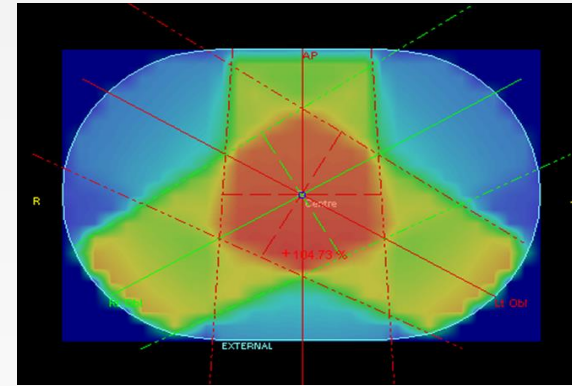
Dose Distribution



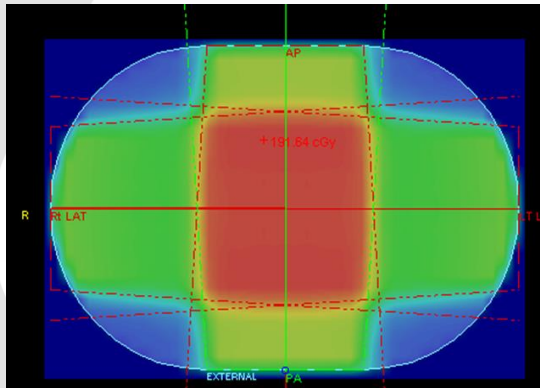
1 beam



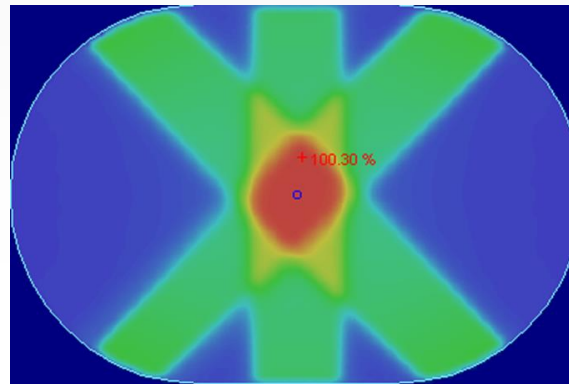
2 beams



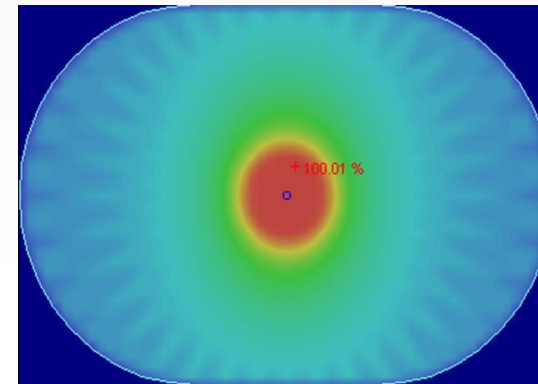
3 beams



4 beams



6 beams



Arc

Dose Calculation – Monte Carlo vs. Treatment Planning System (Pencil beam/Convolution–superposition)

Monte Carlo vs. Collapsed Cone Convolution (CCC)
vs. Adaptive Convolution (AC) vs. ...

- Monte Carlo (MC) simulation is widely regarded as the **most accurate** radiation dose calculation method.
- However, this high level of accuracy comes at the cost of **long computation times**, as the precision of the results depends on the number of particle histories simulated.



Monte Carlo methods (or Monte Carlo experiments) are a broad class of computational algorithms that rely on **repeated random sampling** to obtain numerical results. They are often used in physical and mathematical problems and are most useful when it is **difficult** or impossible to use other mathematical methods.

Monte Carlo methods are mainly used in three distinct problem classes: optimization, numerical integration, and generating draws from a probability distribution.

R Harrison. Introduction to Monte Carlo Simulation.
AIP Conf Proc. 2010;**1204**:17-21

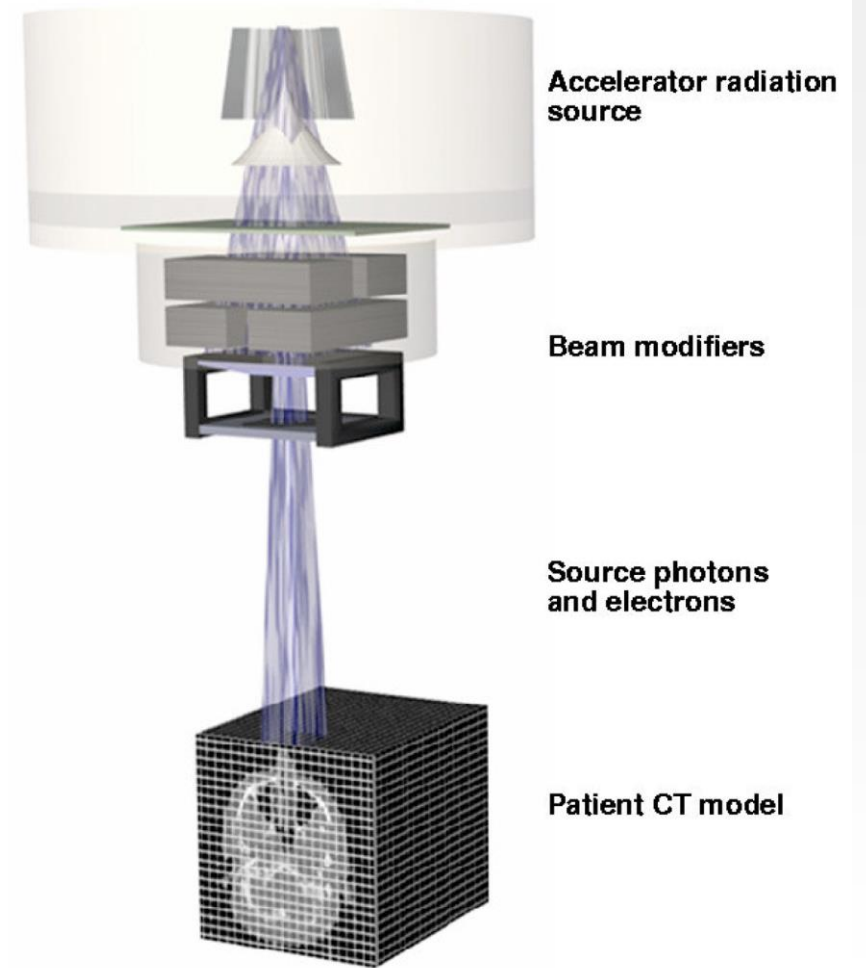
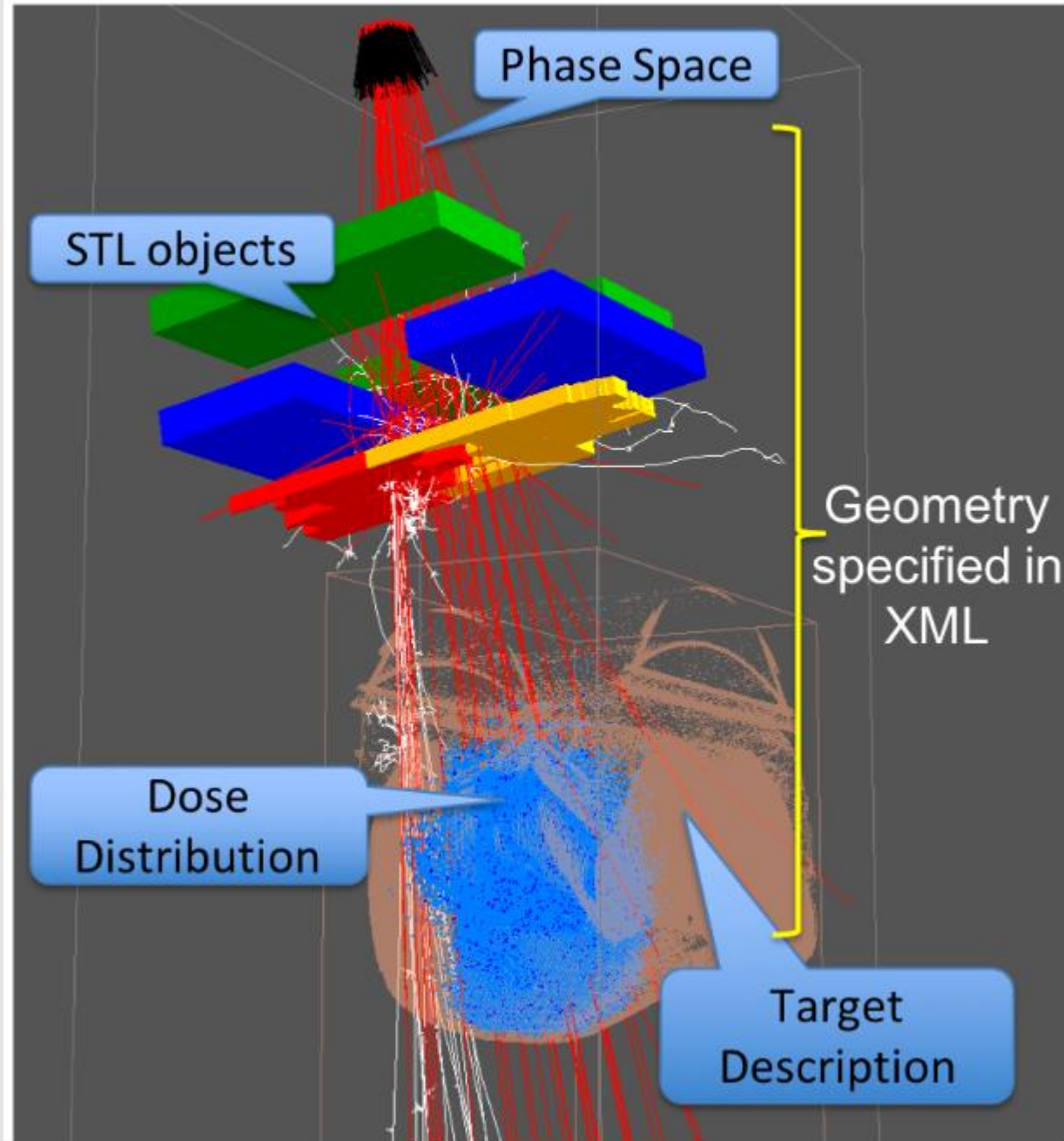


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Monte Carlo Simulation Example



<https://www.preprints.org/manuscript/202509.2179>

<https://radyalis.com/monte-carlo-3/monte-carlo-dose-simulator/>



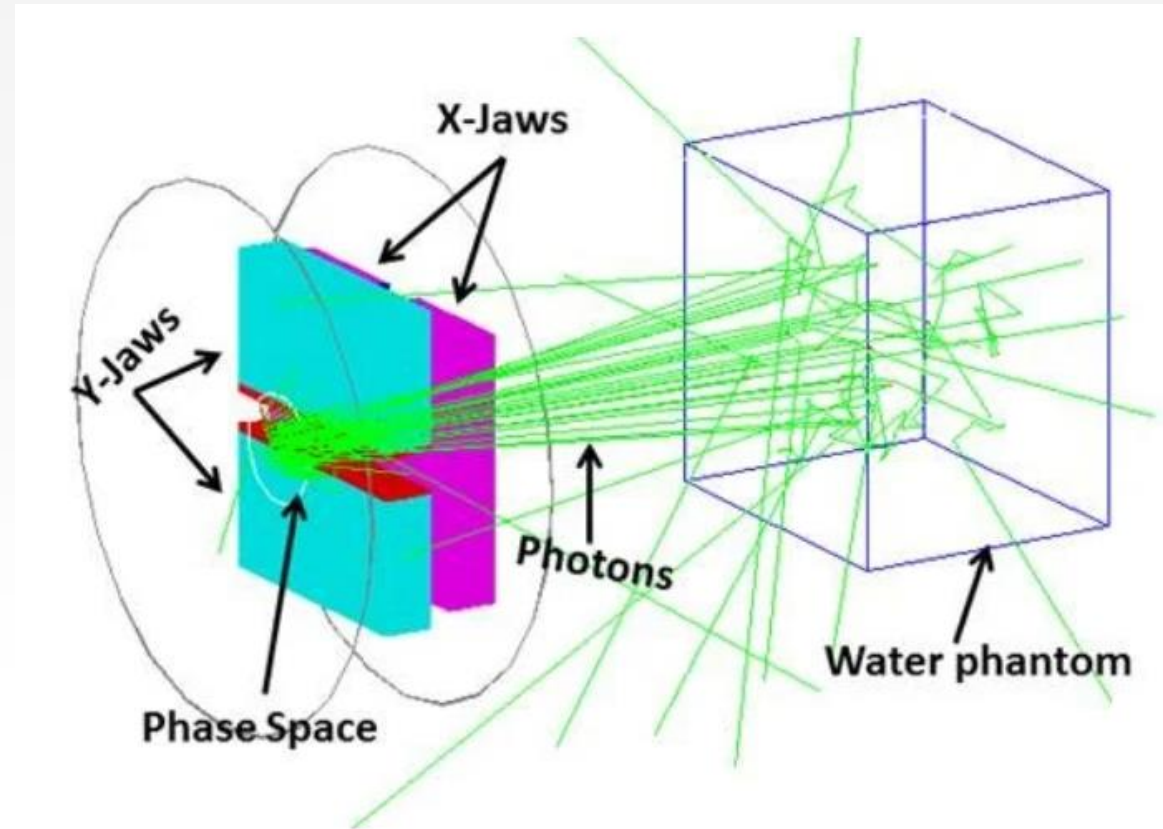
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Monte Carlo: Gold Standard

- Physics-based modeling
- Handles heterogeneity
- Reference for validation



Dose calculation stage in Monte Carlo simulation showing phase space source, X and Y jaws, X-rays beam (green lines), and water phantom.

https://www.researchgate.net/figure/Dose-calculation-stage-in-Monte-Carlo-simulation-showing-phase-space-source-X-and-Y_fig2_344953788

Why Dose Calculation Still Matters

- Accurate dose is central to treatment quality
- Precision radiotherapy depends on reliability

The Core Problem

- Monte Carlo: accurate but slow
- Analytical and semi-analytical models (PBC, CCC, AAA, AXB): fast but approximate
- Persistent trade-off



Limitations of Monte Carlo

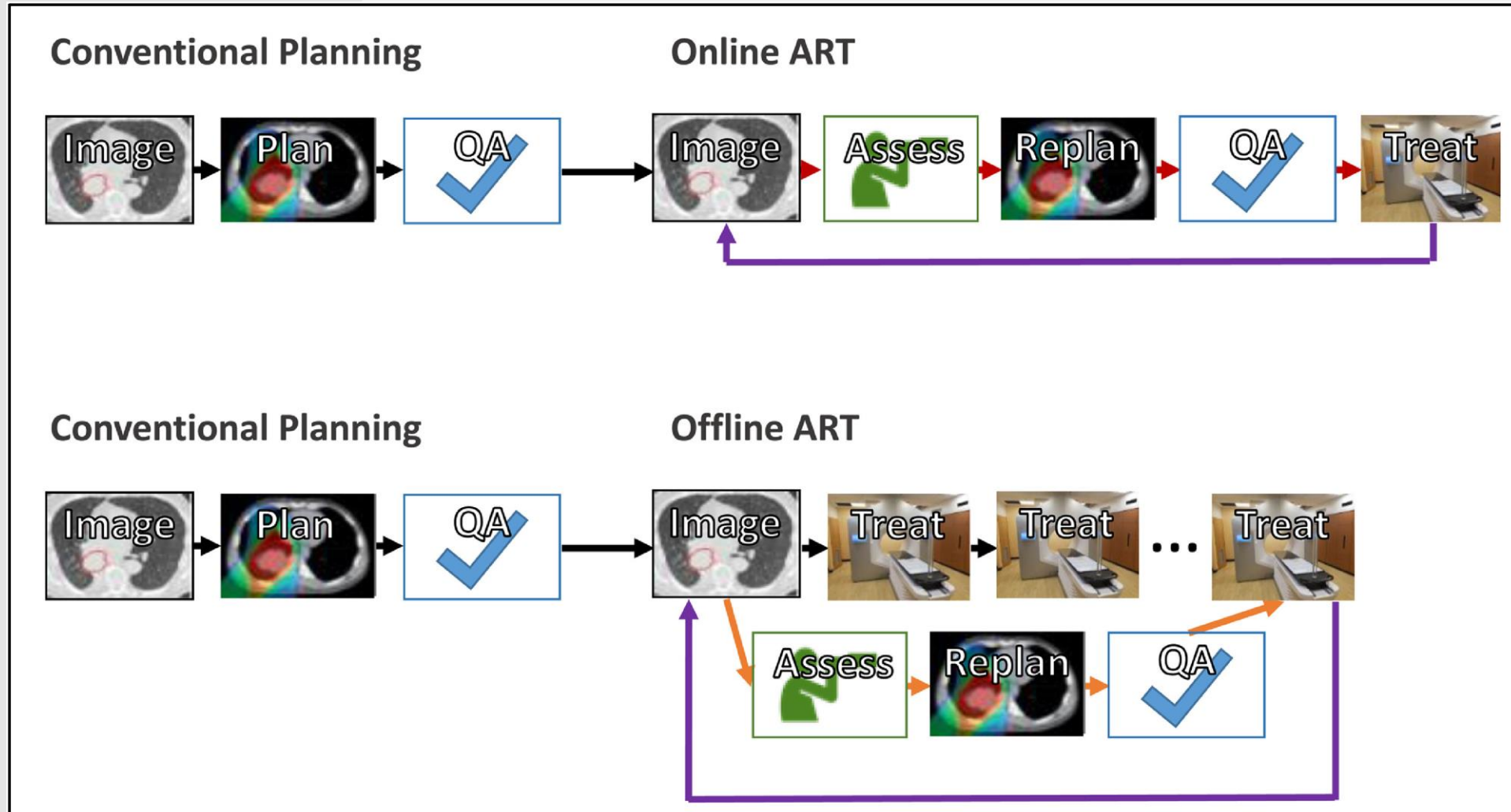
- High computational cost
- Minutes per calculation
- Not suitable for real-time workflows
- Limited in **adaptive radiotherapy**

Adaptive Radiotherapy

- Adaptive radiotherapy (ART) adjusts the treatment plan during therapy.
- It accounts for changes like tumor shrinkage or patient anatomy.
- Imaging is used to monitor changes and update the plan.
- This helps deliver radiation more accurately while protecting healthy tissue.



ART Workflow



<https://doi.org/10.1016/j.semradonc.2019.02.004>



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Clinical Need: Speed

- Adaptive radiotherapy (online) requires real-time decisions
- Patient on couch: limited time window

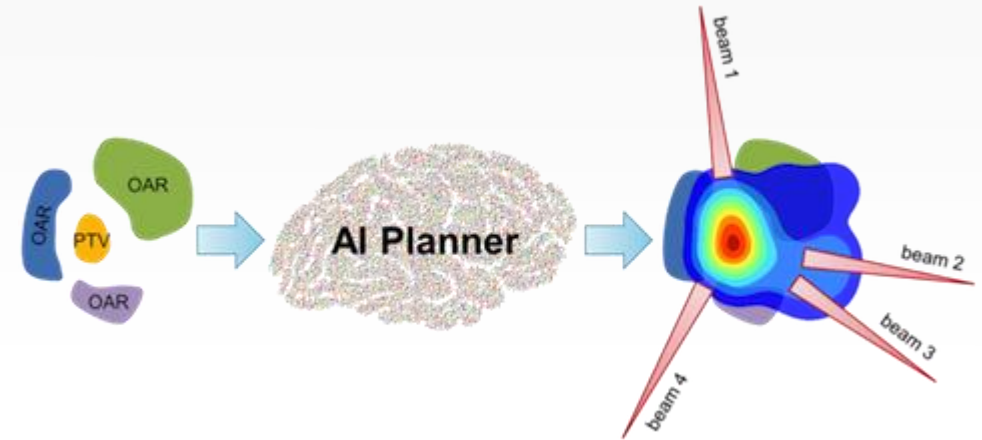


<https://health.economictimes.indiatimes.com/news/health-it/american-oncology-institute-hyderabad-launches-ai-driven-ethos-radiotherapy/101491205>



Enter AI

- Learns dose patterns from data
- Predicts dose in seconds
- Enables rapid workflow



<https://labs.utsouthwestern.edu/maia-lab/research/treatment-planning>



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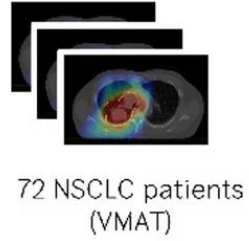


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AI for Dose Prediction

- Deep learning models (e.g., U-Net)
- Input: CT + beam
- Output: 3D dose

Plan selection and data collection

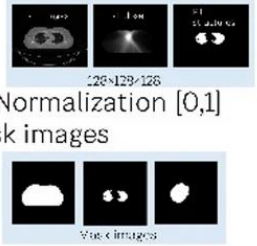


72 NSCLC patients (VMAT)

Plan Recalculation: 50 Gy, 54 Gy, 60 Gy

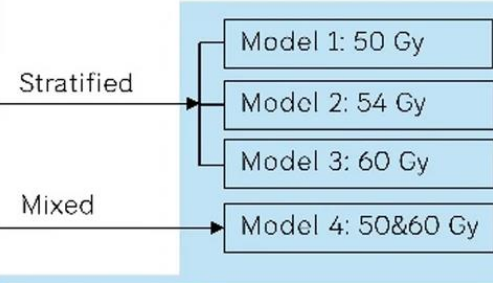
Data preparation

- Image registration (Open REGUI)
- Padding & Resampling (128^3 voxels)
- CT Normalization [0,1]
- Mask images
- Dose normalization
- Data augmentation (Flipped: 28 datasets for training)



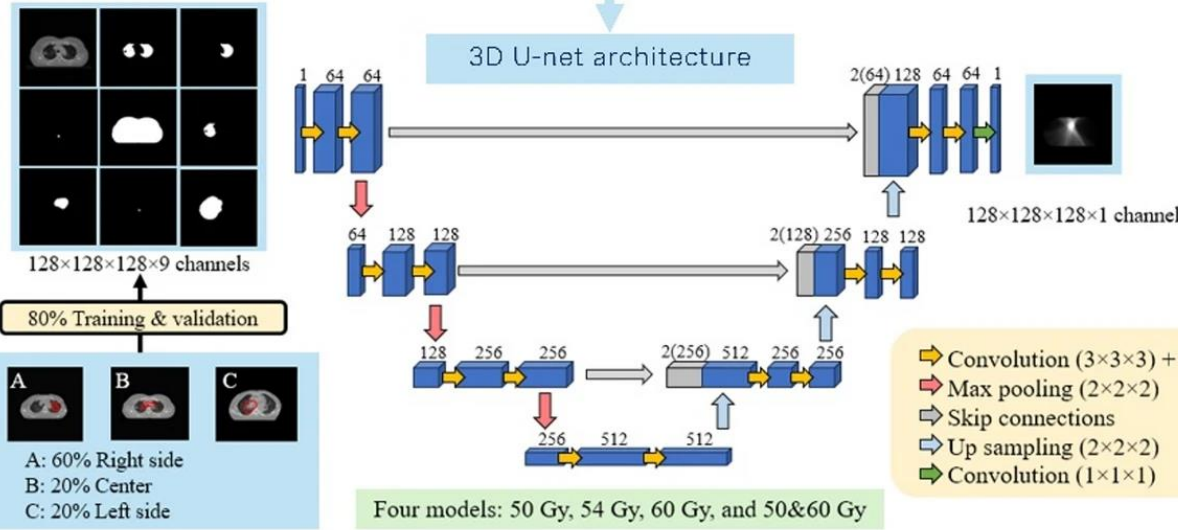
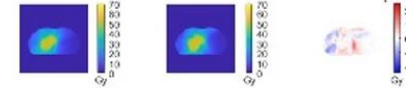
Model development

- Data Split:
- Training (n=70:42+28)
 - Validation (n=10)
 - Testing (n=20)



Model evaluation

- Performance evaluation
- Mean absolute error (MAE) (Dose metrics: $D_{95\%}$, D_{max} , V_{20Gy} etc.).
 - Homogeneity index (HI).
 - Voxel-wise difference maps



<https://link.springer.com/article/10.1038/s41598-026-43192-6/figures/1>

AI Performance

- Fast inference
- Reasonable accuracy
- Useful for planning support



Limitations of AI

- Generalization issues
- No direct physics
- Uncertainty in new cases



Key Idea

- Not AI or MC
- But AI + MC

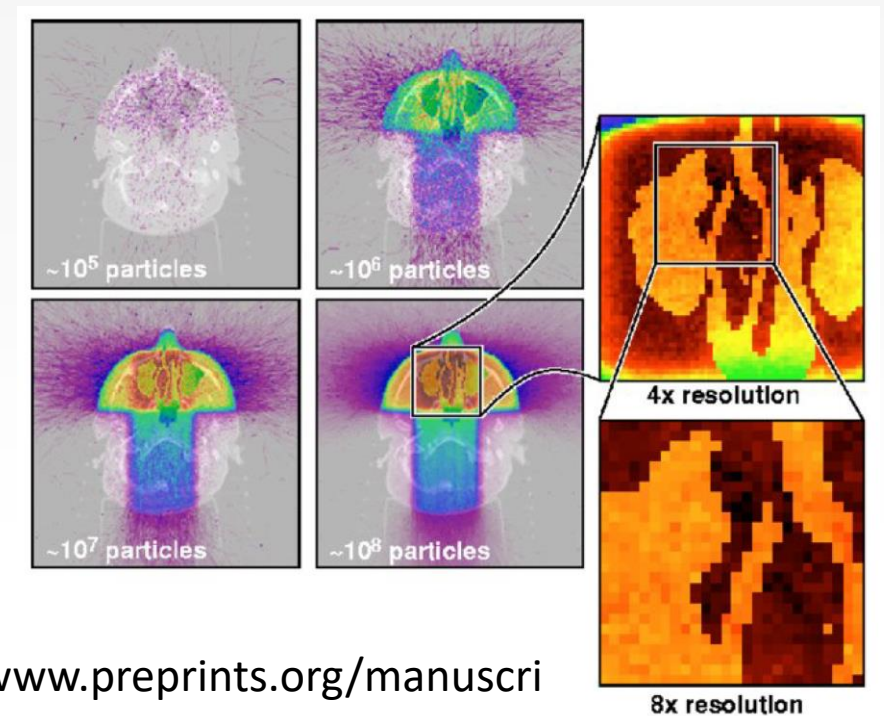
Hybrid AI–MC Framework

- AI: fast full dose
- MC: selective verification
- Combined accuracy and speed



Workflow

- Imaging → AI dose prediction → identify critical regions → MC refinement



<https://www.preprints.org/manuscript/202509.2179>



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From Minutes to Seconds

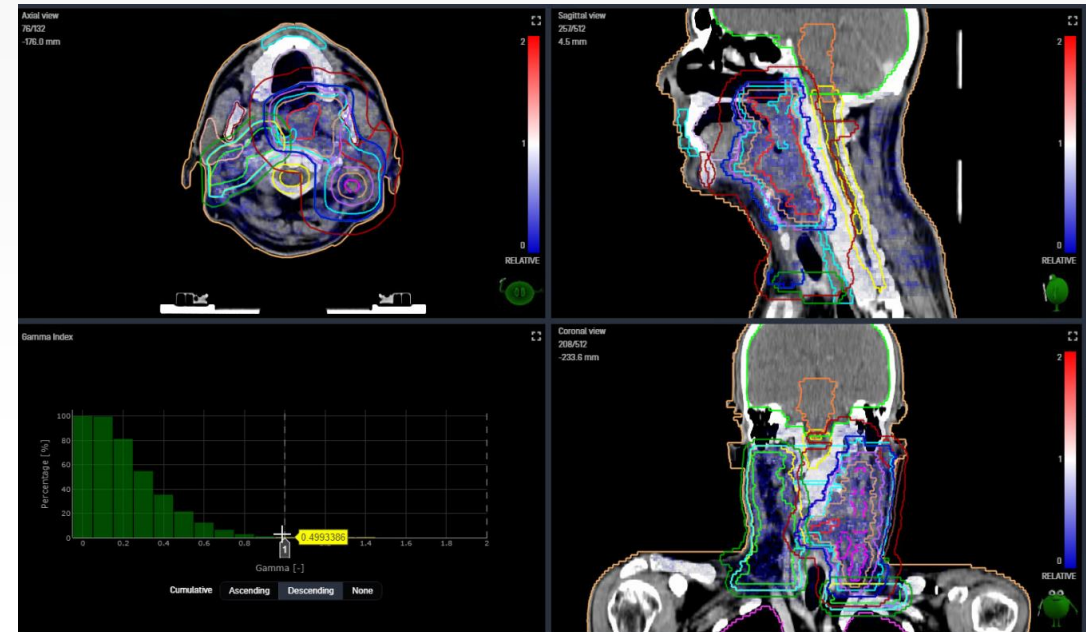
- AI enables rapid estimation
- MC used only where needed
- Significant time reduction



Clinical Scenario

- On-couch adaptive radiotherapy
- AI gives instant estimate
- MC confirms critical regions

<https://www.iba-dosimetry.com/product/myqa-ion-radiation-therapy>



Applications

- Adaptive radiotherapy
- Treatment planning
- Quality assurance

Uncertainty & Safety

- AI: uncertainty estimation
- MC: ensures reliability
- Hybrid: improves confidence



Key Advantage

- From minutes to seconds
- Maintain physical accuracy



Limitations & Challenges

- Data dependence
- Domain shift
 - Differences in anatomy, imaging characteristics, treatment setups and materials properties
- Model maintenance



Future Directions

- Physics-informed AI
- Proton therapy
- Real-time adaptive workflows



Take-Home Messages

- MC = accuracy
- AI = speed
- Hybrid = future



Acknowledgment

- We are grateful to the Natural Sciences and Engineering Research Council of Canada (NSERC) Discovery Grant Program for funding this project.

