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

3DCRT

IMRT

Intensity

Dose
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
MC for Fluence Prediction

Direct particle transport

- Simulate individual particles through MLC
- Geometric details can be 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)
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

\[ \frac{W_f}{N} = \frac{W_i}{N} \sum_{k=1}^{N} e^{-\mu(E)t_k / \cos \theta_z} \]

Determine mean weight by sampling at multiple random “times”.
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

![Graph showing dose distribution for 18 MV and 6 MV with measured and calculated data.](image)
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

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 \(~1\times1\, \text{cm}^2\) 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
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)
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)
Combining Fluence Prediction and Patient Dose

Fluence Prediction
- Analytic
- MC

Dose Prediction
- Analytic
- MC
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.
$\psi_{MLC}(x, y) = \psi_o(x, y) \times T(x, y)$
$w_f(x, y) = w_i(x, y) \times I(x, y)$
MC-MC compared to Analytic-Analytic show $\Delta D > 5\%$ 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. $MC_{\text{fluence}} + \text{Convolution dose error} < 2\%$
- 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
Monte Carlo in IMRT Optimization
**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
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
Including MLC leaf sequences into MC optimization

1. Initial Intensity \( I(x,y) \)
2. Compute Dose \( D_0 \)
3. Evaluate Plan Objective
4. Converged?
5. Adjust \( I(x,y) \)
6. Create Leaf Sequence
7. Create Deliverable Intensities \( I_0(x,y) \)
8. Compute Dose \( D_0 \)
9. "Deliverable" Dose \( D_0 \)

Final dose is deliverable
Clinical Case Comparisons
Patient Comparison

SC optimized

Recomputed with MC

66 Gy Hot-Spot
57 Gy line not cover PTV

66 Gy  60 Gy  57 Gy  40 Gy  20 Gy
(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.
MC to reduce errors

Head and Neck IMRT 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-recalculated

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 iterative 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

Initialize $I_i$
Set $C=0$

Optimize using $D_{PB} + C = D_C$

Optimized Dose $D_{C,O}$

Calculate $C = D_{MC} - D_{PB}$

Compute $D_{MC}$

No

$D_{C,O} = D_{MC}$?

Yes

Optimized Dose $(D_{C,O} = D_{MC})$

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

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

$(\Delta I_n \rightarrow 0), \ D_C \rightarrow D_{MC}$
Hybrid Optimization
Final DVH Results Agree
Hybrid Optimization

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