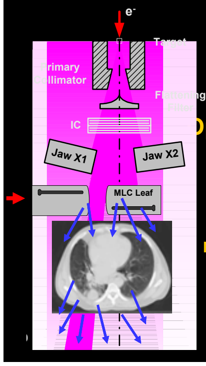
VCU The Department of Radiation Oncology



Monte Carlo II Planning: Applications in IMRT QA, IMRT Optimization, Motion Compensation, and 4D Dose Calculation

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Medical College of Virginia Hospitals
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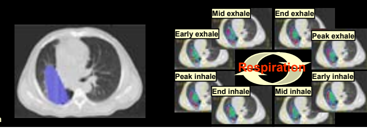
Objectives

- To understand methods and role of MC for
  - IMRT dose calculation
  - Patient-specific IMRT QA
  - IMRT optimization
  - 4D dose calculation



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What is new

- Vendors are showing IMRT specific IMRT products
  - CMS : Monoco
  - Elekta
- MC optimized plans are being achieved in <30 minutes
- MC is being applied to fluence prediction with conventional algorithms for patient dose calculation

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Justification of Monte Carlo for IMRT

- IMRT is so complex, patient specific QA is mandated
  - Planning dose prediction
  - Information transfer
  - Device delivery
- Conventional dose algorithms can be inaccurate for
  - Small fields
  - Regions of dose gradients (radiation disequilibrium)
  - Heterogeneous conditions
- If algorithm was always accurate, there would be no need for per-patient algorithm QA

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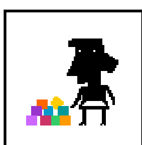

Dose Calculation Basics

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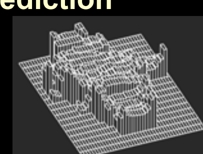
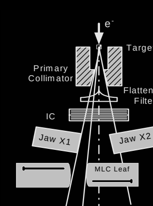
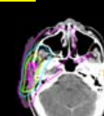
Dose Calculation is a Two Step Process

- Incident fluence prediction





- Energy deposition in the patient/phantom



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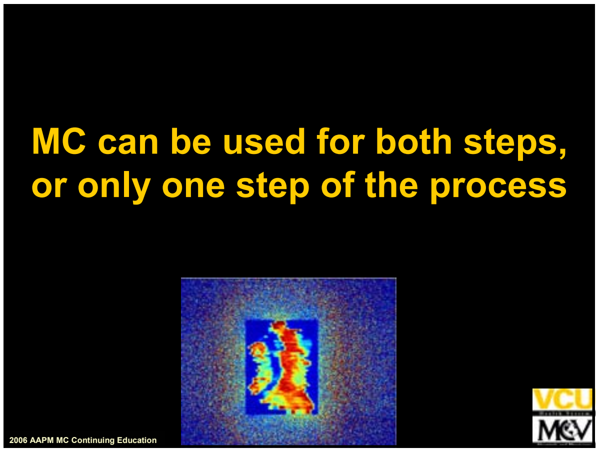
MC can be used for both steps, or only one step of the process
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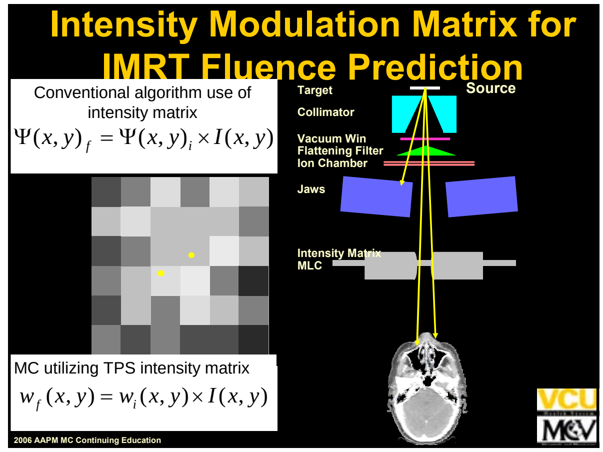
Intensity Modulation Matrix for IMRT Fluence Prediction
Conventional algorithm use of intensity matrix
$\Psi(x,y)_f = \Psi(x,y)_i \times I(x,y)$
Target
Collimator
Vacuum Win
Flattening Filter
Ion Chamber
Jaws
Source
Intensity Matrix
MLC
MC utilizing TPS intensity matrix
$w_f(x,y) = w_i(x,y) \times I(x,y)$
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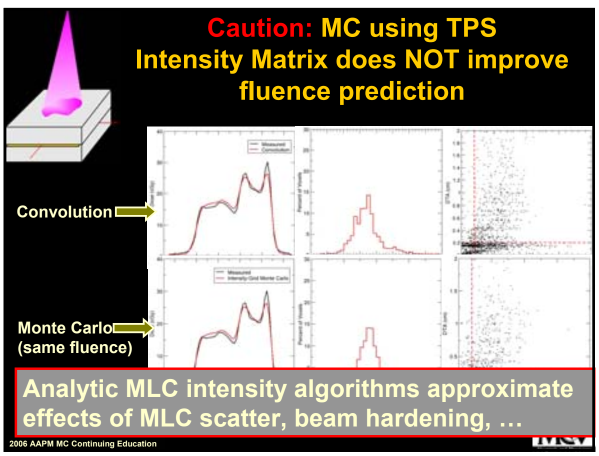
Caution: MC using TPS Intensity Matrix does NOT improve fluence prediction
Convolution
Monte Carlo
(same fluence)
Analytic MLC intensity algorithms approximate effects of MLC scatter, beam hardening, …
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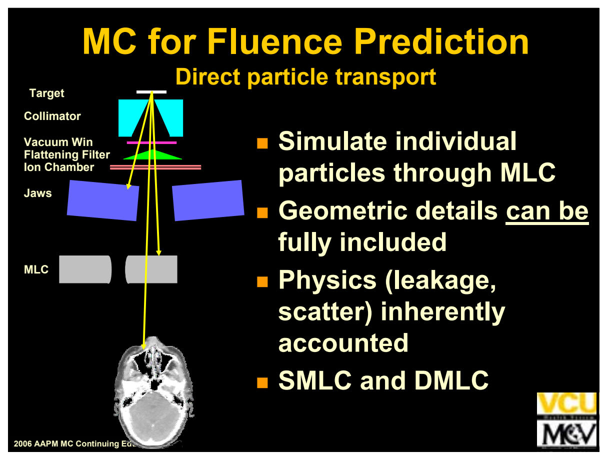
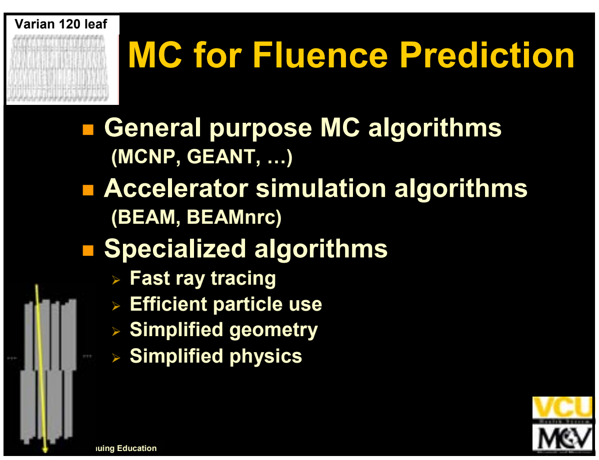
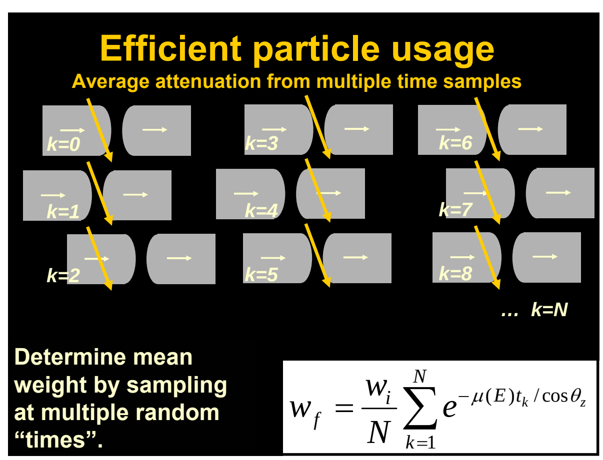

MC for Fluence Prediction
Direct particle transport
Target
Collimator
Vacuum Win
Flattening Filter
Ion Chamber
Jaws
MLC
Simulate individual particles through MLC
Geometric details can be fully included
Physics (leakage, scatter) inherently accounted
SMLC and DMLC


Varian 120 leaf
MC for Fluence Prediction
General purpose MC algorithms
(MCNP, GEANT, …)
Accelerator simulation algorithms
(BEAM, BEAMnrc)
Specialized algorithms
Fast ray tracing
Efficient particle use
Simplified geometry
Simplified physics


Efficient particle usage
Average attenuation from multiple time samples
k=0
k=1
k=2
k=3
k=4
k=5
k=6
k=7
k=8
… k=N
Determine mean weight by sampling at multiple random "times".
$w_f = \frac{w_i}{N} \sum_{k=1}^{N} e^{-\mu(E) t_k / \cos\theta_z}$

Methods for MC For Patient Dose Prediction

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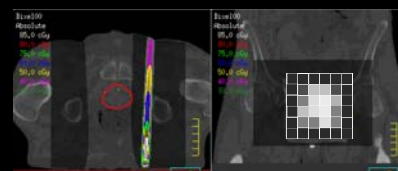
MC for patient dose prediction
Bixel based MC calculations

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



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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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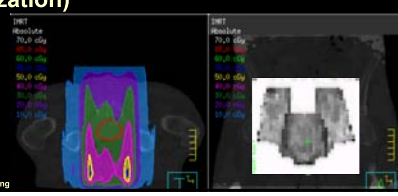
MC for patient dose prediction
Field-based dose calculation

- 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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MC for patient dose prediction
Field-based dose calculation

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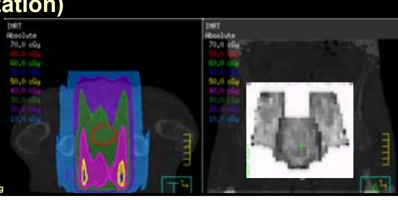

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MC for patient specific IMRT QA

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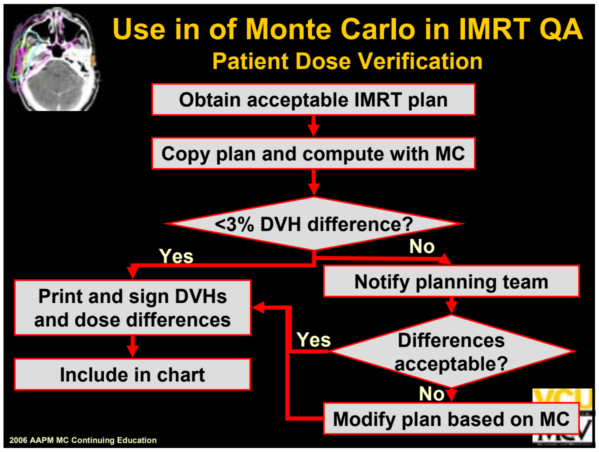
Use in of Monte Carlo in IMRT QA
Patient Dose Verification
Obtain acceptable IMRT plan
Copy plan and compute with MC
<3% DVH difference?
Yes
No
Print and sign DVHs and dose differences
Notify planning team
Include in chart
Yes
Differences acceptable?
No
Modify plan based on MC
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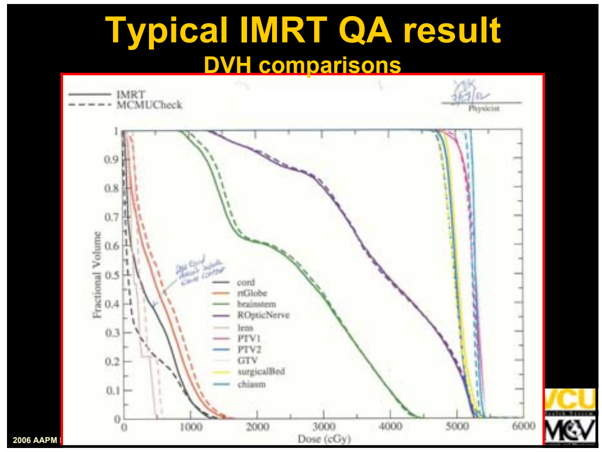
Typical IMRT QA result
DVH comparisons
IMRT
MCMUCheck
Fractional Volume
Dose (cGy)
cord
rtGlobe
brainstem
ROpticNerve
lens
PTV1
PTV2
GTV
surgicalBed
chiasm
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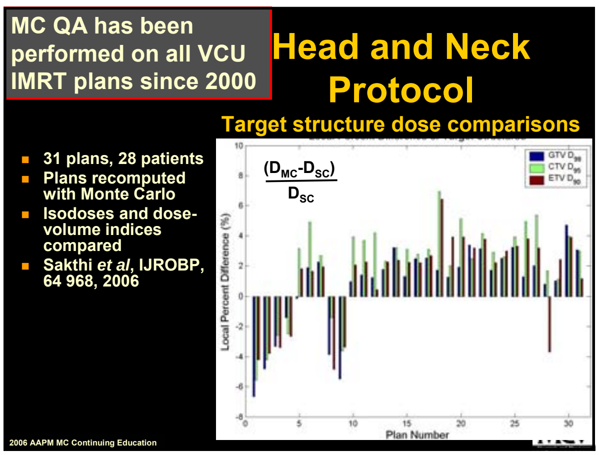
MC QA has been performed on all VCU IMRT plans since 2000
Head and Neck Protocol
Target structure dose comparisons
31 plans, 28 patients
Plans recomputed with Monte Carlo
Isodoses and dose-volume indices compared
Sakthi et al, IJROBP, 64 968, 2006
(D_MC-D_SC) / D_SC
Local Percent Difference (%)
Plan Number
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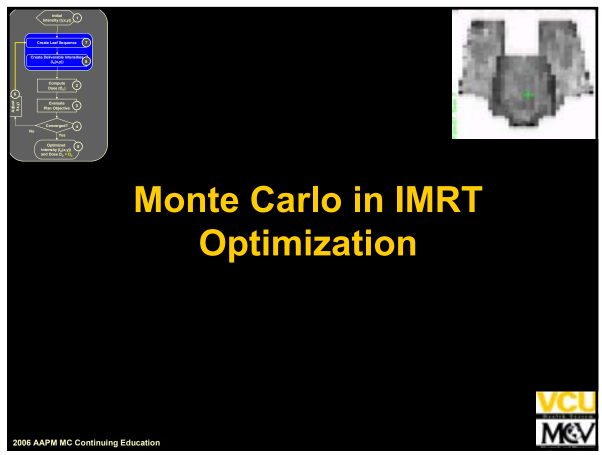
Monte Carlo in IMRT Optimization
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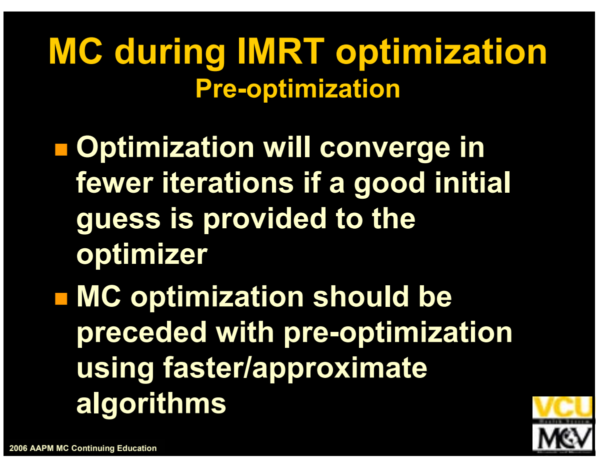
MC during IMRT optimization
Pre-optimization
Optimization will converge in fewer iterations if a good initial guess is provided to the optimizer
MC optimization should be preceded with pre-optimization using faster/approximate algorithms
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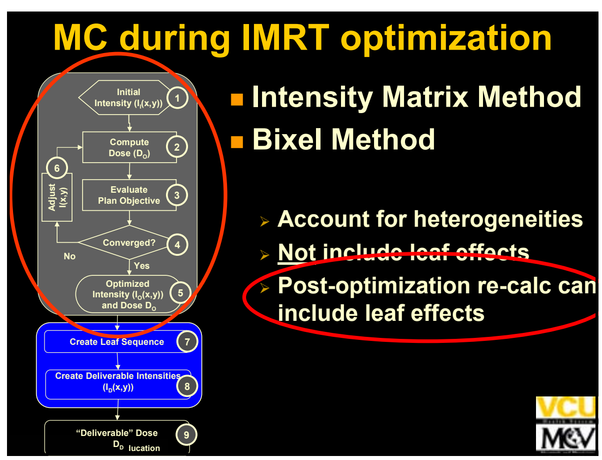
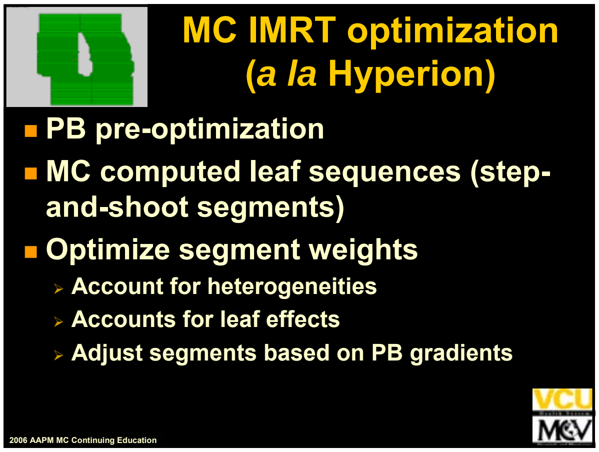

MC during IMRT optimization
Intensity Matrix Method
Bixel Method
Account for heterogeneities
Not include leaf effects
Post-optimization re-calc can include leaf effects
Initial Intensity (I_i(x,y))
Compute Dose (D_o)
Evaluate Plan Objective
Converged?
Optimized Intensity (I_o(x,y)) and Dose D_o
Adjust I(x,y)
No
Yes
Create Leaf Sequence
Create Deliverable Intensities (I_D(x,y))
"Deliverable" Dose D_D


MC IMRT optimization
(a la Hyperion)
PB pre-optimization
MC computed leaf sequences (step-and-shoot segments)
Optimize segment weights
Account for heterogeneities
Accounts for leaf effects
Adjust segments based on PB gradients
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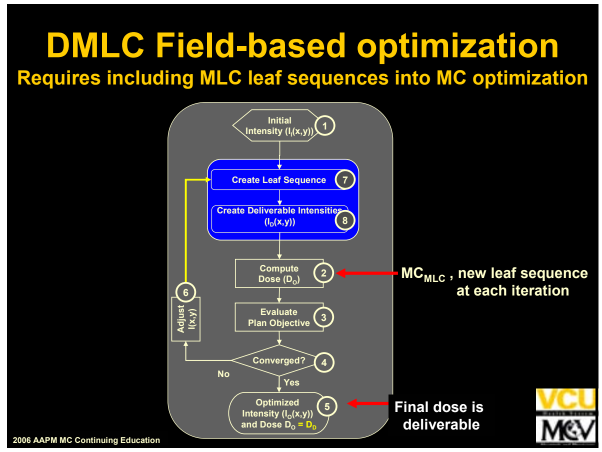
DMLC Field-based optimization
Requires including MLC leaf sequences into MC optimization
Initial Intensity (I_i(x,y))
Create Leaf Sequence
Create Deliverable Intensities (I_D(x,y))
Compute Dose (D_D)
Evaluate Plan Objective
Converged?
No
Yes
Adjust I(x,y)
Optimized Intensity (I_D(x,y)) and Dose D_D = D_D
MC_MLC , new leaf sequence at each iteration
Final dose is deliverable
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Clinical Case Comparisons
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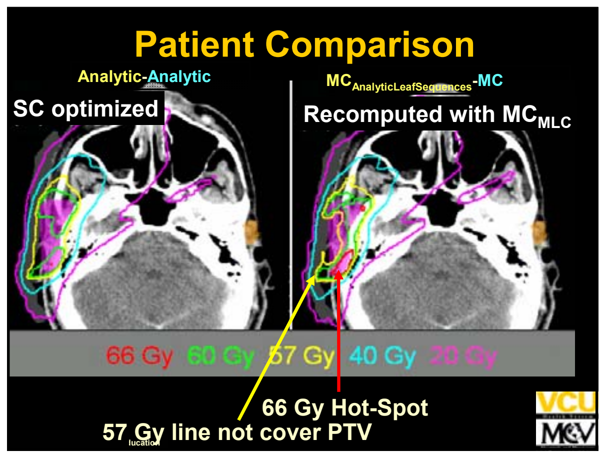
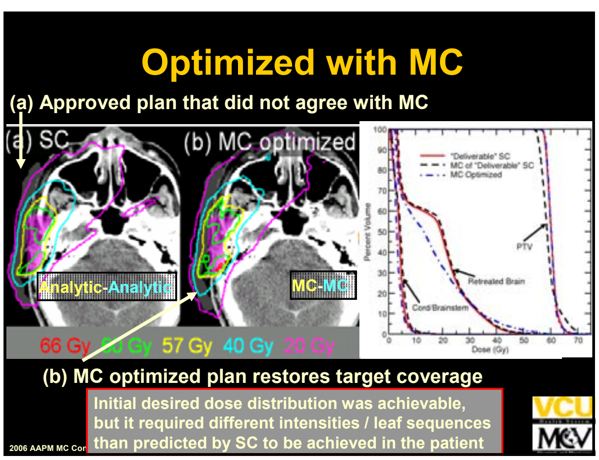

Patient Comparison
Analytic-Analytic
MC_AnalyticLeafSequences-MC
SC optimized
Recomputed with MC_MLC
66 Gy 60 Gy 57 Gy 40 Gy 20 Gy
66 Gy Hot-Spot
57 Gy line not cover PTV


Optimized with MC
(a) Approved plan that did not agree with MC
(a) SC
(b) MC optimized
Analytic-Analytic
MC-MC
66 Gy 60 Gy 57 Gy 40 Gy 20 Gy
"Deliverable" SC
MC of "Deliverable" SC
MC Optimized
PTV
Retreated Brain
Cord/Brainstem
Percent Volume
Dose (Gy)
(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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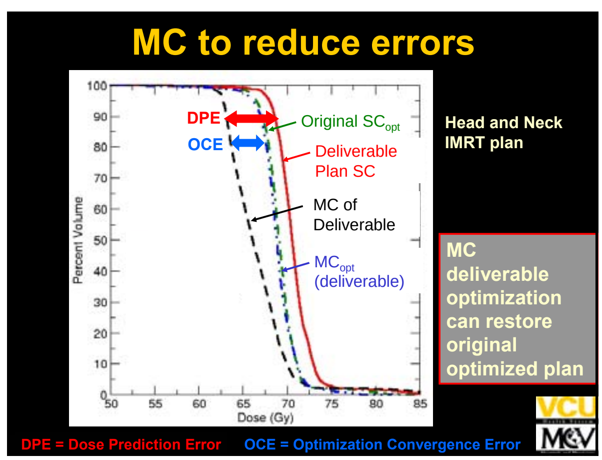
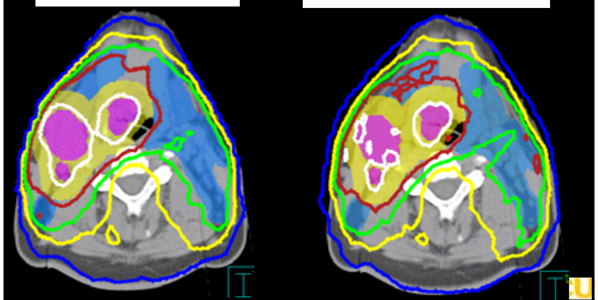

MC to reduce errors
DPE
OCE
Original SC_opt
Deliverable Plan SC
MC of Deliverable
MC_opt (deliverable)
Percent Volume
Dose (Gy)
Head and Neck IMRT plan
MC deliverable optimization can restore original optimized plan
DPE = Dose Prediction Error
OCE = Optimization Convergence Error

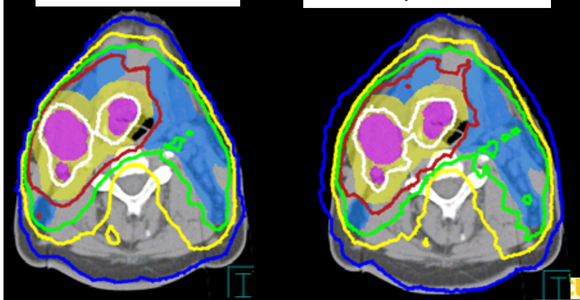
MC Verification

(Dose Prediction Error Evaluator)



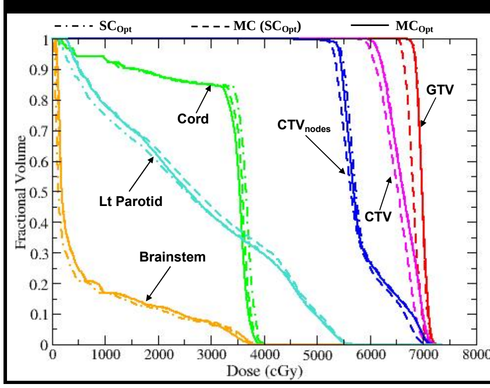
68.1 Gy, 60.0 Gy, 54.0 Gy, 45.0 Gy, 30.0 Gy

MC Optimization



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

H&N Patient



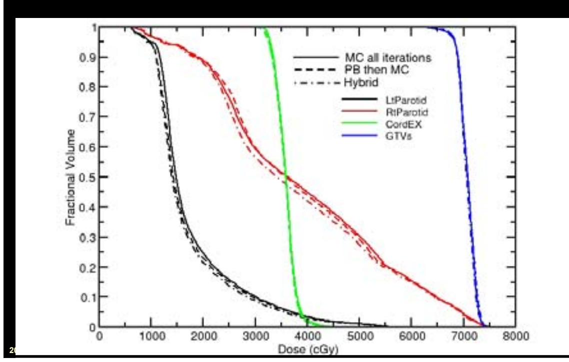
MC optimization restores desired DVHs (requires different MLC segments / weights)

MC optimization times

- Hyperion
  - Step-and-shoot
  - XVMC
  - < 1 hour
- VCU
  - Dynamic MLC field-based dose computation
  - VMC++ with hybrid algorithm
  - 20 processors
  - < 30 minutes (2 MC iterations)
  - Poster TU-EE-A2-04

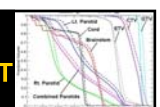
Hybrid Optimization

Final DVH Results Agree

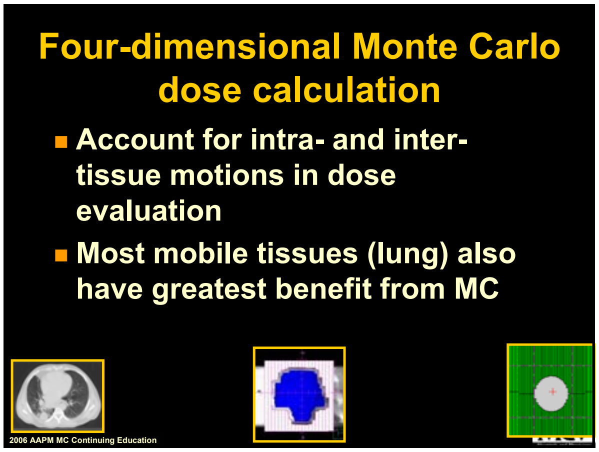


Summary

MC applications in IMRT



- MC can account for heterogeneities and/or fluence prediction errors
- Useful for patient specific QA
- MC can improve IMRT dose accuracy (QA implications)
- MC optimization has become clinically practical
- Vendors demonstrating MC-IMRT products


Four-dimensional Monte Carlo dose calculation
Account for intra- and inter-tissue motions in dose evaluation
Most mobile tissues (lung) also have greatest benefit from MC
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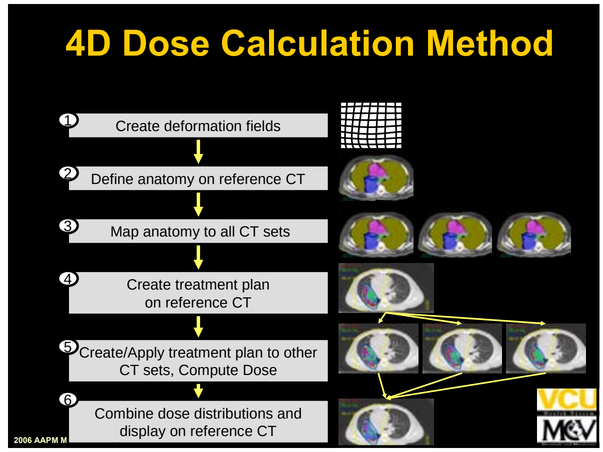
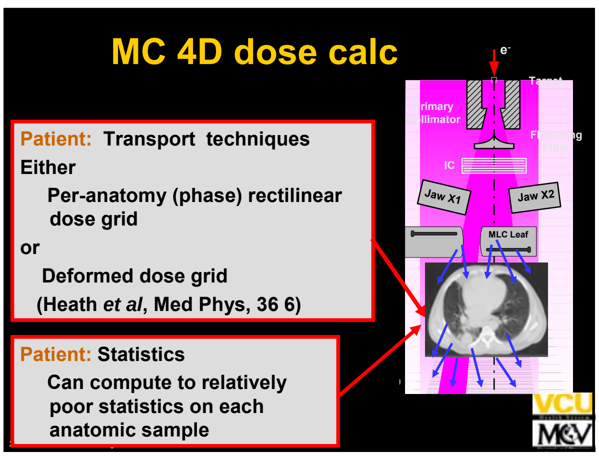
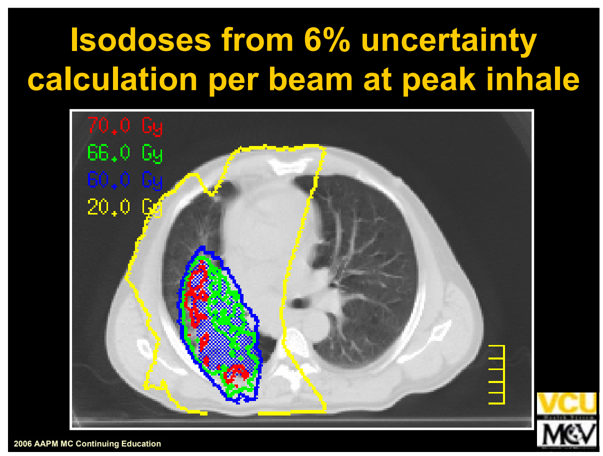

4D Dose Calculation Method
1 Create deformation fields
2 Define anatomy on reference CT
3 Map anatomy to all CT sets
4 Create treatment plan on reference CT
5 Create/Apply treatment plan to other CT sets, Compute Dose
6 Combine dose distributions and display on reference CT
VCU
MCV


MC 4D dose calc
Patient: Transport techniques
Either
Per-anatomy (phase) rectilinear dose grid
or
Deformed dose grid
(Heath et al, Med Phys, 36 6)
Patient: Statistics
Can compute to relatively poor statistics on each anatomic sample
Jaw X1
Jaw X2
MLC Leaf
IC
VCU
MCV


Isodoses from 6% uncertainty calculation per beam at peak inhale
70.0 Gy
66.0 Gy
60.0 Gy
20.0 Gy
VCU
MCV
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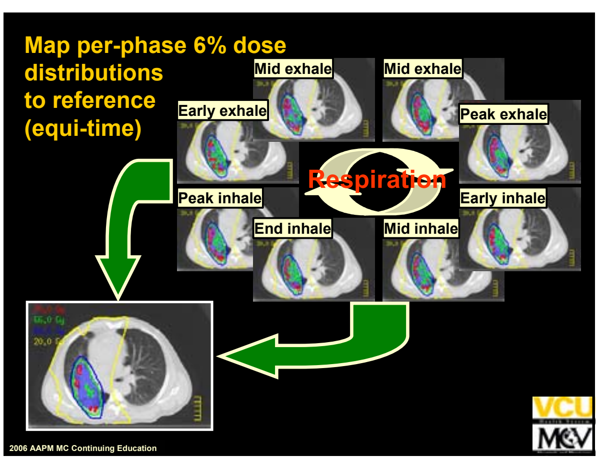
Map per-phase 6% dose distributions to reference (equi-time)
Mid exhale
Mid exhale
Early exhale
Peak exhale
Respiration
Peak inhale
Early inhale
End inhale
Mid inhale
VCU
MCV
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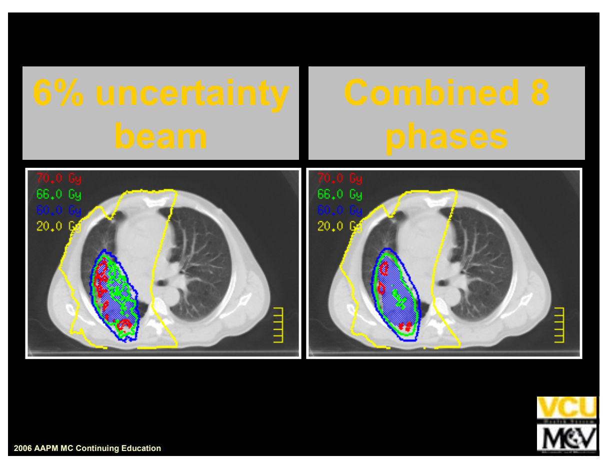
6% uncertainty beam
Combined 8 phases
70.0 Gy
66.0 Gy
60.0 Gy
20.0 Gy
VCU
MCV
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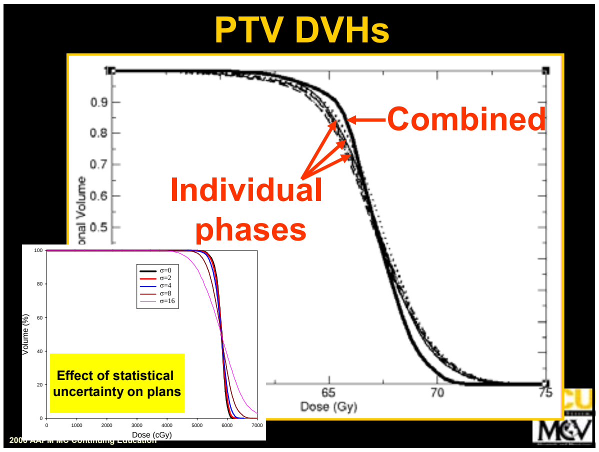

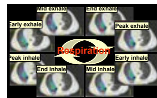

4D MC Summary

- Advantages of MC for 4D dose evaluation
  - (1) higher accuracy for calculation in electronic disequilibrium conditions such as those encountered during lung radiotherapy
  - (2) if deformable image registration is used, the calculation time for Monte Carlo is ≈independent of the number of 3D CT image sets constituting a 4D CT (same time for 4D and 3D calculation)

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Thank You for Your Attention

- Note
  - Several groups are using MC and IMRT
  - 14 abstracts at this meeting on MC and IMRT
- Acknowedgements/Contributors
  - Paul Keall
  - Ivaylo Mihaylov
  - Weidong Li
  - Iwan Kawrakow
  - Radhe Mohan
  - S. Joshi

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