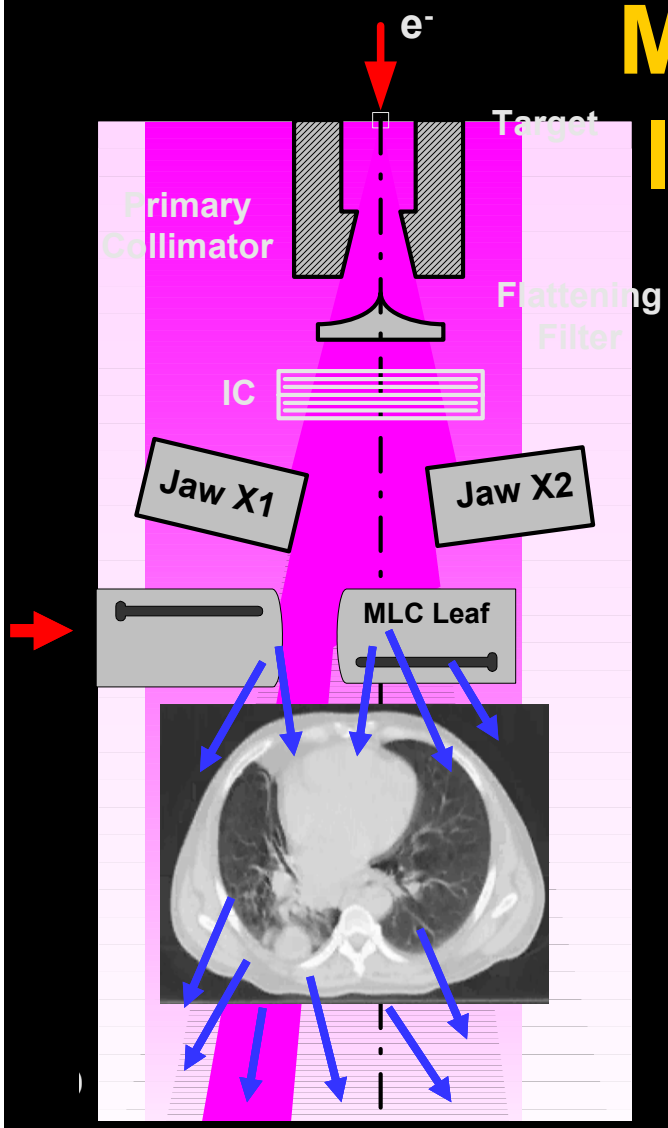
The Department of
Radiation Oncology



Monte Carlo Applications in IMRT Planning and Quality Assurance

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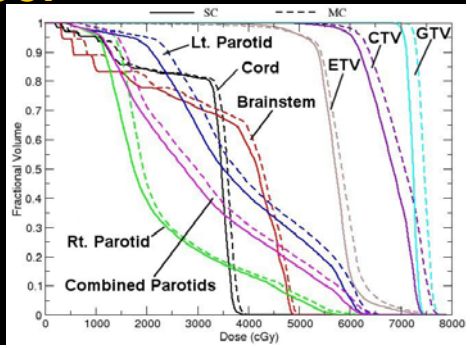
2006 AAPM Summer School



Objectives

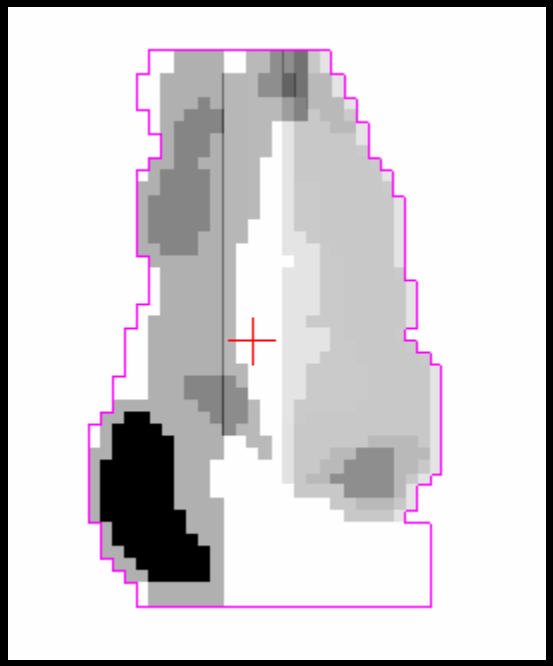
- Describe methods to incorporate MC into the IMRT dose calculation process
- Review systematic and convergence errors revealed by MC dose calculation and optimization
- Describe role of MC in patient-specific IMRT QA
- Methods of making photon-beam IMRT optimization clinically feasible
- Electron intensity modulated radiation therapy optimization
- Role of MC in treatment IMRT QA

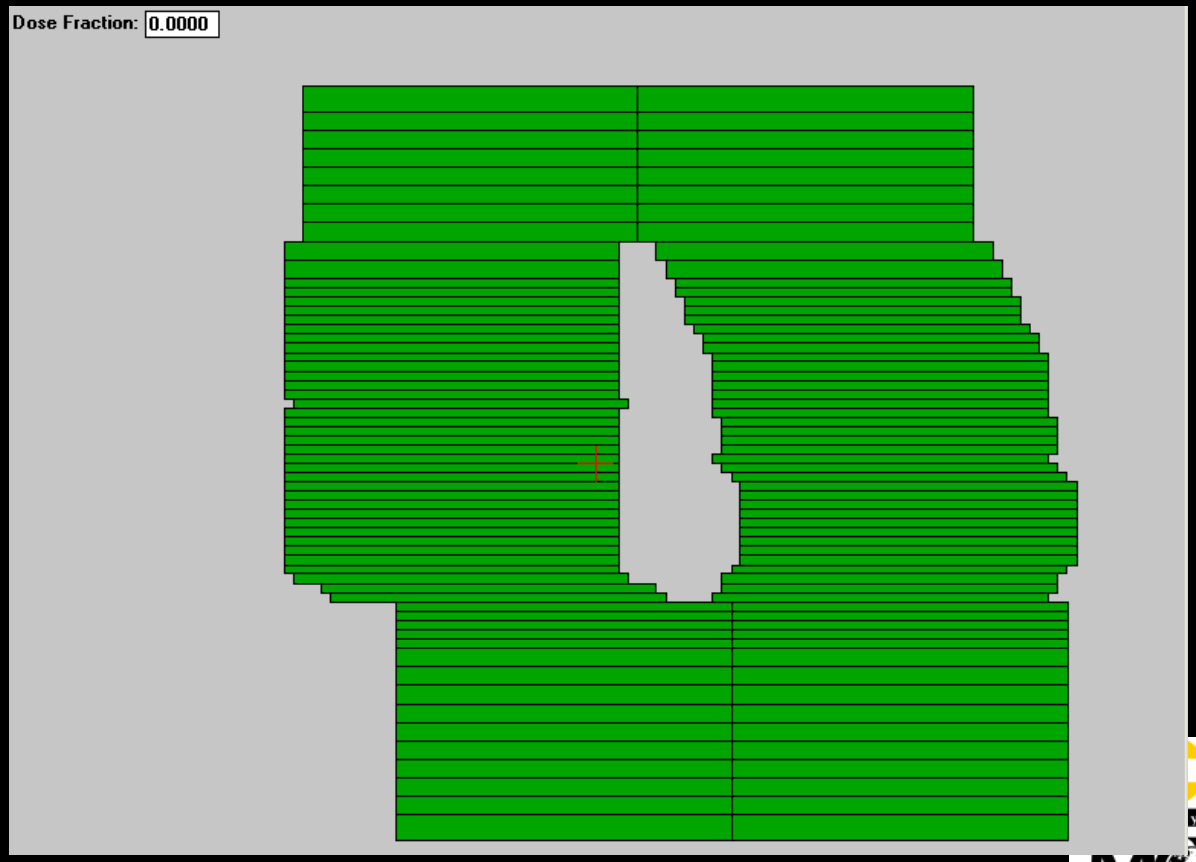
Outline of the next 28 minutes

- Why MC for IMRT?
- MC for IMRT fluence prediction
- MC for patient dose prediction
- MC for IMRT optimization
- Hybrid methods for MC optimization

Why Monte Carlo for IMRT?

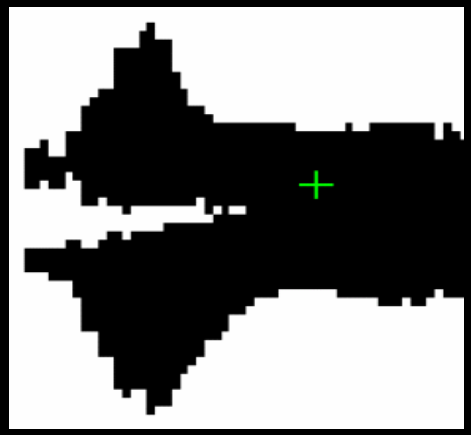
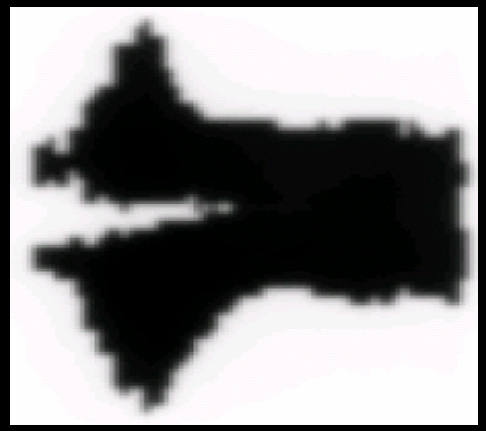
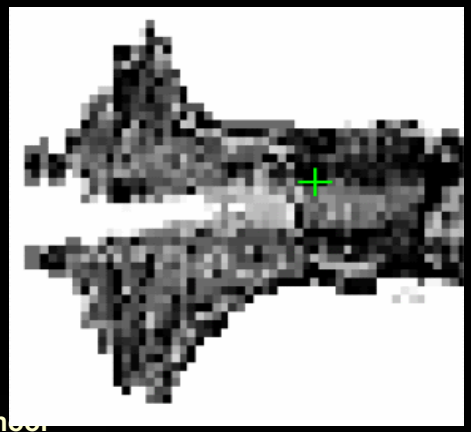
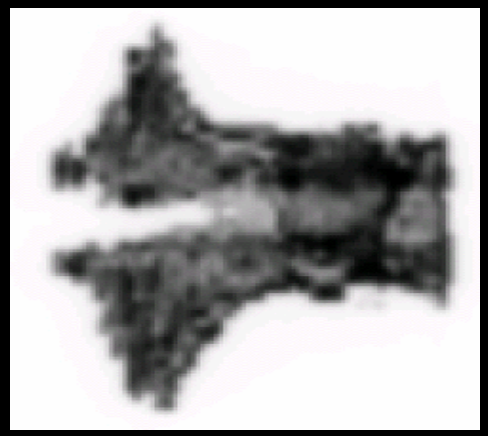
- Small fields

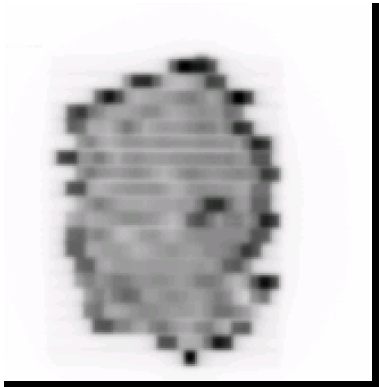




Why MC for IMRT?

Fluence gradients⟶Loss of Radiation Equilibrium

	Intensity	Dose
3DCRT		
IMRT		

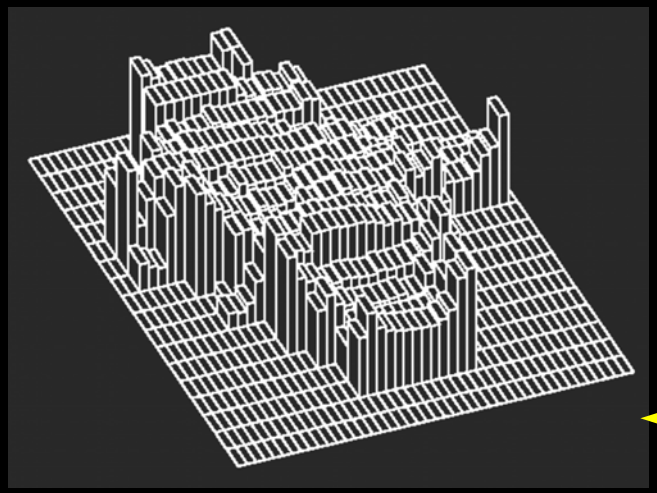


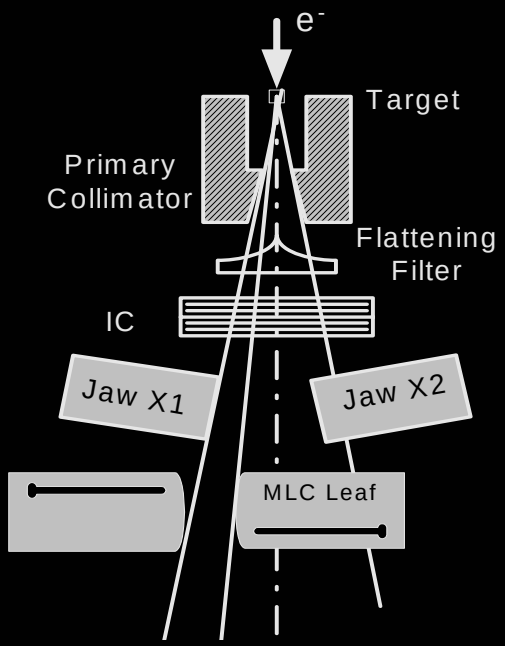
Why Monte Carlo for IMRT?

- Conventional dose algorithms can be inaccurate for
  - Small fields
  - Regions of dose gradients (radiation disequilibrium)
  - Heterogeneous conditions

Dose Calculation is a Two Step Process

- Incident fluence prediction





- Energy deposition in the patient/phantom

MC for Fluence Prediction

IMRT Delivery Modes

- **SMLC**

  "step and shoot" or multi-segmented

- **DMLC**
  - dynamic MLC or sliding window

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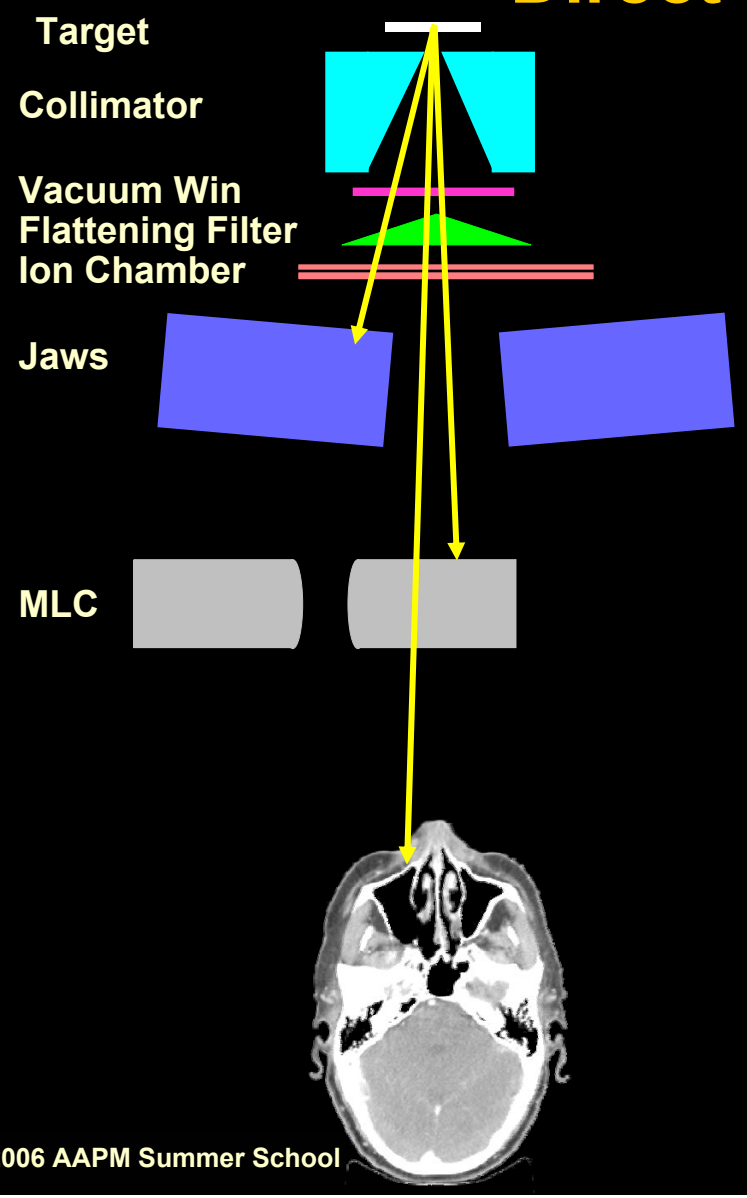
MC for Fluence Prediction

Direct particle transport



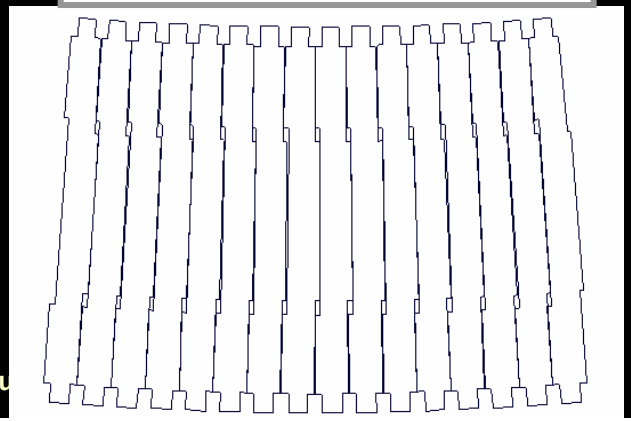
- Simulate individual particles through MLC
- Geometric details <u>can be</u> fully included
- Physics (leakage, scatter) inherently accounted
- SMLC and DMLC

MC for Fluence Prediction

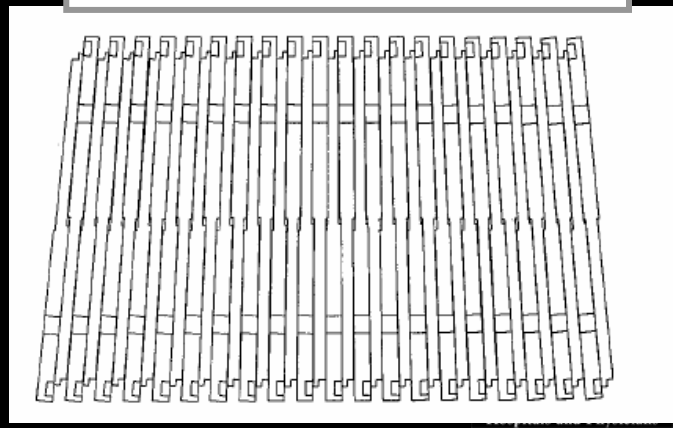
General Purpose MC modules

- General purpose MC algorithms
  - MCNP, GEANT, …
  - Detailed modeling of MLC leaf geometry
  - Detailed modeling of interactions
  - Slow (50-100 hrs for MLC transport alone)

Varian 80 leaf MLC



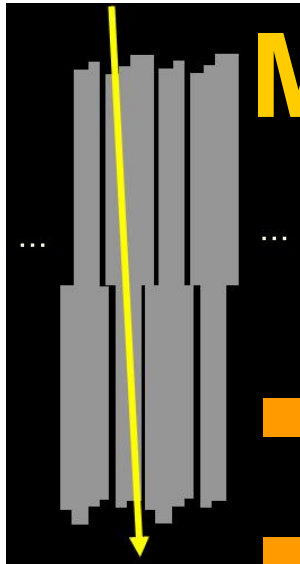
Varian 120 leaf MLC



MC for Fluence Prediction

BEAMnrc MC modules

- BEAMnrc Modules
  - Full simulation of interactions
  - 10s to 100s of CPU hours for IMRT calculation
  - Modules
    - MLC
      - Generic, double focused
    - MLCQ
      - Single focuses, rounded leaf ends
    - VARMLC
      - Varian 80-leaf with tongue-and-groove
    - DYNVMLC
      - Varian 120-leaf
    - MLCE
      - Elekta MLC, including tongue/groove



MC for Fluence Prediction

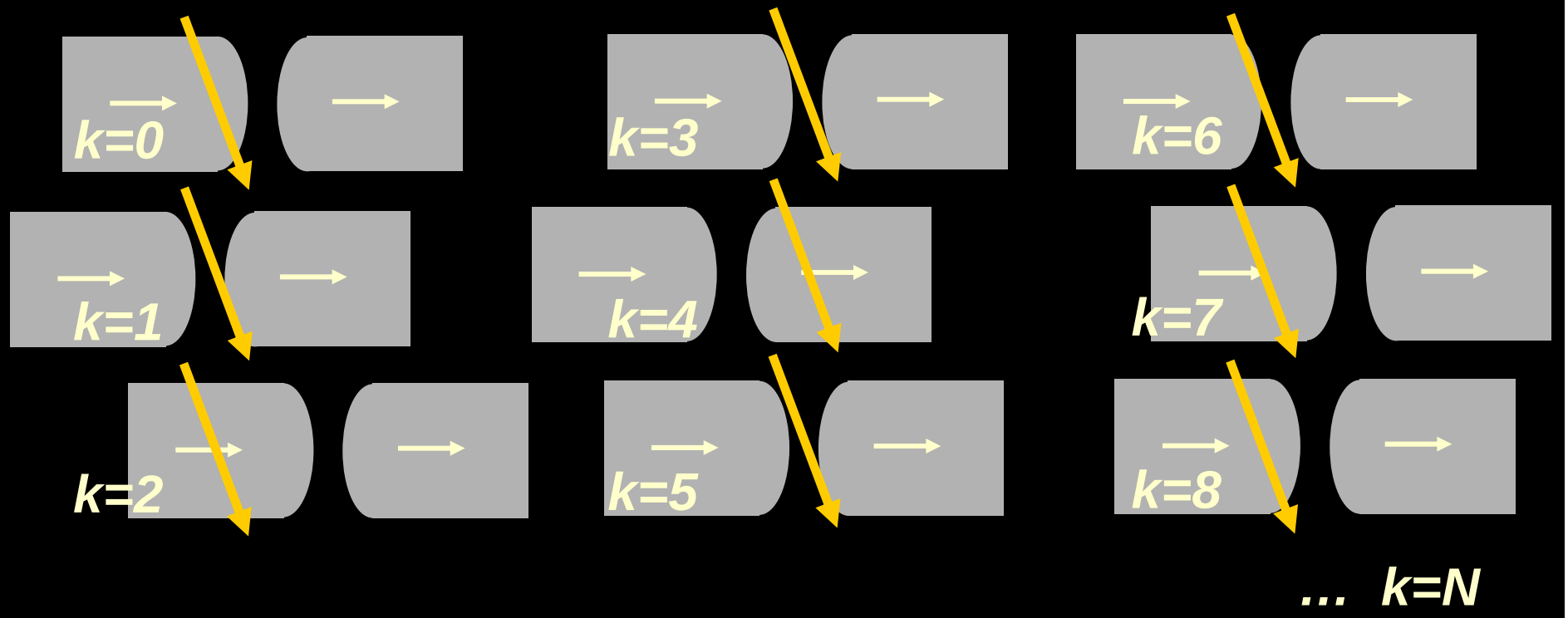
Independent modules

- Fast ray tracing
- Efficient particle use
- Simplified geometry
- Simplified physics

- Benchmarking results
  - Neglecting electron MLC transport introduces little error in photon dose

Efficient particle usage

Average attenuation from multiple time samples

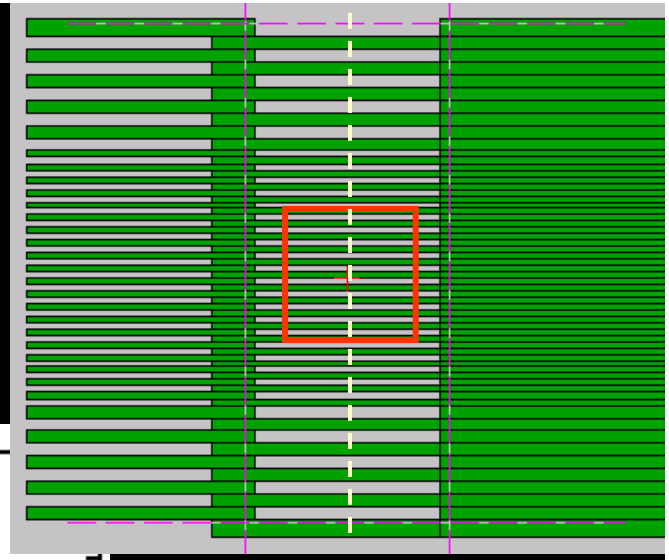


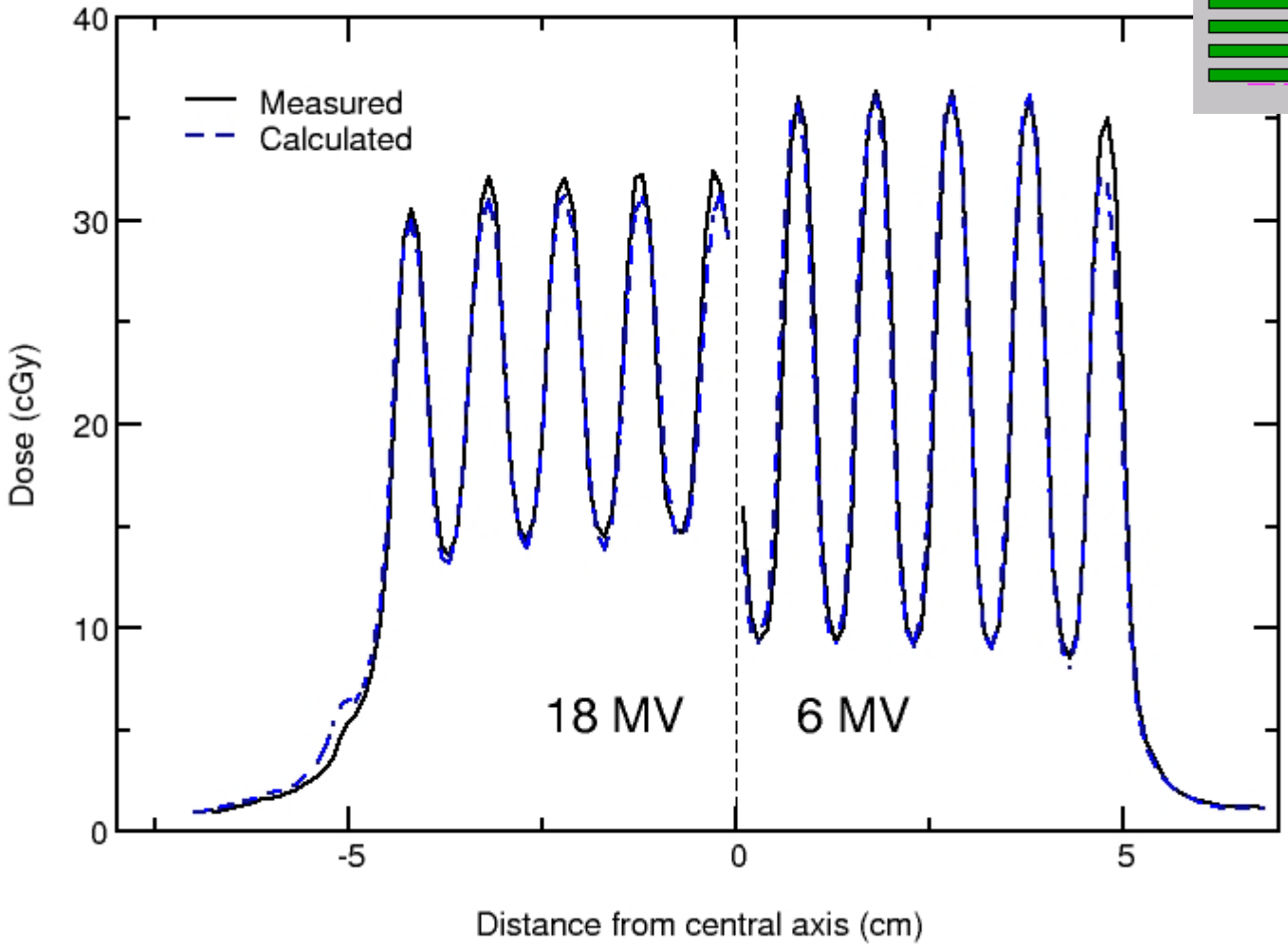
Determine mean weight by sampling at multiple random "times".

$$w_f = \frac{w_i}{N} \sum_{k=1}^{N} e^{-\mu(E) t_k / \cos\theta_z}$$

Independent MC MLC Model

Even leaves blocking field, Jaws set for 10x10 field





- 90% of points within ±1%, ±1 mm
- Leaf edge effects accurately predicted

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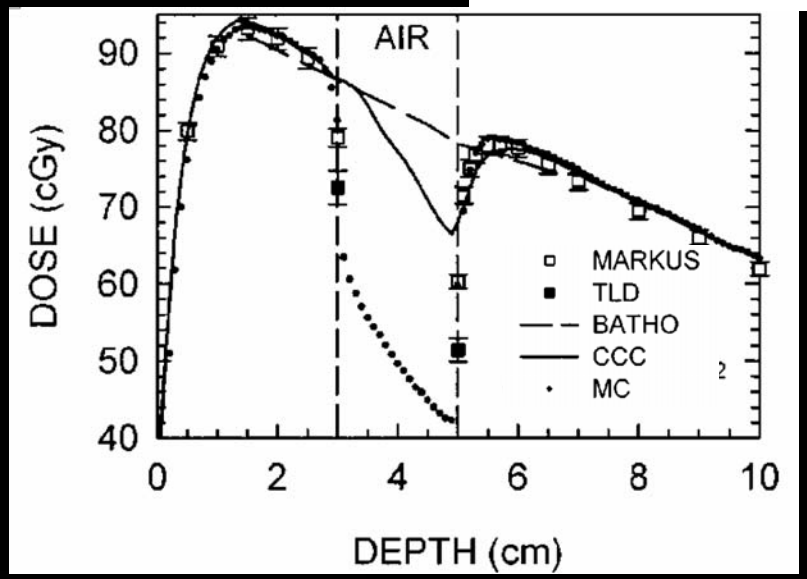
Methods for MC For Patient Dose Prediction

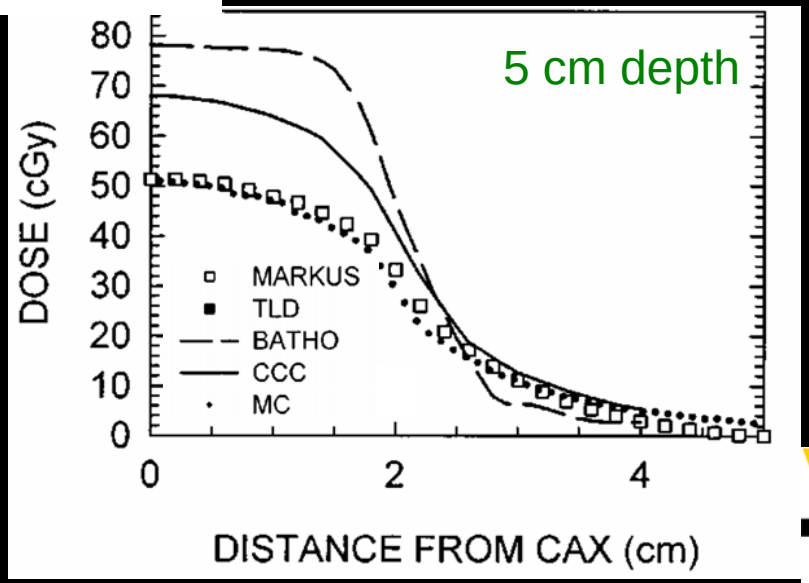
MC for patient dose prediction

Motivation

- Conventional dose algorithms can be inaccurate for regions of radiation disequilibrium
  - Small fields
  - Regions of dose gradients
  - Heterogeneous conditions

6 MV 4 cm x 4 cm field



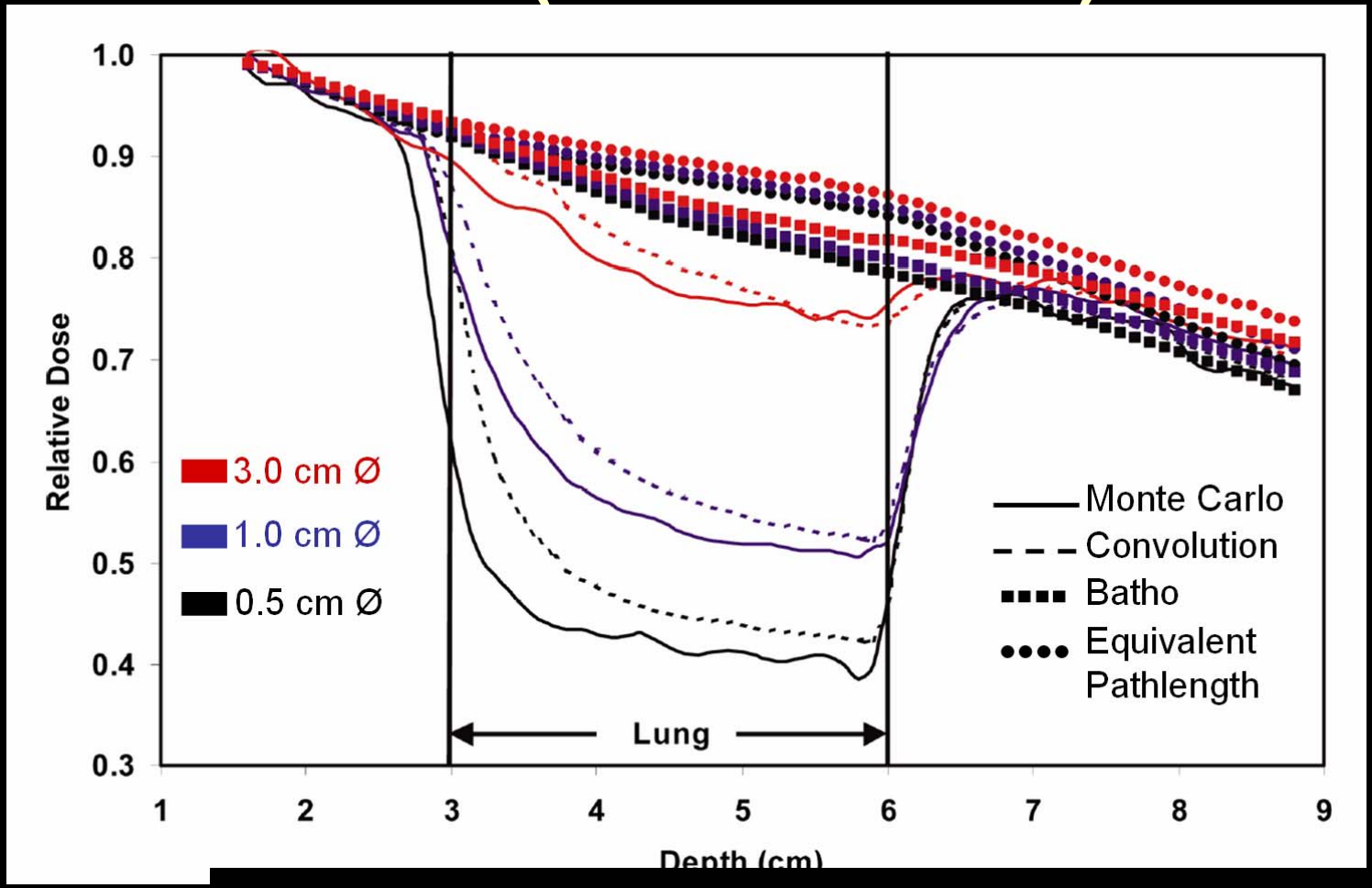


Adapted from Arnfield et al, Med Phys, 27 (6)

MC for patient dose prediction

Motivation

- Small fields (beamlet size)



Adapted from Jones and Das, Med Phys, 32 (3) page 770

MC for patient dose prediction

Caution!

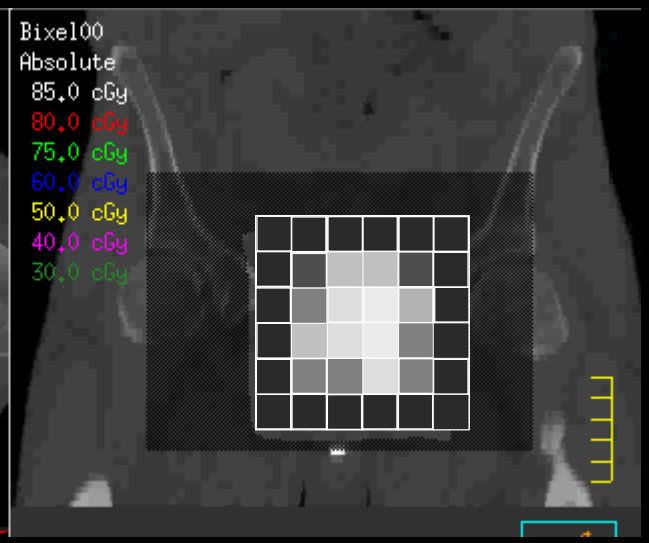
- Differences wrt conventional algorithms greatest in regions of fluence dis-equilibrium

- Where do you perform your IMRT QA?

MC for patient dose prediction

Bixel based MC calculations

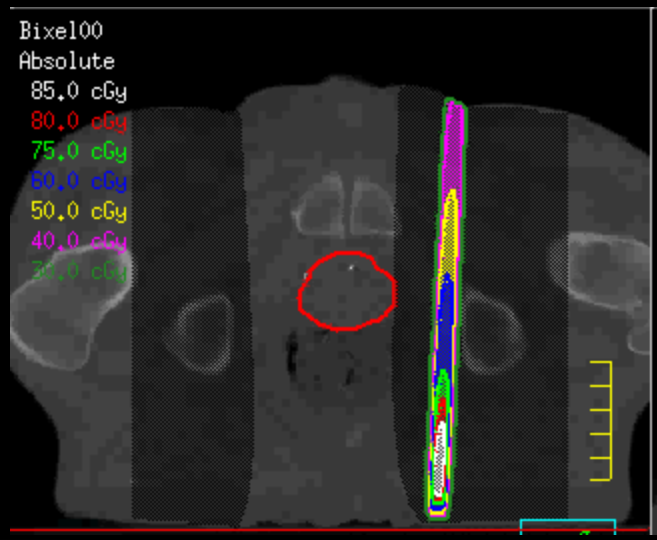
- Incident fluence sub-divided into ~1x1 cm^2 beamlets
- One-time dose computation for each beamlet to generate bixels
- Optimization determines bixel weights

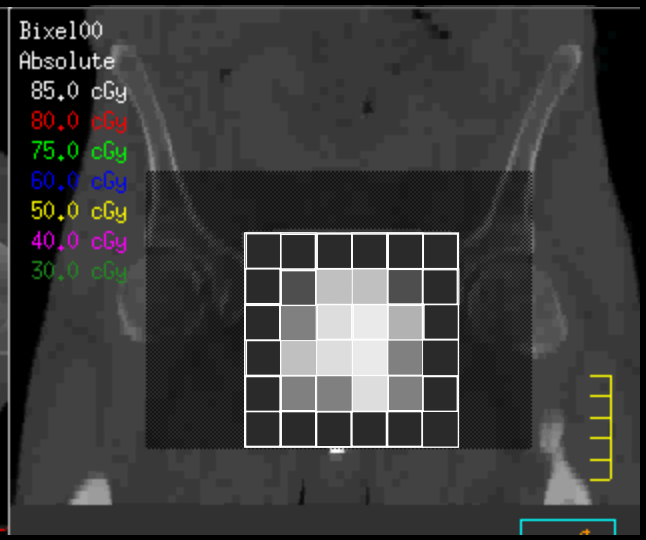


MC for patient dose prediction

Bixel based MC calculations

- **Advantages:**
  - One-time dose computation
- **Disadvantages:**
  - Limited resolution
  - Memory storage
  - Neglects effect of beam delivery





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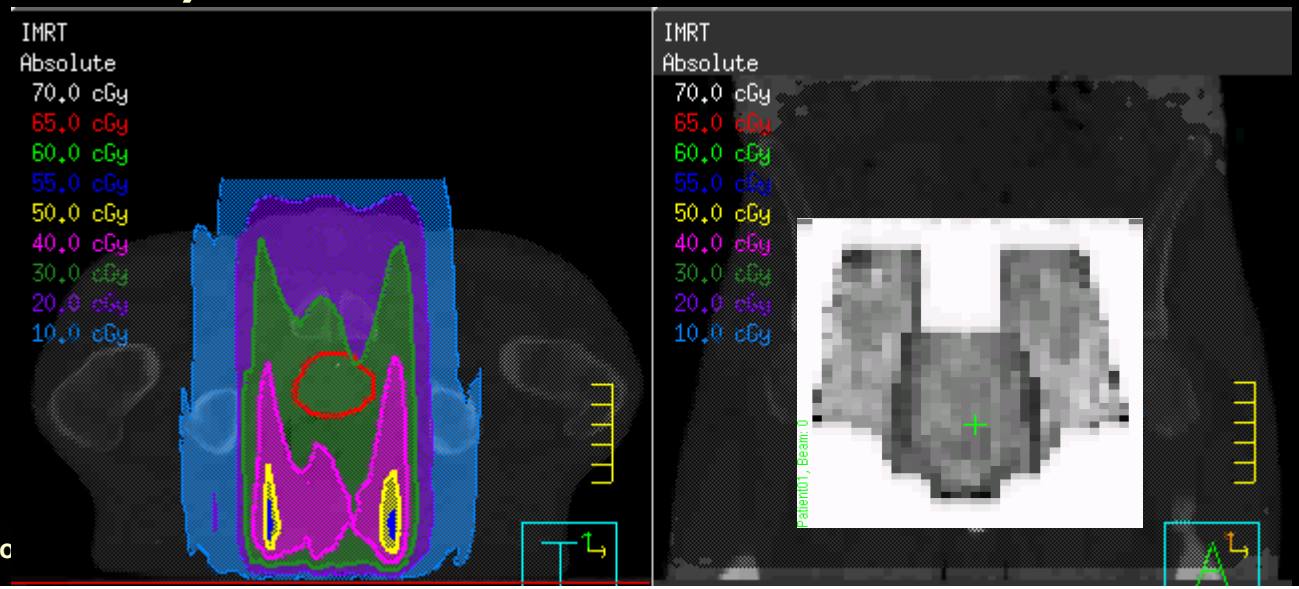
MC for patient dose prediction

Field-based dose calculation

- Compute dose for entire beam
- For SMLC, can compute per-segment dose computation (use in segment weight optimization)

- Advantages:
  - Fluence can include MLC effects (leakage / scatter)
- Disadvantage:
  - Re-computation each time fluence changes (different leaf positions)



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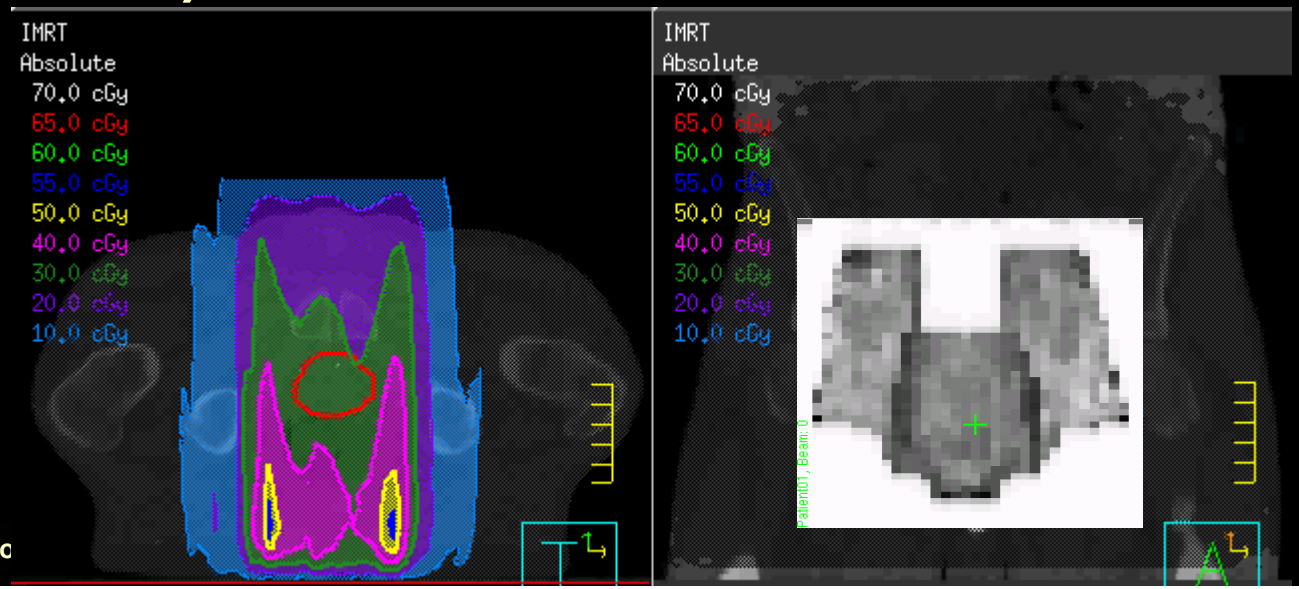

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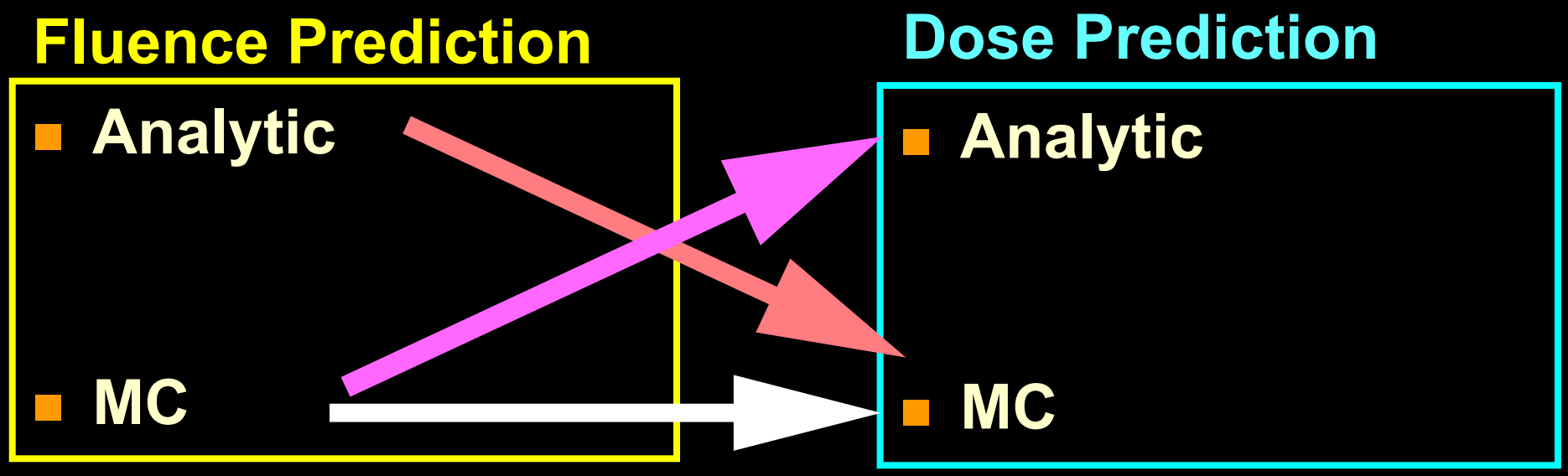
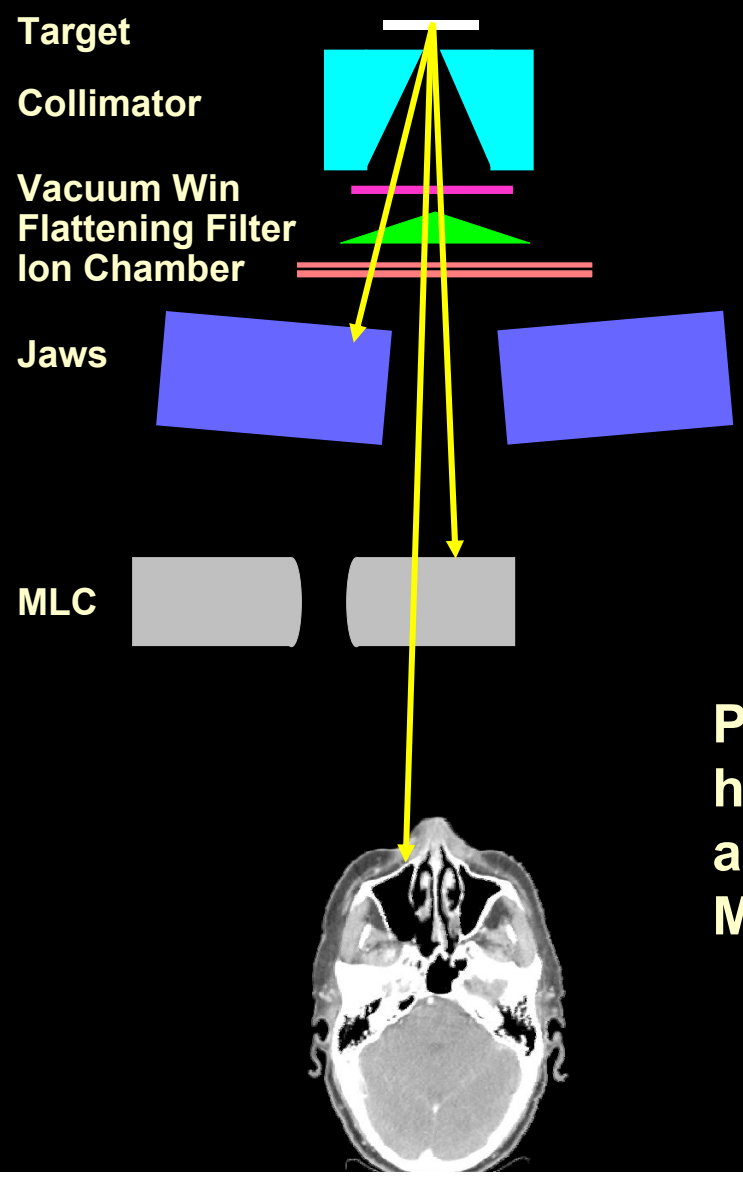
Combining Fluence Prediction and Patient Dose



MC fluence + MC Patient

MC directly transport particles through (moving) MLC

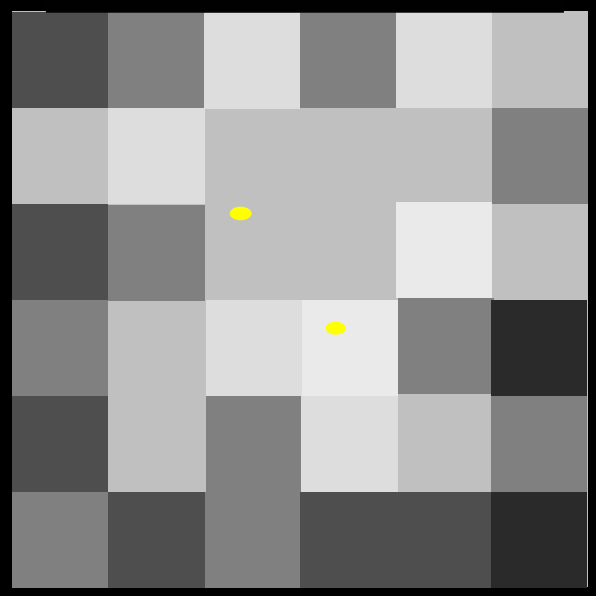


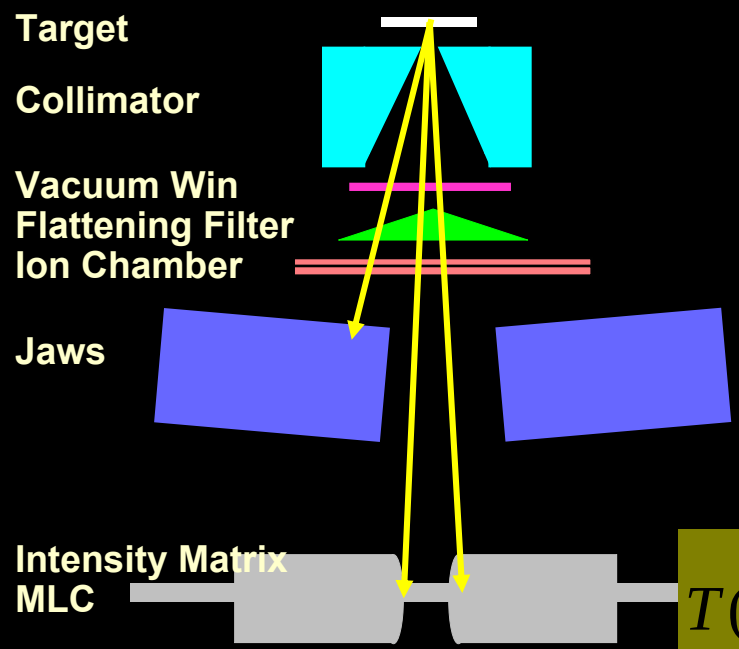
Transport particles through detailed geometry of moving MLC.

Tongue-groove, leakage, scatter, and particle energy dependent effects are inherently taken into account

Patient heterogeneities accounted for via MC

MC fluence + Analytic dose

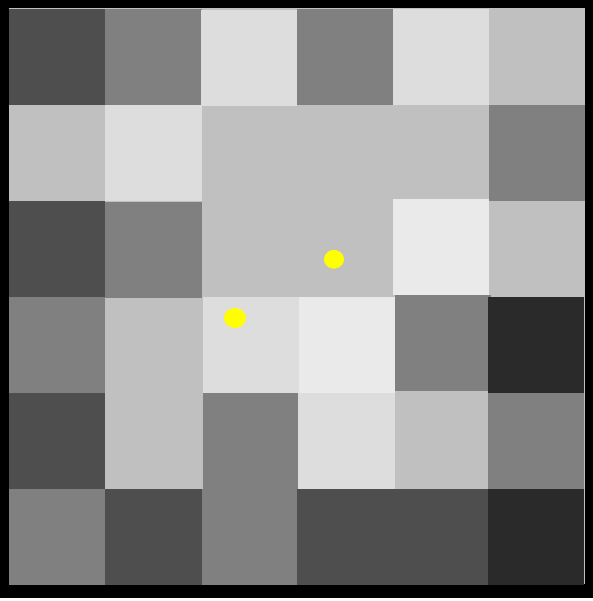


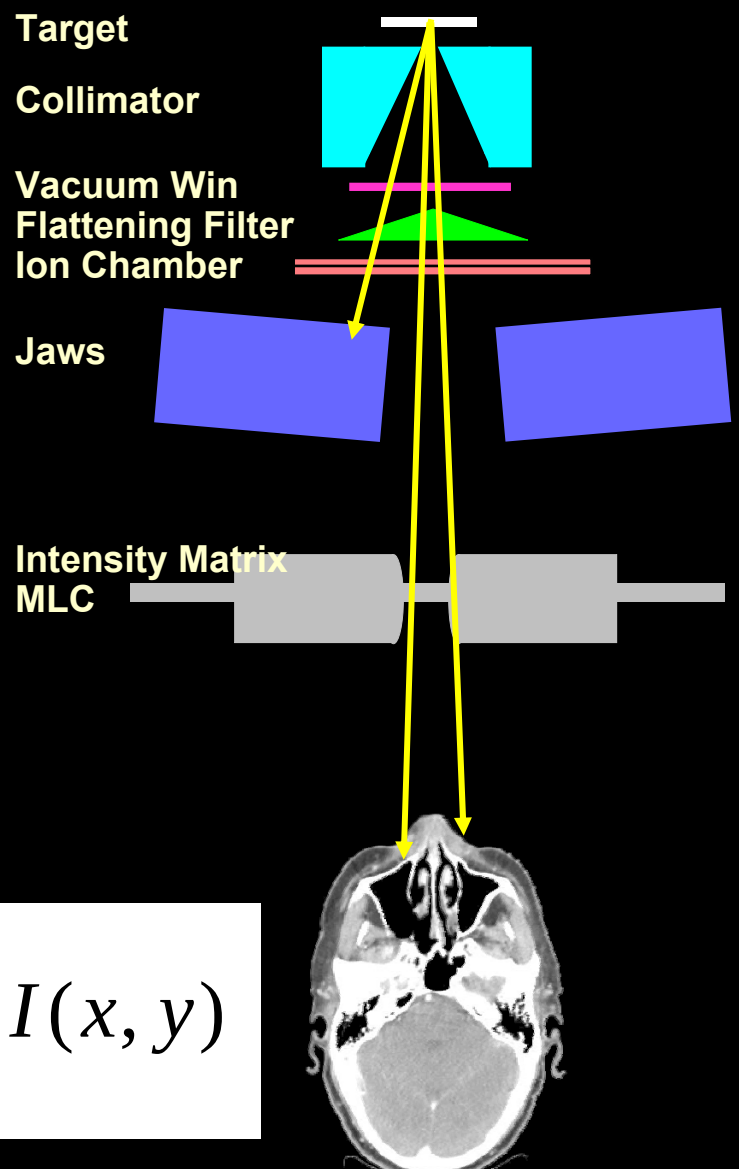


$$T(x,y) = \frac{\psi_{MLC}(x,y)}{\psi_o(x,y)}$$

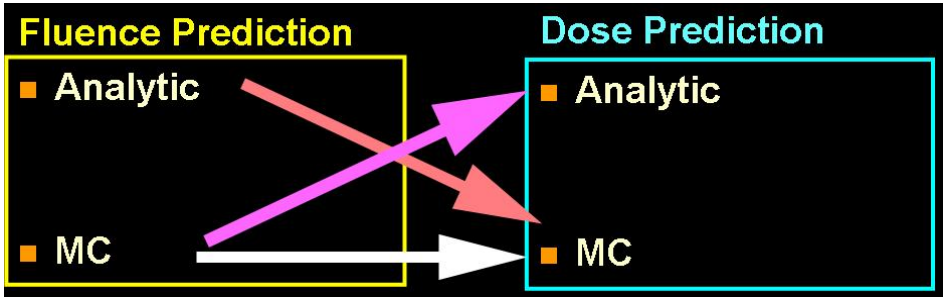
$$\psi_{MLC}(x,y) = \psi_o(x,y) \times T(x,y)$$

Analytic fluence +MC dose





$$w_f(x,y) = w_i(x,y) \times I(x,y)$$



Comparison of methods

VCU Studies

- MC-MC compared to Analytic-Analytic show ΔD>5% in 27/31 cases
  - Fluence likely cause
  - Sakthi et al., IJROBP, 64, 3, 2006
- Analytic-MC retains any dose errors from analytic fluence estimation
- MC-Analytic can effectively eliminate fluence errors. $MC_{fluence}$+Convolution dose error < 2%
  - Mihaylov et al., Med Phys, 33, 4, 2006,
  - Mihaylov et al., Med Phys, Submitted
- MC-MC
  - Effectively minimizes optimization convergence errors
  - Dogan, Med Phys, Accepted

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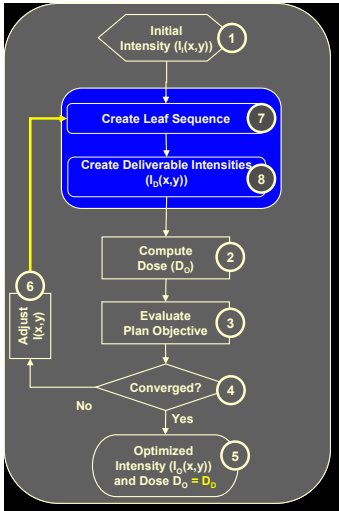

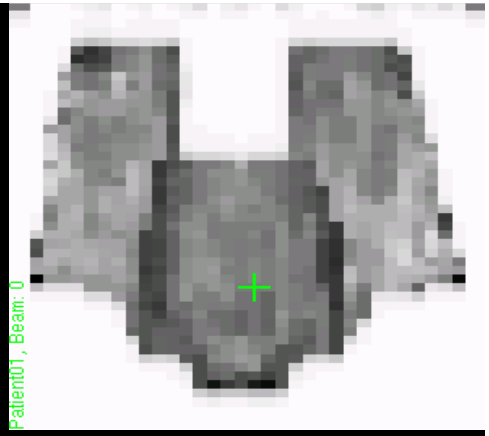

Monte Carlo in IMRT Optimization

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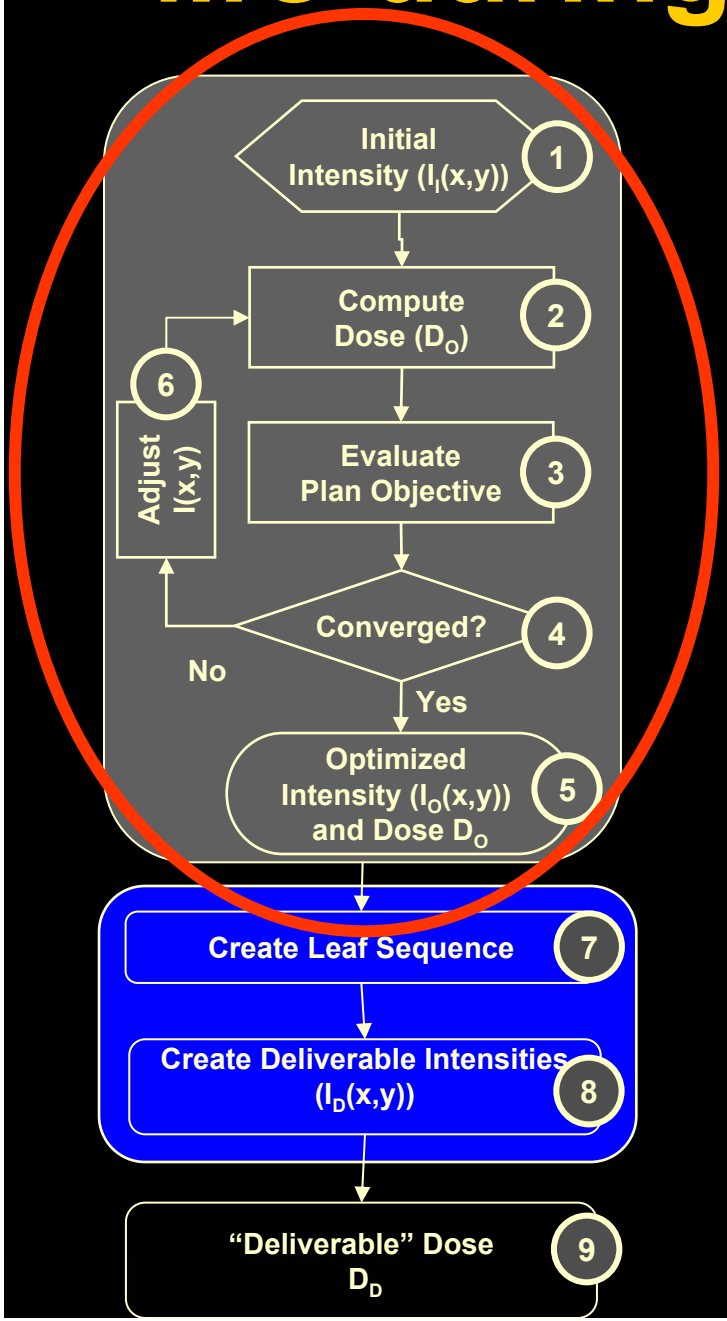
MC during IMRT optimization



- Intensity Matrix Method
- Bixel Method
- Inverse MC Optimization
  - Account for heterogeneities
  - Not include leaf effects
  - Post-optimization re-calc can include leaf effects

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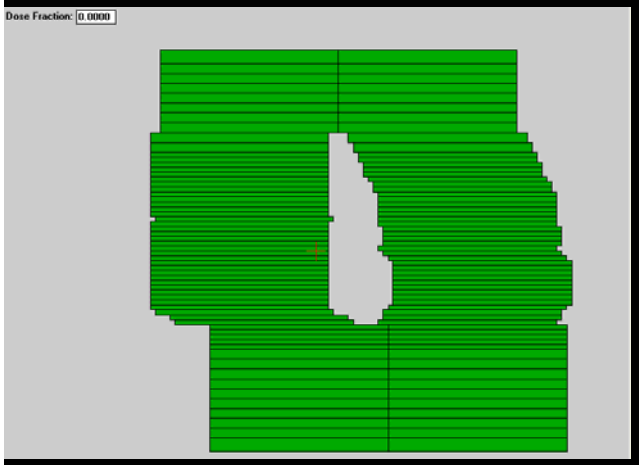
MC during IMRT optimization
Pre-optimization

- Optimization will converge in fewer iterations if a good initial guess is provided to the optimizer
- MC optimization should be preceded with pre-optimization using faster/approximate algorithms

MC during IMRT optimization

- MC computed leaf sequences (step-and-shoot segments)



- Optimize segment weights
  - Account for heterogeneities
  - Accounts for leaf effects
  - Optimization solution space limited to simulated steps

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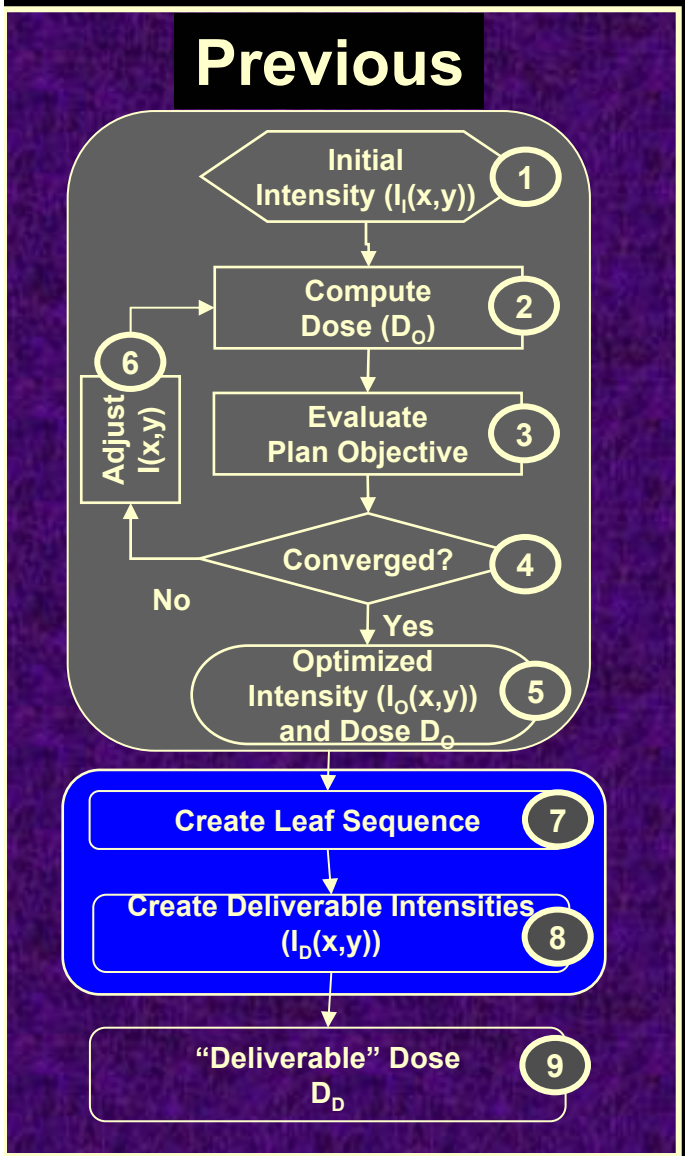
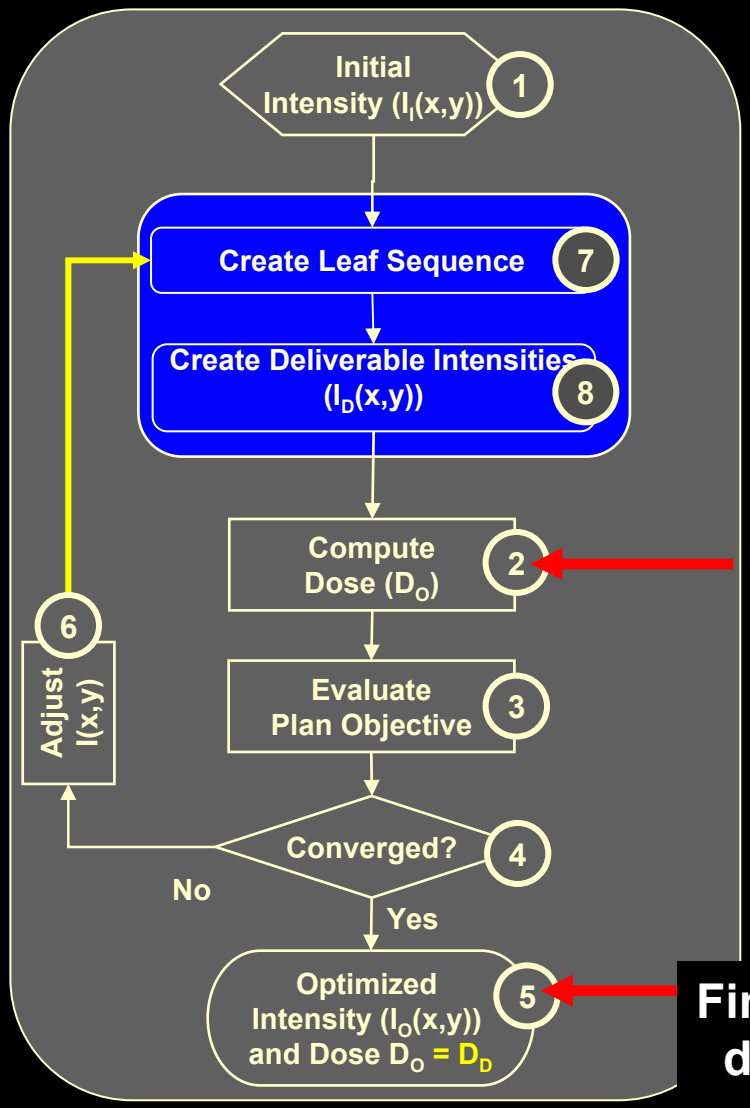
Including MLC leaf sequences into MC optimization





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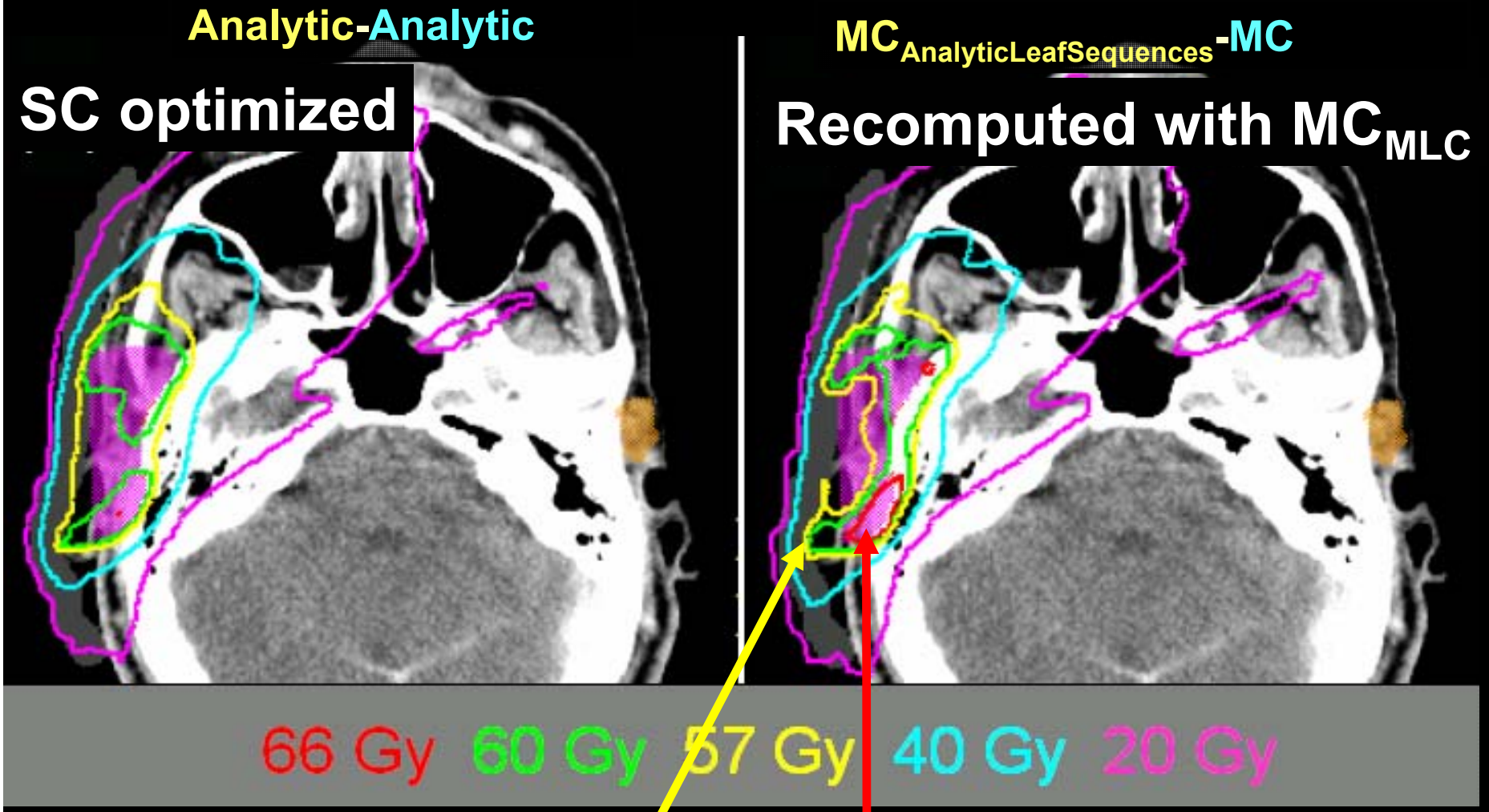
Clinical Case Comparisons

Patient Comparison

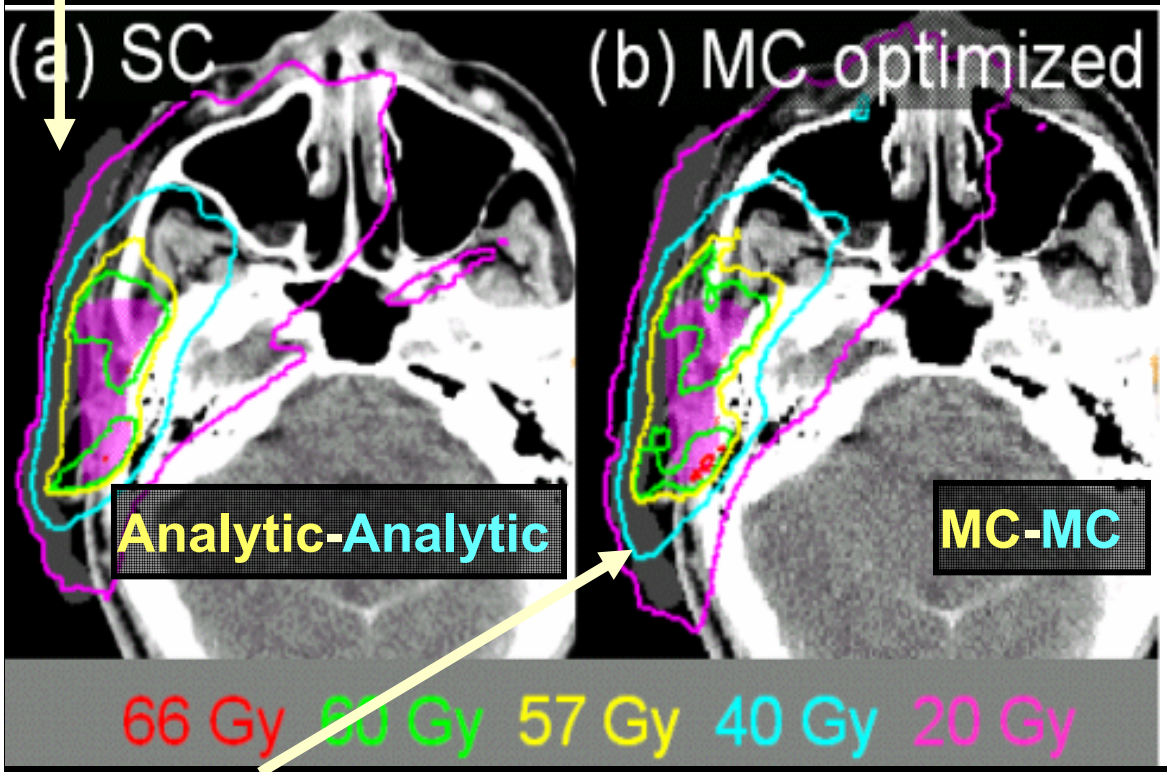


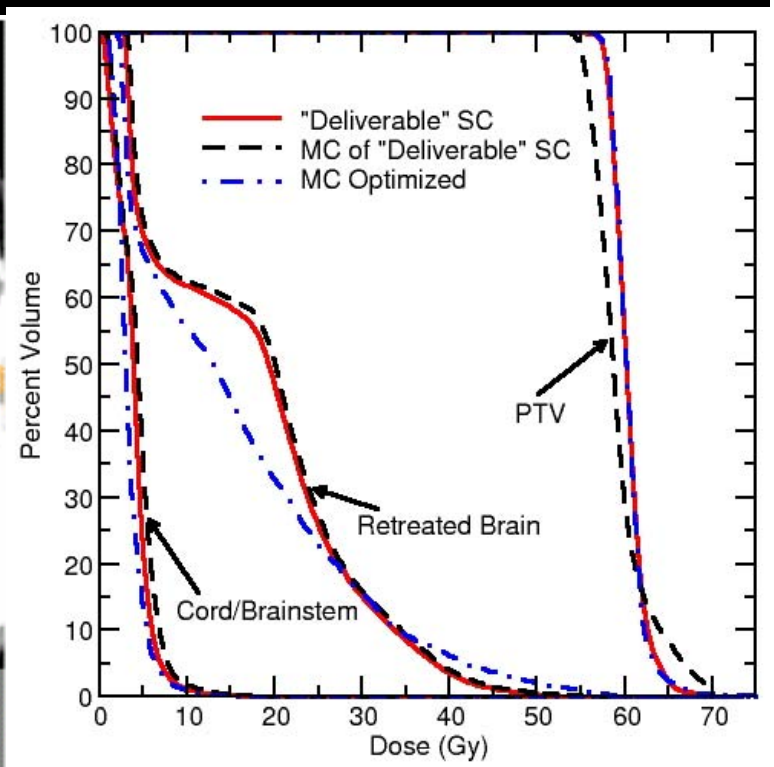
66 Gy Hot-Spot

57 Gy line not cover PTV

Optimized with MC

(a) Approved plan that did not agree with MC





(b) MC optimized plan restores target coverage

Initial desired dose distribution was achievable, but it required different intensities / leaf sequences than predicted by SC to be achieved in the patient

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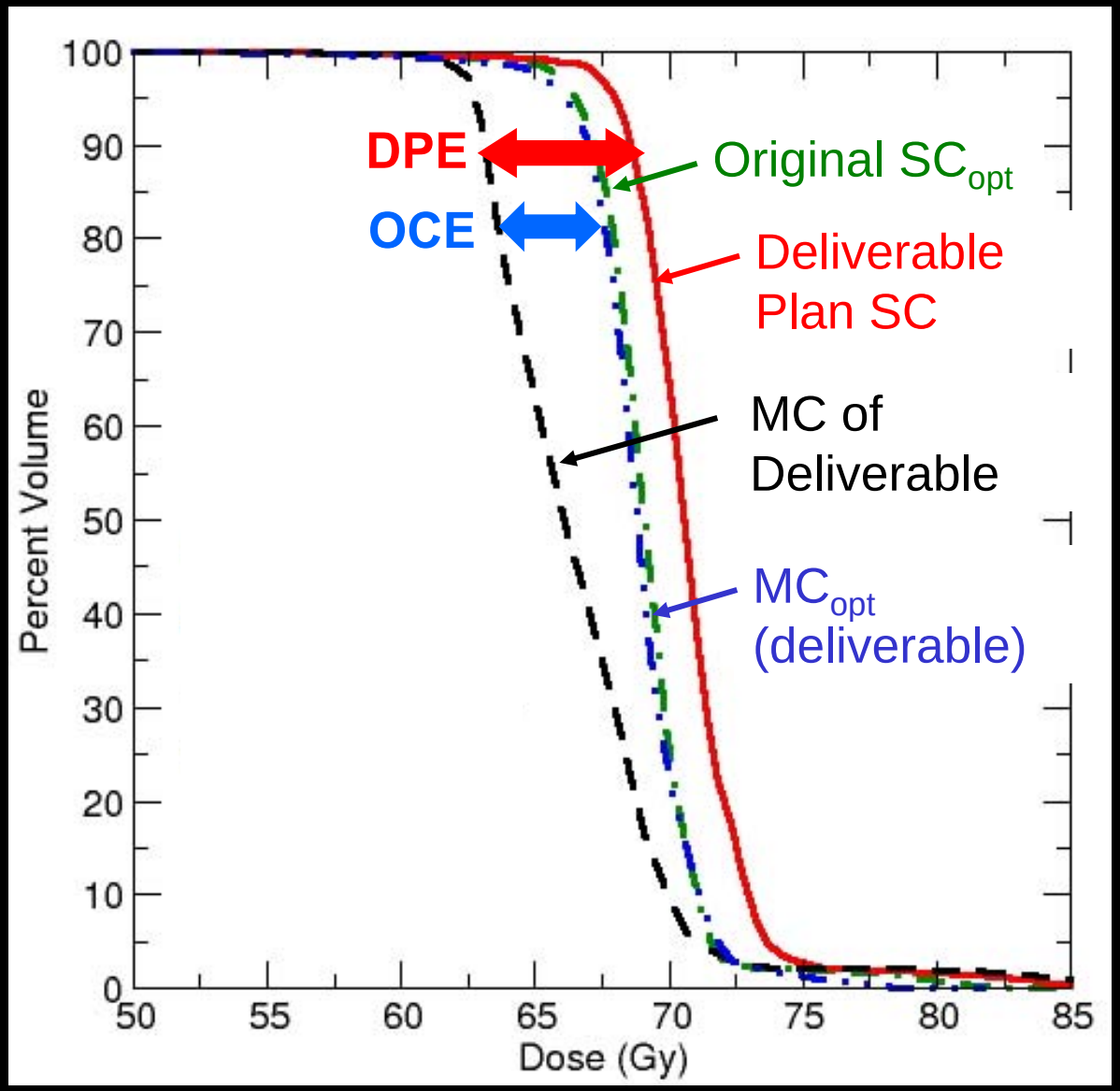
MC to reduce errors



Head and Neck IMRT plan

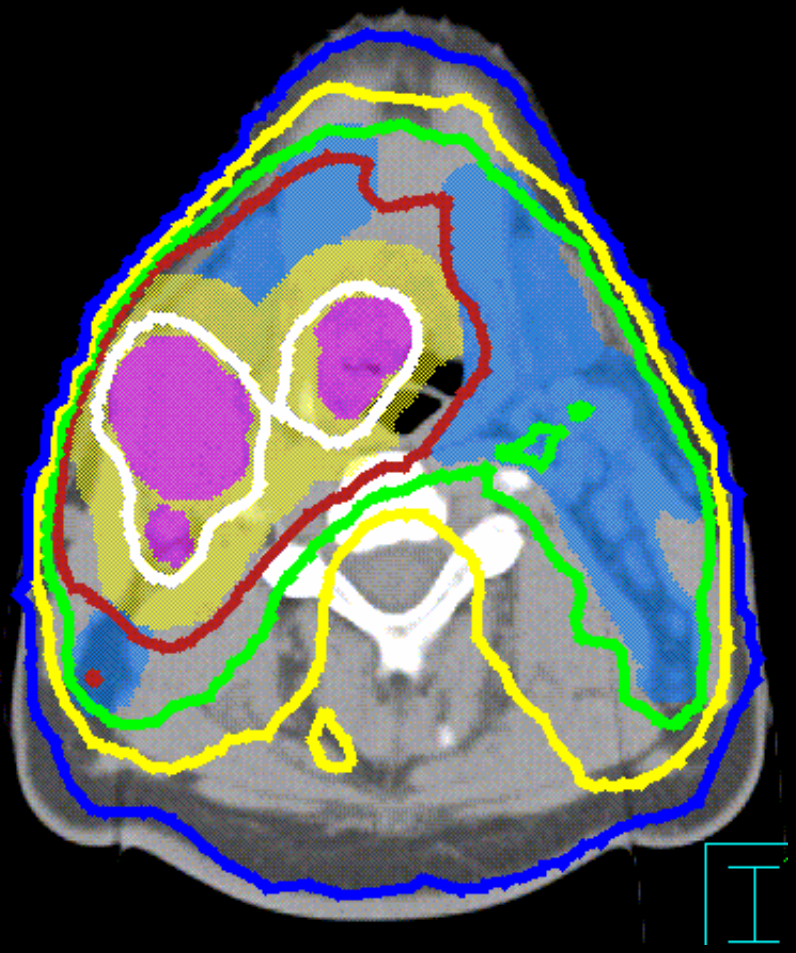
MC deliverable optimization can restore original optimized plan

DPE = Dose Prediction Error **OCE = Optimization Convergence Error**

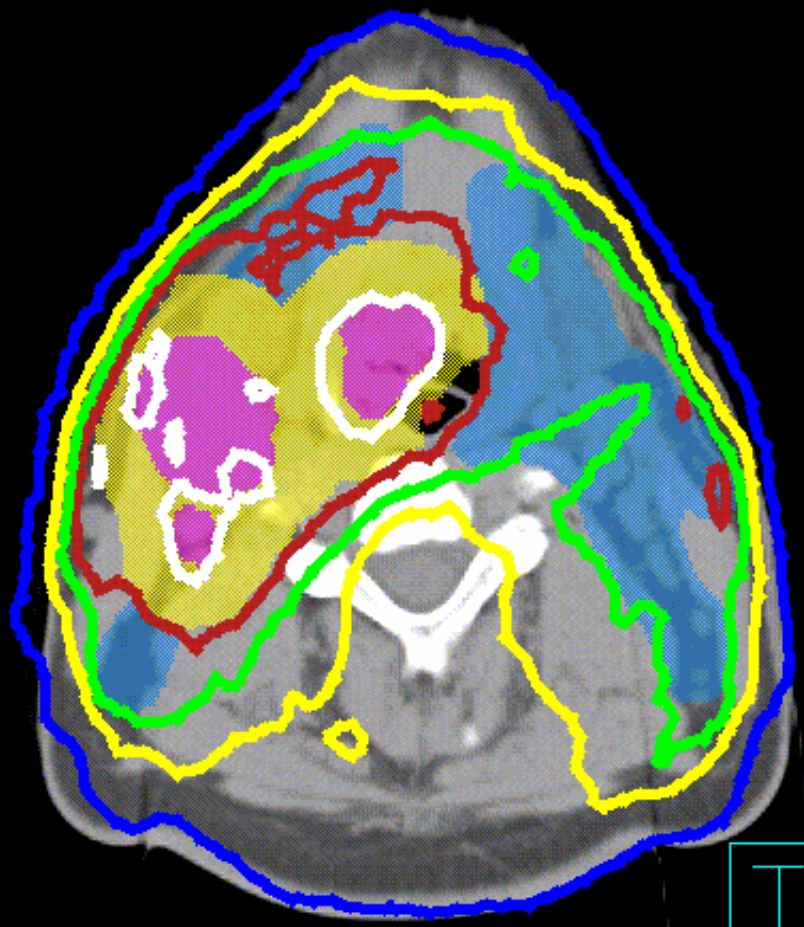
MC Verification

(Dose Prediction Error Evaluator)

Original SC optimization



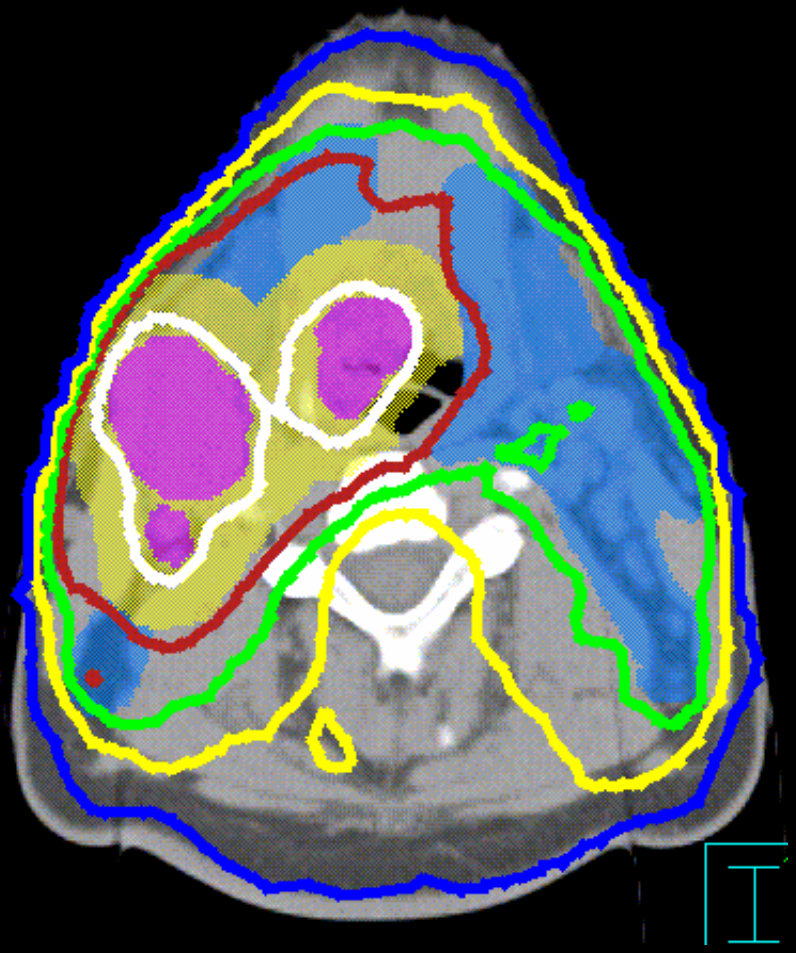
MC re-calculation of SC plan



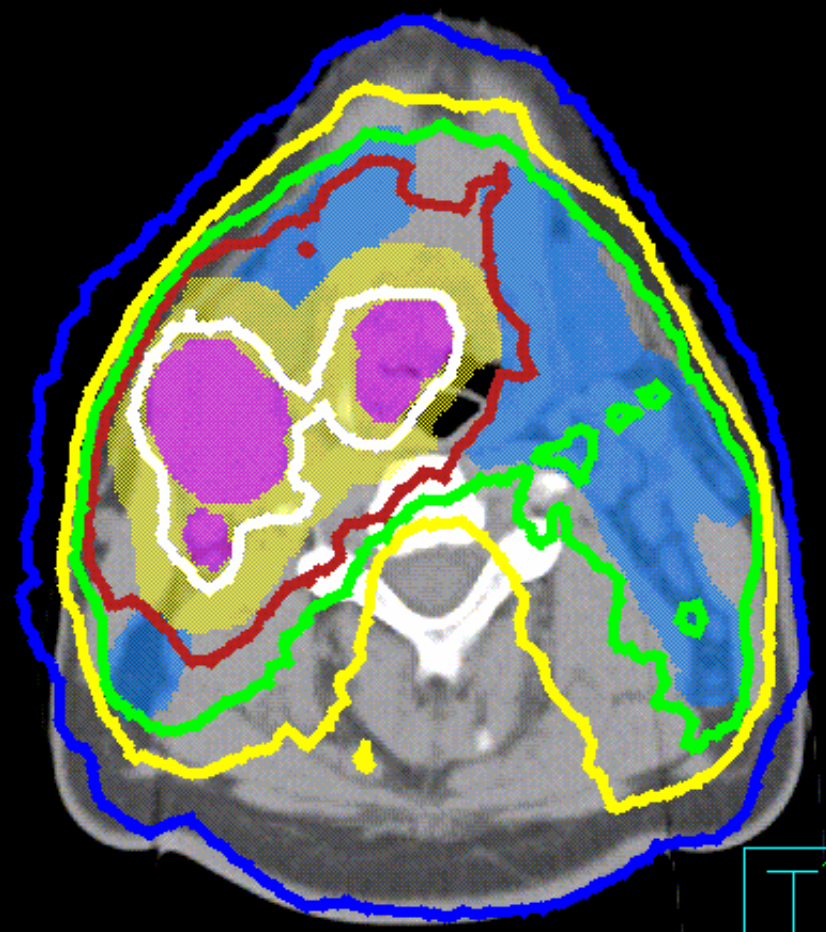
68.1 Gy, 60.0 Gy, 54.0 Gy, 45.0 Gy, 30.0 Gy

MC Optimization

Original SC optimization

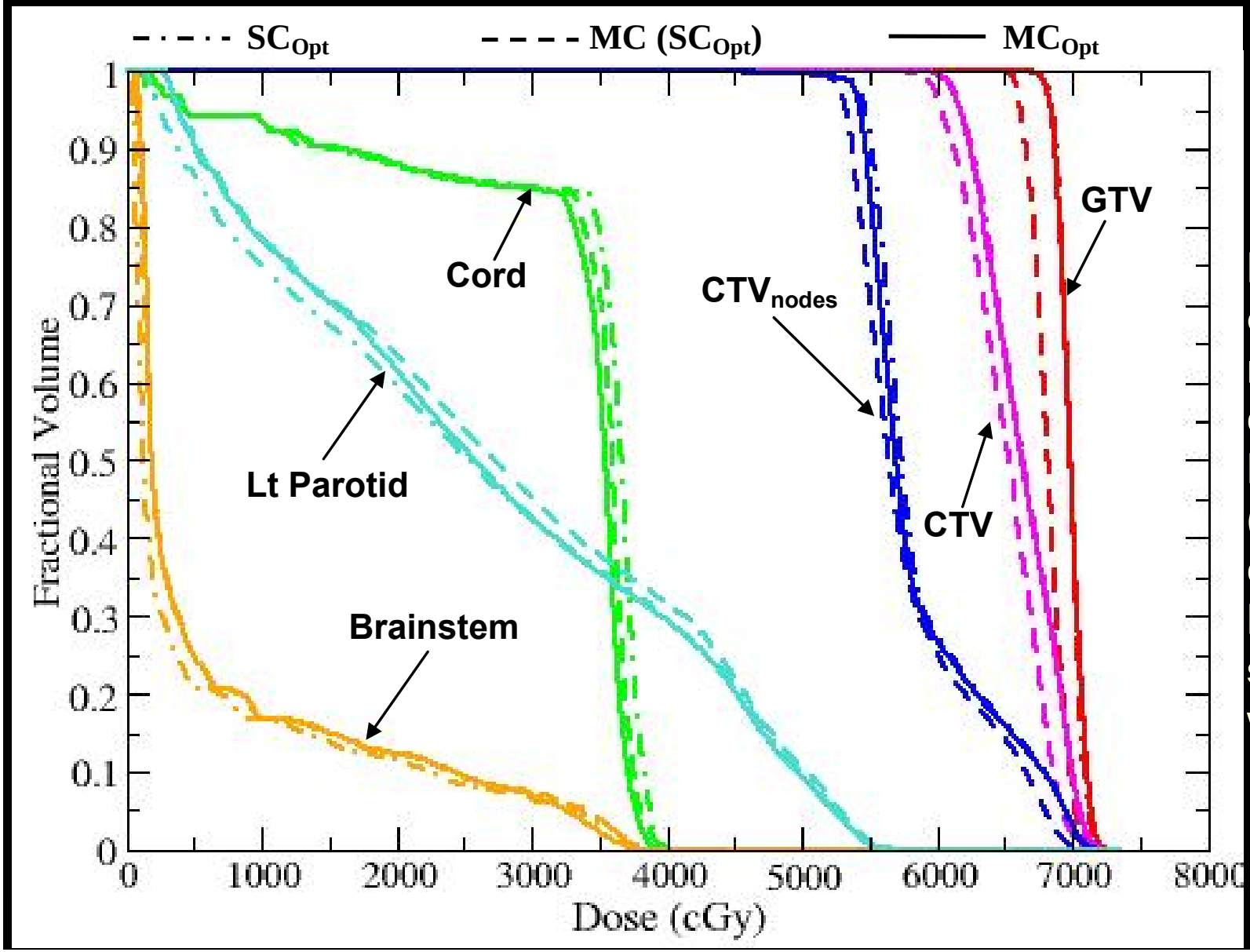


MC optimization



68.1 Gy, 60.0 Gy, 54.0 Gy, 45.0 Gy, 30.0 Gy

H&N Patient



MC optimization restores desired DVHs (requires different MLC segments / weights)

Dose Prediction Error

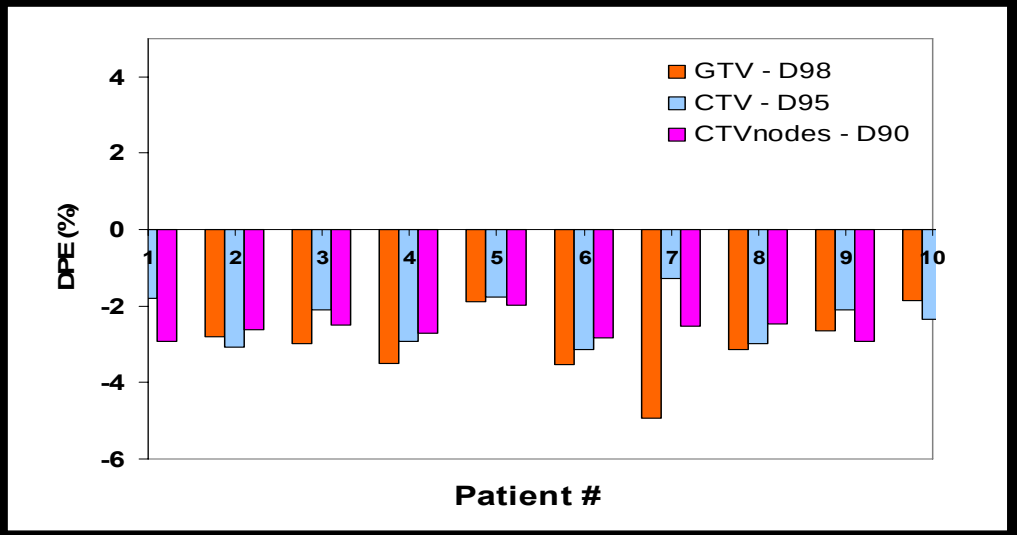
Difference between planned and delivered

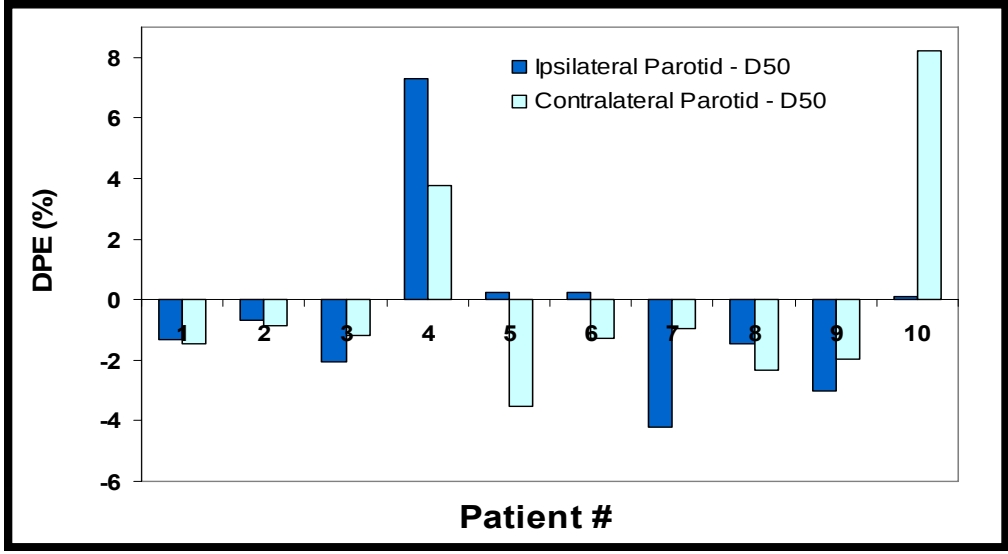
10 H&N cases

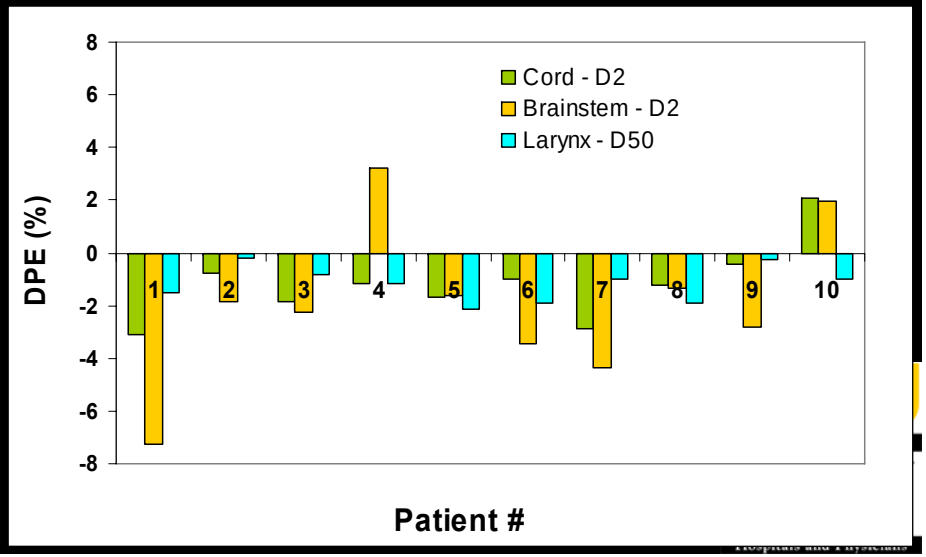
SC_{opt}: SC optimized

$MC(SC_{opt})$: MC recalculated

$DPE = MC(SC_{opt}) - SC_{opt}$







Optimization Convergence Error

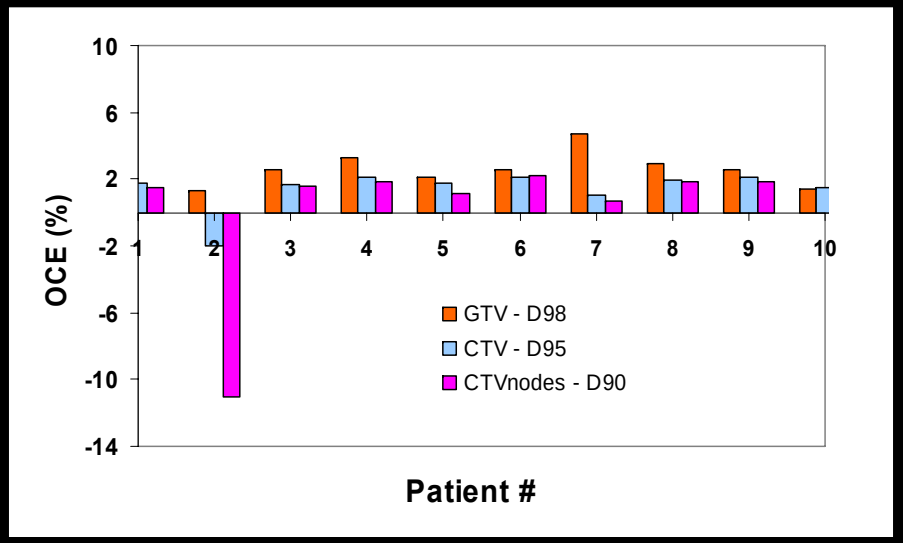
Difference between Deliverable SC optimized and MC optimized

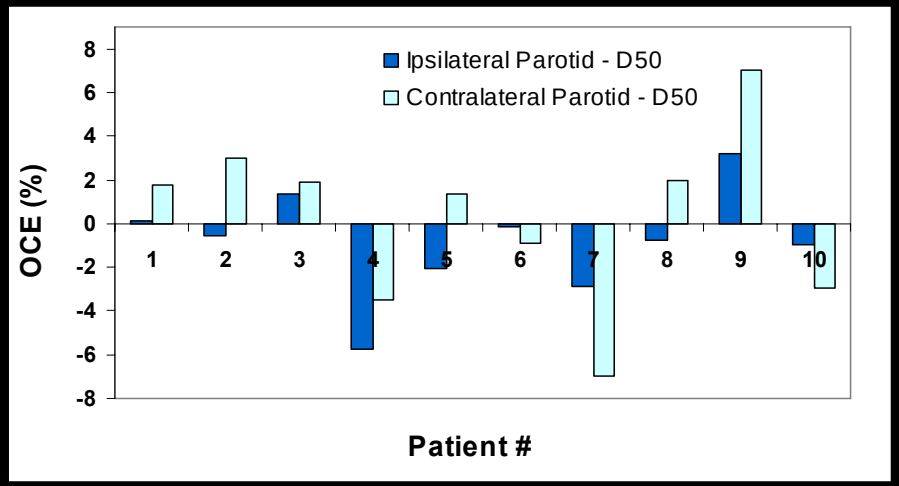
10 H&N Cases

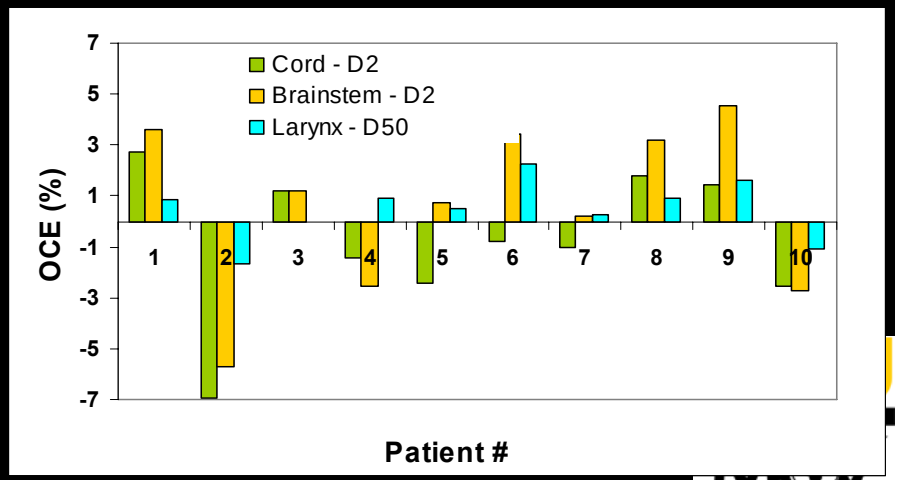
$MC(SC_{opt})$: SC optimized, MC-recalcuated

MC_{opt} : MC optimized

$OCE = MC_{opt} - MC(SC_{opt})$







Pitfalls of MC optimization

- Bixels
  - Per-bixel dose computation time
  - ...
- Full-field
  - Multiple (time consuming) dose iterations

Full field solution: Hybrid Algorithms

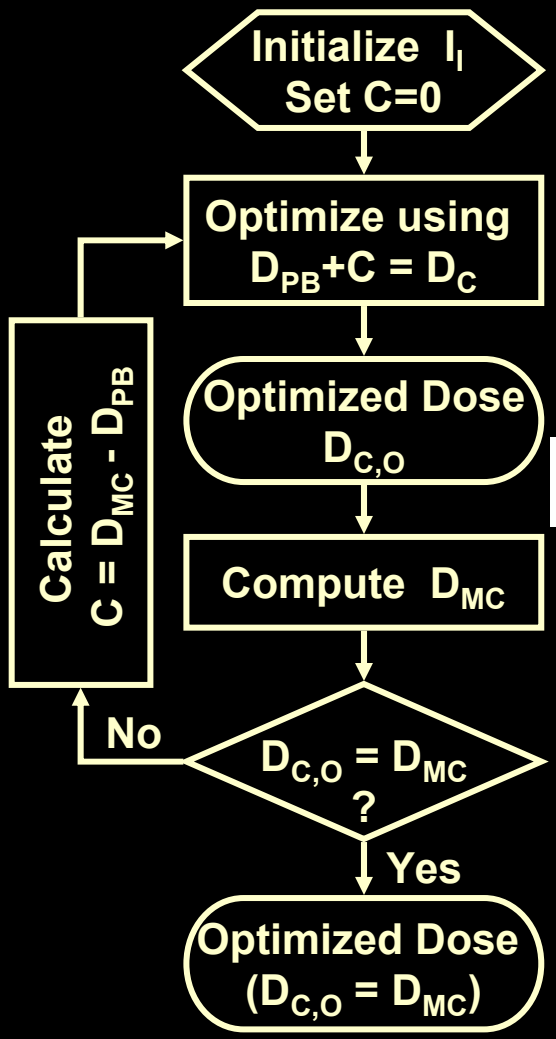
- Combining or mixing of different dose calculation algorithms
  - Pencil beam or Convolution + MC
- Useful for <u>iterative</u> IMRT calculation

Objectives of hybrid algorithms?

- Decrease (wall clock) time required to do plan optimization
- Final optimized result as good as if accurate algorithm used for all iterations

Hybrid Dose Calc Methods

Correction Method



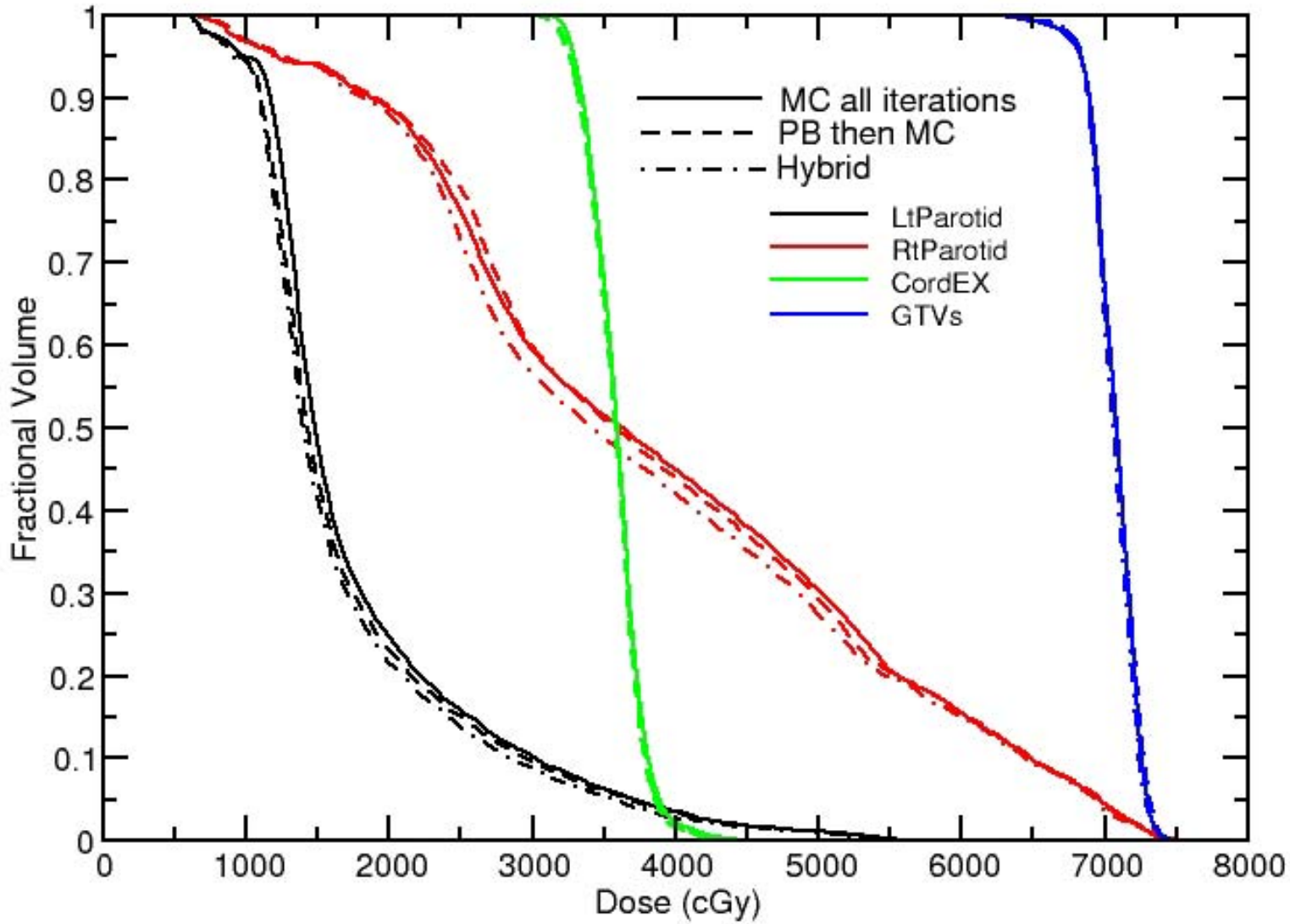
$$I_n = I_{C_{MC}} + \Delta I_n$$

$$D_C = \left(T_{I_n} \otimes K\right) + C = \left(T_{I_{C_{MC}}} \otimes K\right) + \left(T_{\Delta I_n} \otimes K\right) + C = D_{MC} + \left(T_{\Delta I_n} \otimes K\right).$$

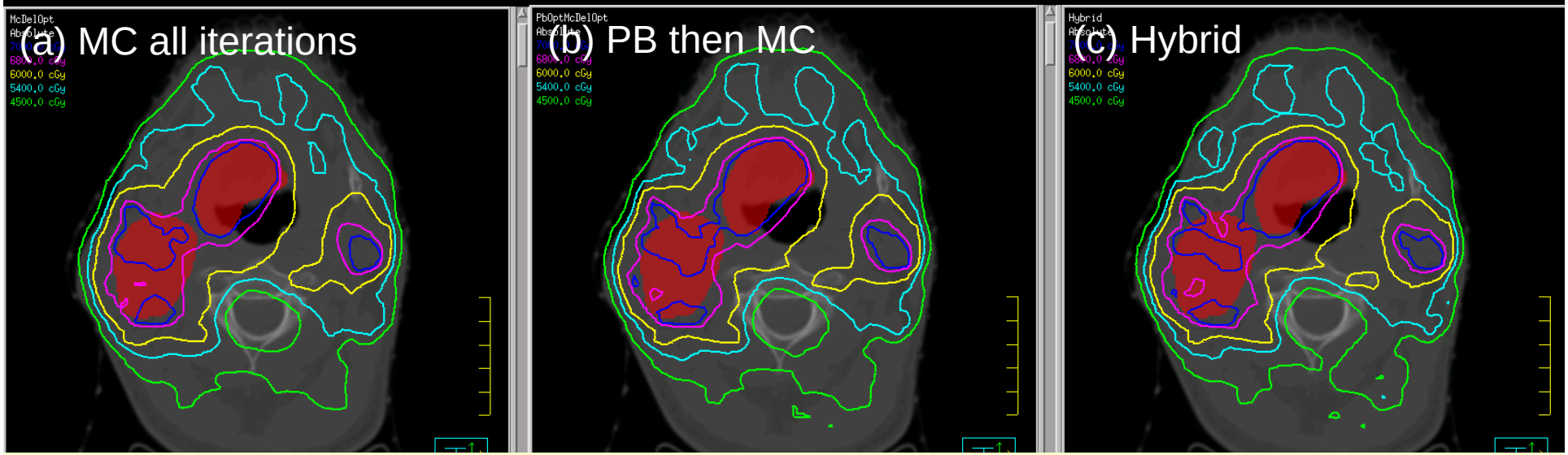
$$(\Delta I_n \rightarrow 0),\ D_C \rightarrow D_{MC}$$

Hybrid Optimization

Final DVH Results Agree



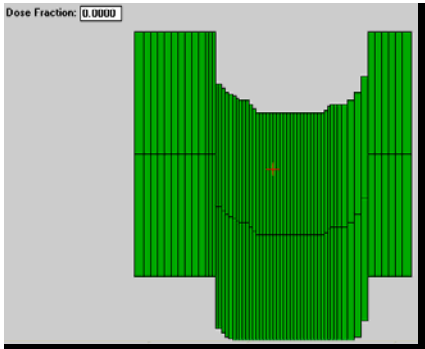
Hybrid Optimization



70 Gy 68 Gy 60 Gy 54 Gy 45 Gy

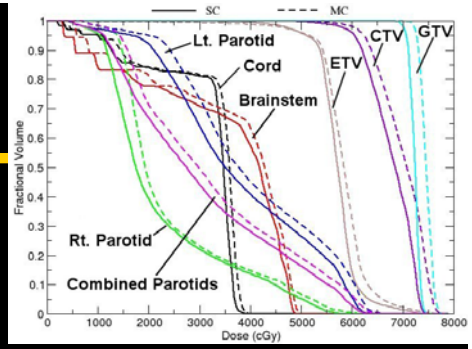
- **Hybrid methods yield same results as pure MC optimization, but only require 2-3 MC iterations.**

VCU Health System
MCV Hospitals and Physicians



Conclusions

MC applications in IMRT



- MC suitable for IMRT ….radiation dis-equilibrium
- MC can account for heterogeneities and/or fluence prediction errors
- MC fluence predictions are more accurate since it inherently includes MLC effects
- MC fluence predictors may improve conventional dose calculation accuracy
- MC optimization reduces optimization convergence errors
- Hybrid MC algorithms will make MC optimization practical
- MC is not currently used for IMRT outside of research centers, but should be in the future to minimize convergence errors