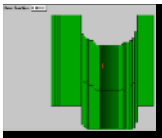
Monte Carlo Dose Calculation for Clinical IMRT Treatment Planning

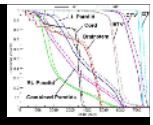
J.V. Siebers
Virginia Commonwealth University
Medical College of Virginia Hospitals
Richmond, Virginia USA

2008 AAPM Continuing Education

Funded by: NIH R01 CA98524



Objectives

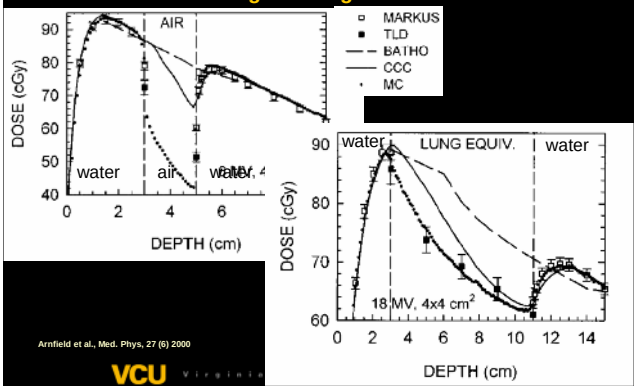


- To understand stages of an MC-IMRT dose calculation
- To illustrate the role of MC for
  - Treatment Planning System QA
  - Patient-specific IMRT QA
  - Clinical IMRT plan optimization
- To compare clinical IMRT dose calculations/optimization with MC-based results

VCU Virginia Commonwealth University

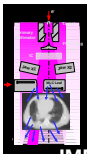
Effect of Heterogeneities on Dose

Errors in other algorithms are largest for small fields in heterogeneous geometries



Arnfield et al., Med. Phys, 27 (6) 2000

VCU Virginia

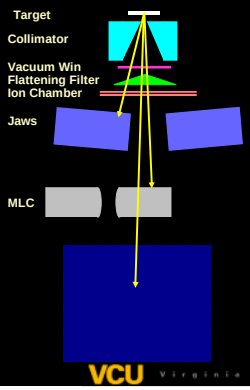


Justification of Monte Carlo for IMRT

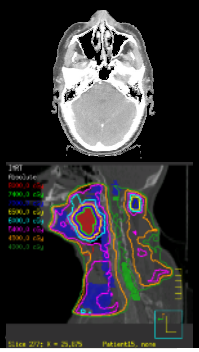
- IMRT mandates patient specific QA
  - Treatment planning system dose prediction
  - Information transfer
  - Device delivery
- Conventional TPS dose algorithms can be inaccurate for
  - Small fields
  - Regions of dose gradients (radiation disequilibrium)
  - Heterogeneous conditions
- If dose prediction was always accurate, there would be no need for per-patient QA
  - Simpler methods exist for checking information transfer and device delivery than doing measurement-based QA

VCU Virginia Commonwealth University

MC can be used in IMRT QA to validate fluence prediction



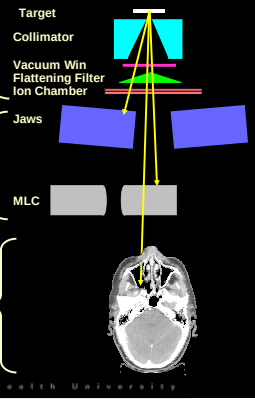
patient dose (heterogeneities)



VCU Virginia Commonwealth University

Stages of a Monte Carlo

- Particle Source
- Field Specific Beam Modifiers
- Patient



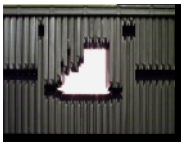
VCU Virginia Commonwealth University

Particle Source

- Direct Simulation through tx head
  - On-the-fly simulation
  - Stored particles (phase space file)
- Source Models
  - Simulation-based models
  - Measurement-driven empirical source models

Covered in detail elsewhere (TG-105, …)
Overall accuracy is no better than least accurate sub-component

VCU Virginia Commonwealth University



Field-specific beam modifiers

- May be part of the source model

Or

- Explicit simulation

MLC Movie courtesy
Jai-Woong Yoon
Stanford

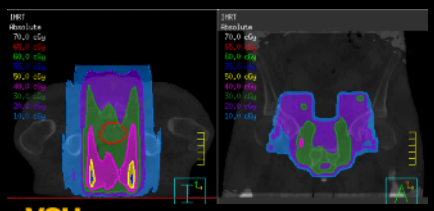
VCU Virginia Commonwealth University

Preliminary Requirements

- Integrated MC system
- Commissioned MC algorithm
  - Source model tuning
  - Open field matching
  - MLC test fields
  - IMRT test fields
- Other
  - See TG-105 ++

VCU Virginia Commonwealth University

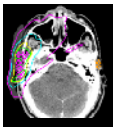
MC for patient specific IMRT QA



VCU Virginia Commonwealth University

Use in of Monte Carlo in IMRT QA

Patient Dose Recalculation



Obtain acceptable IMRT plan

Copy plan and comp

MC QA has been performed on all VCU IMRT plans since 2000

<3% DVH difference?

Yes

No

Print and sign DVHs and dose differences

Include in chart

Notify planning team

Differences acceptable?

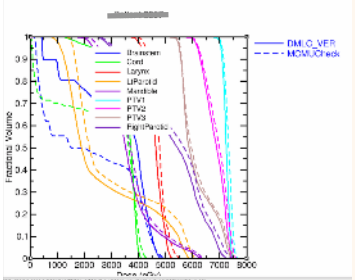
Yes

No

Modify plan based on MC

VCU Virginia Comm

MC QA Results

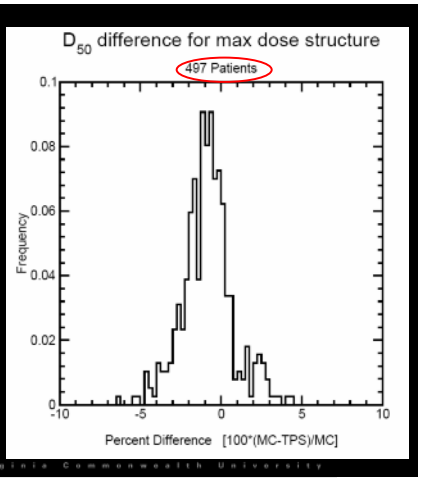


	DMLC_VER	MCMUCheck
Brainstem D_0.01	4742.8	4848.4 (−2.23)
Brainstem D_0.05	4604.4	4596.8 (+0.16)
Brainstem D_0.50	3949.9	1536.8 (+61.09)
Brainstem D_0.90	490.2	236.0 (+51.86)
Brainstem D_0.98	428.3	181.8 (+57.56)
Cord D_0.01	4049.2	4235.2 (−4.59)
Cord D_0.05	3980.4	4104.1 (−3.11)
Cord D_0.50	3713.8	3639.5 (+2.00)
Cord D_0.90	3422.9	89.3 (+97.39)
Cord D_0.98	1713.5	49.5 (+97.11)
Larynx D_0.01	5180.5	5435.1 (−4.91)
Larynx D_0.05	5073.3	5252.1 (−3.52)
Larynx D_0.50	4634.8	4772.7 (−2.98)
Larynx D_0.90	4232.1	4388.8 (−3.70)
Larynx D_0.98	3988.1	4164.8 (−4.43)
LtParotid D_0.01	5808.3	6036.9 (−3.94)
LtParotid D_0.05	5614.9	5873.8 (−4.24)
LtParotid D_0.50	1895.9	2180.9 (−15.03)
LtParotid D_0.90	1260.3	1663.0 (−31.99)
LtParotid D_0.98	995.8	1519.0 (−52.54)
Mandible D_0.01	6182.7	6301.1 (−1.92)
Mandible D_0.05	5584.7	5750.8 (−2.97)
Mandible D_0.50	3524.3	3697.2 (−4.90)
Mandible D_0.90	2575.0	2759.8 (−7.18)
Mandible D_0.98	2168.3	2378.1 (−9.68)
PTV1 D_0.01	7465.3	7607.0 (−1.90)
PTV1 D_0.05	7422.9	7547.7 (−1.68)
PTV1 D_0.50	7246.1	7336.8 (−1.25)
PTV1 D_0.90	7093.6	7140.7 (−0.66)
PTV1 D_0.98	6993.7	7036.8 (−0.62)
PTV2 D_0.01	7437.9	7565.4 (−1.71)
PTV2 D_0.05	7368.4	7482.9 (−1.55)
PTV2 D_0.50	6889.4	6992.4 (−1.50)
PTV2 D_0.90	6289.0	6338.6 (−0.79)
PTV2 D_0.98	6092.8	6123.0 (−0.50)
PTV3 D_0.01	7399.6	7518.5 (−1.61)
PTV3 D_0.05	7281.7	7383.1 (−1.39)
PTV3 D_0.50	5871.0	5956.2 (−1.45)
PTV3 D_0.90	5567.1	5587.9 (−0.37)
PTV3 D_0.98	5446.2	5483.6 (−0.69)
RightParotid D_0.01	7162.6	7373.0 (−2.94)
RightParotid D_0.05	6949.3	7143.7 (−2.80)
RightParotid D_0.50	5442.6	5693.7 (−4.61)
RightParotid D_0.90	3296.6	3468.0 (−5.23)
RightParotid D_0.98	2776.0	2851.0 (−2.70)

VCU Virginia Comm

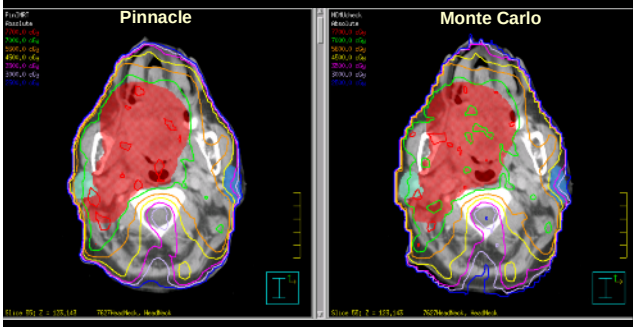
QA Summary

- Pinnacle vs MC Dose
- Pinnacle &VCU IMRT
- Any IMRT Tx Site
- Δ = -0.77%
- σ = 1.43%
- 7% of cases have > 3% dose difference



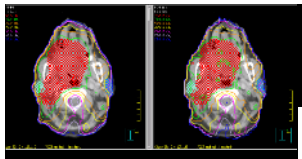
VCU Virginia Commonwealth University

Head and Neck Example



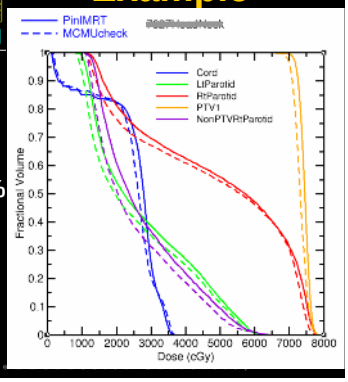
77 Gy 70 Gy 55 Gy 45 Gy 35 Gy 30 Gy 25 Gy

VCU Virginia Commonwealth University

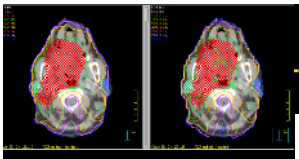


Head and Neck Example

- PTV D_{98} Δ=-2.8%
- LtParotid D_{50} Δ=- 11%
- Cord D_1 Δ<1%

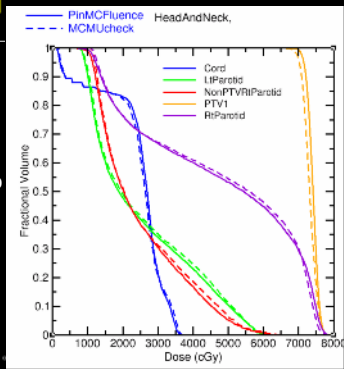


VCU

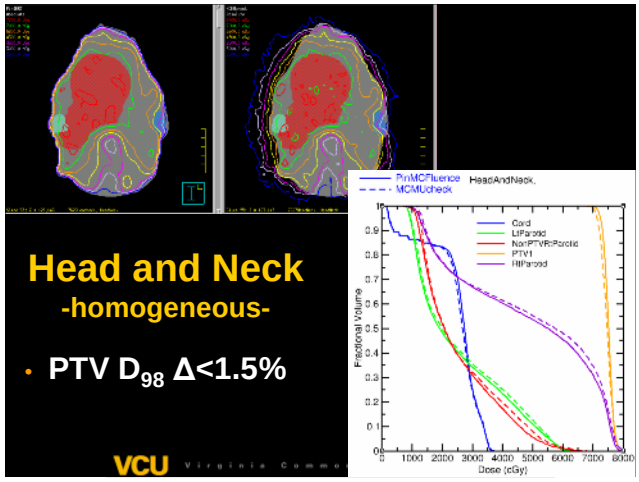


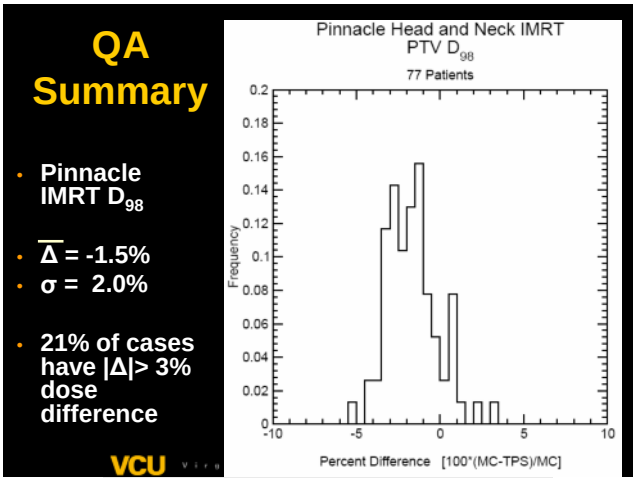
Head and Neck
-Pinnacle using MC Fluence-

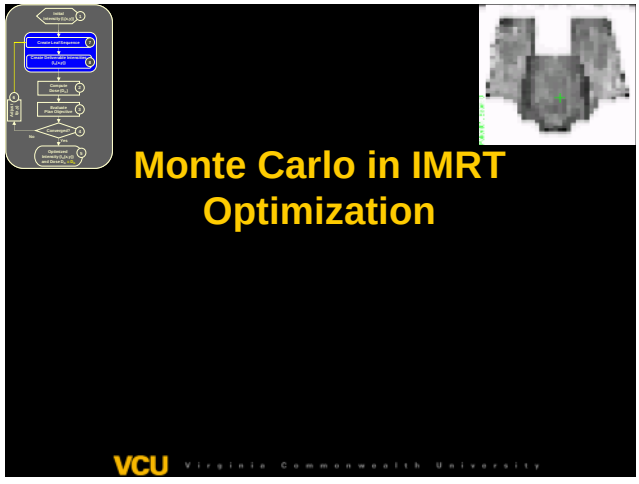
- PTV D_{98} Δ=- 2%
- LtParotid D_{50} Δ=- 3.5%

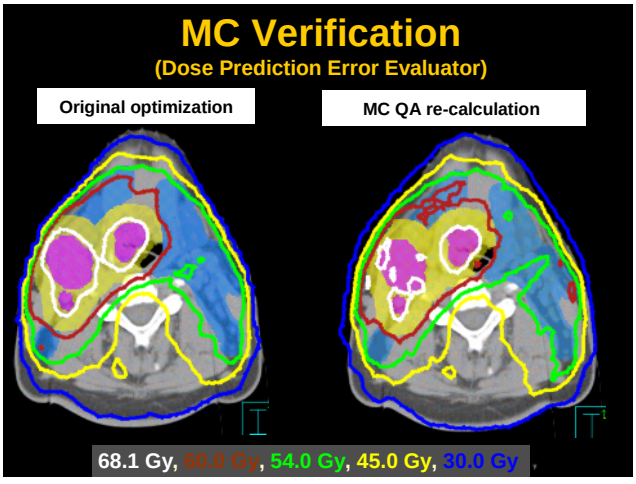


VCU

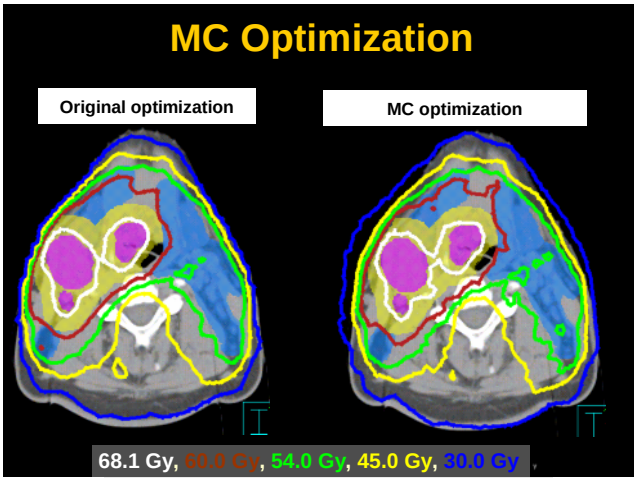

Head and Neck
-homogeneous-
• PTV D_{98} Δ<1.5%
PinMCFluence
MCMUcheck
HeadAndNeck
Fractional Volume
Dose (cGy)
VCU


QA Summary
• Pinnacle IMRT D_{98}
• $\overline{\Delta}$ = -1.5%
• σ = 2.0%
• 21% of cases have |Δ|> 3% dose difference
Pinnacle Head and Neck IMRT
PTV D_{98}
77 Patients
Frequency
Percent Difference [100*(MC-TPS)/MC]
VCU


Monte Carlo in IMRT Optimization
VCU

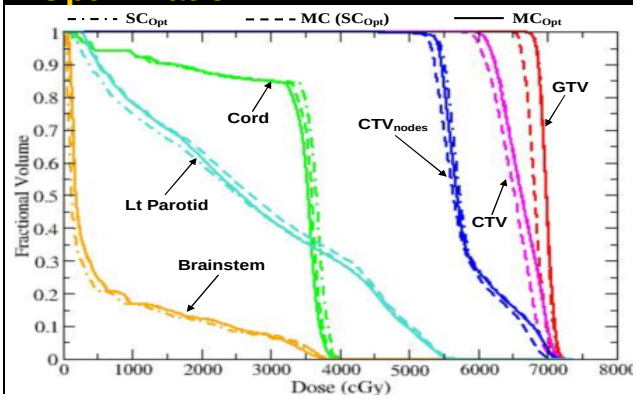

MC Verification
(Dose Prediction Error Evaluator)
Original optimization
MC QA re-calculation
68.1 Gy, 60.0 Gy, 54.0 Gy, 45.0 Gy, 30.0 Gy

MC Optimization



MC Optimization

MC optimization restores desired DVHs
BUT requires different MLC segments



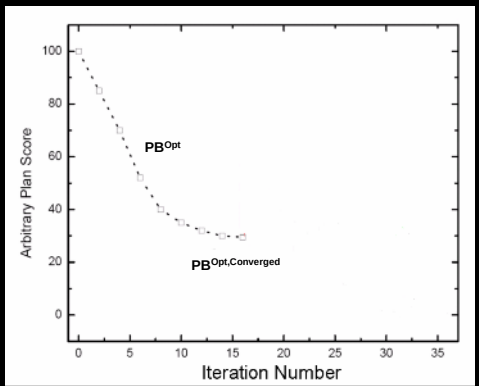
MC during IMRT optimization

Pre-optimization

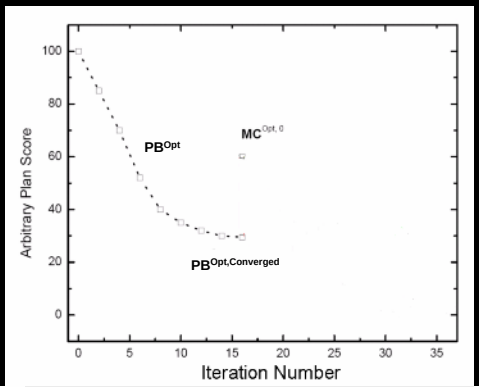
- **Since**
  - Optimization will converge in fewer iterations if a good initial guess is provided to the optimizer
- **Then**
  - MC optimization should be preceded with pre-optimization using faster/approximate algorithms

VCU Virginia Commonwealth University

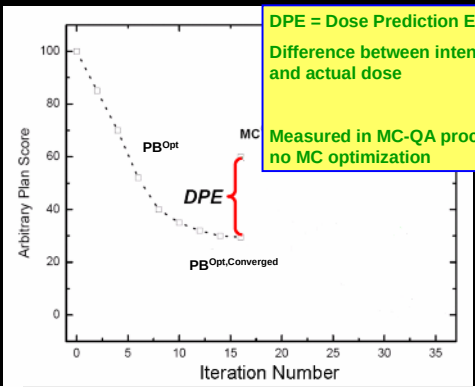
Optimization Sequence



Optimization Sequence



Optimization Sequence

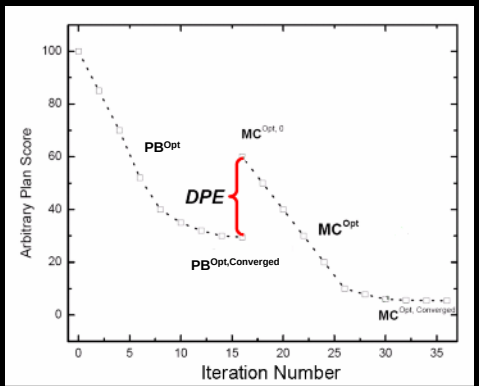


DPE = Dose Prediction Error

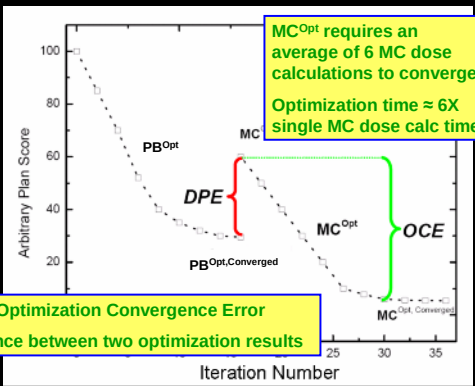
Difference between intended and actual dose

Measured in MC-QA process if no MC optimization

Optimization Sequence



Optimization Sequence

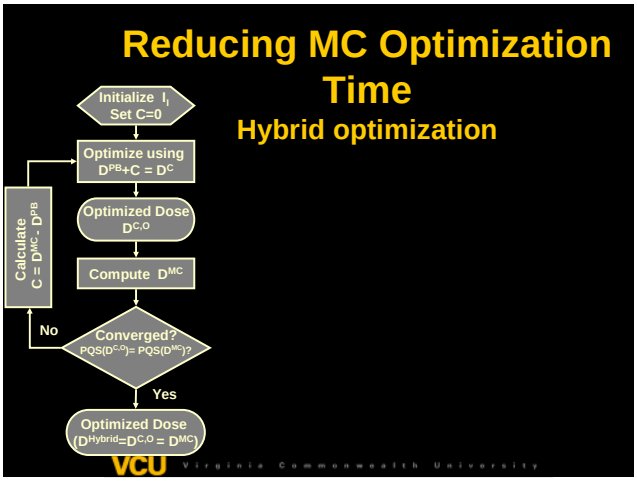


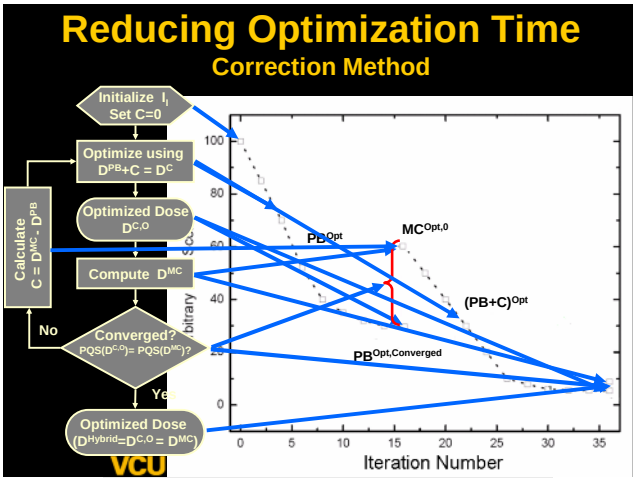
MC^Opt requires an average of 6 MC dose calculations to converge

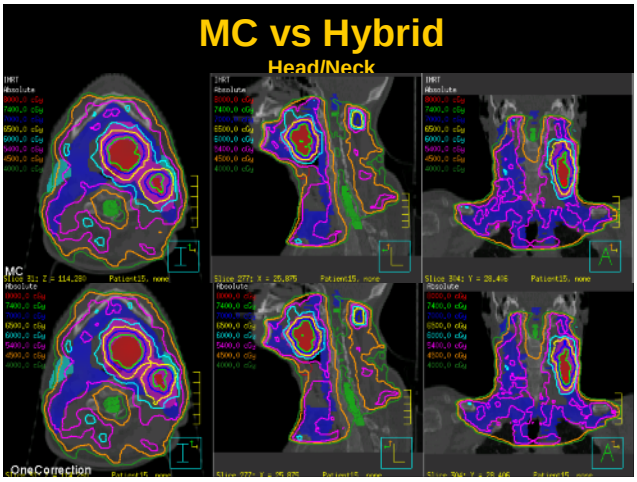
Optimization time ≈ 6X single MC dose calc time

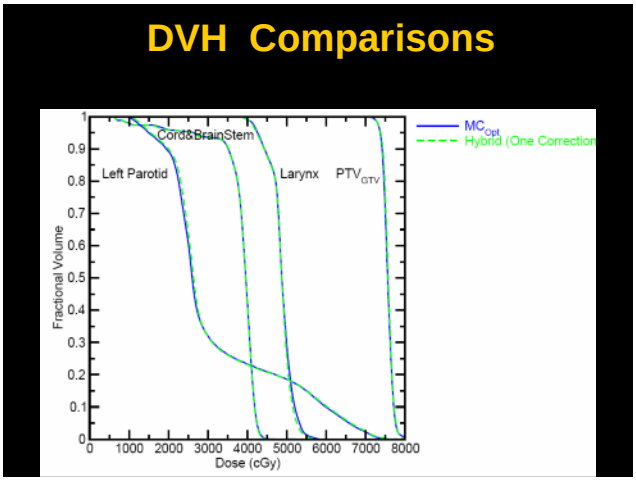
OCE = Optimization Convergence Error

Difference between two optimization results


Reducing MC Optimization Time
Hybrid optimization
Initialize I_1 Set C=0
Optimize using $D^{PB}+C = D^{C}$
Optimized Dose $D^{C,O}$
Compute D^{MC}
Converged? $PQS(D^{C,O}) = PQS(D^{MC})$?
No
Yes
Calculate $C = D^{MC} - D^{PB}$
Optimized Dose $(D^{Hybrid} = D^{C,O} = D^{MC})$
VCU
Virginia Commonwealth University

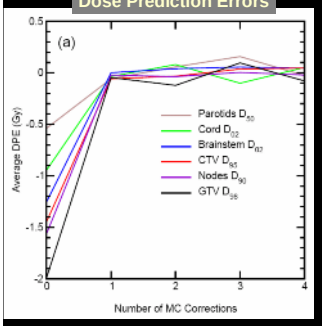

Reducing Optimization Time
Correction Method
Initialize I_1 Set C=0
Optimize using $D^{PB}+C = D^{C}$
Optimized Dose $D^{C,O}$
Compute D^{MC}
Converged? $PQS(D^{C,O}) = PQS(D^{MC})$?
No
Calculate $C = D^{MC} - D^{PB}$
Optimized Dose $(D^{Hybrid} = D^{C,O} = D^{MC})$
PB^{Opt}
$MC^{Opt,0}$
$(PB+C)^{Opt}$
$PB^{Opt,Converged}$
Iteration Number
VCU


MC vs Hybrid
Head/Neck
MC
OneCorrection

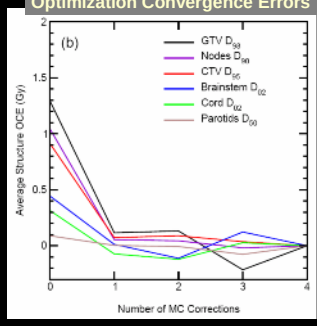

DVH Comparisons
Cord&BrainStem
Left Parotid
Larynx
PTV_{GTV}
MC_{Opt}
Hybrid (One Correction
Fractional Volume
Dose (cGy)

Head and Neck

Dose Prediction Errors



Optimization Convergence Errors



1 MC-based correction sufficient

VCU Virginia Commonwealth University

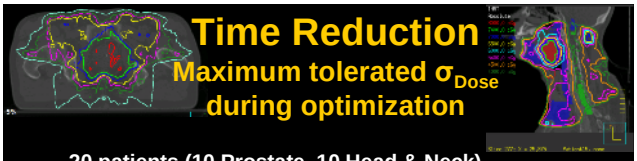
MC vs One Correction Hybrid Comparisons

Structure	Dose Volume Constraint (Gy)	DPE of initial PB calc D^{PB} (Gy)	DPE of D^{C} (Gy)	OCE of initial PB optimization D^{PB} (Gy)	OCE of D^{C} (Gy)
GTV	D_{99}>68.1, 70.8, or 73.8		-0.05±0.09		0.12±0.17
CTV	D_{99}>60.0		-0.06±0.06		0.07±0.12
ETV	D_{99}<54.0		-0.02±0.05		0.05±0.09
Parotids	D_{15}<30.0		-0.06±0.04		0.00±0.11
Cord	D_{2}<45.0		-0.03±0.07		-0.07±0.18
Brainstem	D_{2}<55.0		-0.00±0.19		0.01±0.06

VCU Virginia Commonwealth University

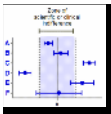
Time Reduction

Maximum tolerated σ_{Dose} during optimization



- 20 patients (10 Prostate, 10 Head & Neck)
- Optimize with different σ_{Dose}
  - MC optimization & One-MC correction optimization
  - σ_{Dose} = 2, 5, 8, 10, 12, 15, 20 % per beam
    - Achieved stats 0.9%-9% wrt local dose
- Verification calculation with 2% per beam statistics
- Compare with 2% per beam MC optimization
  - DVH indices used to compute PQS during optimization with statistical equivalence tests
  - Isodoses, Full DVH's, ….
- Rejection Criteria: 1 Gy Dose Difference (~1.5% of Rx dose) between optimized plans

VCU Virginia Commonwealth University

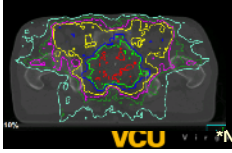


Statistical Equivalence Test Results

Prostate

- Dose window size (in cGy) required to state optimization results are equivalent to the MC 2%/beam optimization result

	2%*	5%*	8%*	10%*	12%*	15%*	20%*
MC	--	77	47	88	131	214	180
OC	40	63	51	67	130	195	181



Maximum tolerated < 100 cGy threshold.

10% per beam corresponds with per-plan σ~5% wrt D_{local}

*Nominal per-beam statistical precision

VCU Virginia Commonwealth University

Dose computation time

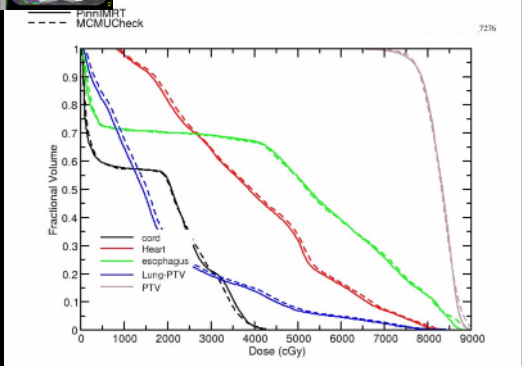
Prostate Optimizations

Statistical Precision (%)			Dose Calculation Time Required for Optimization (min)		
Nominal Per Beam	$\bar{\sigma}_{D_{prost}}$ Achieved	$\bar{\sigma}_{D_{Rect}}$ Achieved	MC_{opt}	Hybrid	One Correction
2	0.9	0.6	700	326	164
5	2.4	1.5	102	48	25
8	3.7	2.4	40	18.6	9.6
10	4.7	3	25.7	12.1	6.2
12	5.6	3.5	17.6	8.3	4.3

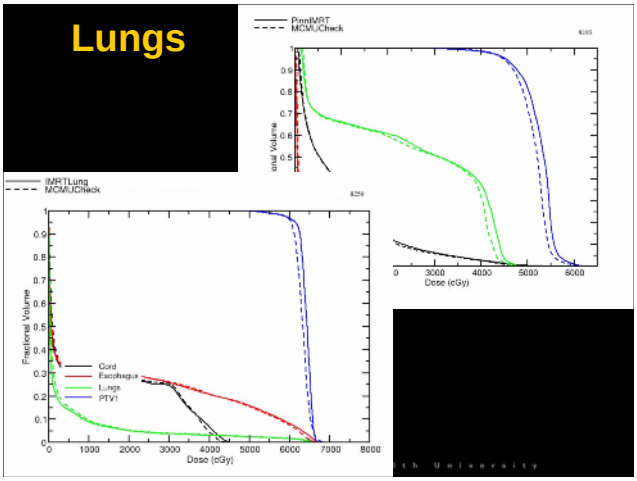
- Scaled to single OLD 3 Ghz Xeon processor (Current CPUs 3X faster)
- 32-bit version of VMC++, DMLC, BEAM (64-bit version reported to be faster)
- Phase-space style source (source model would be 2x faster)
- 4x4x4 mm^3 voxels
- Head/Neck optimizations take ~1.5x longer (split beams)

VCU Virginia Commonwealth University

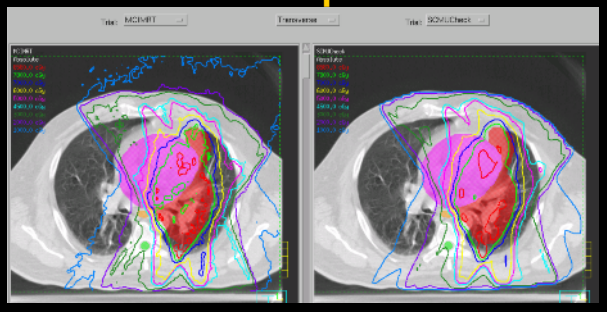
MC Lung Case: QA



Lungs



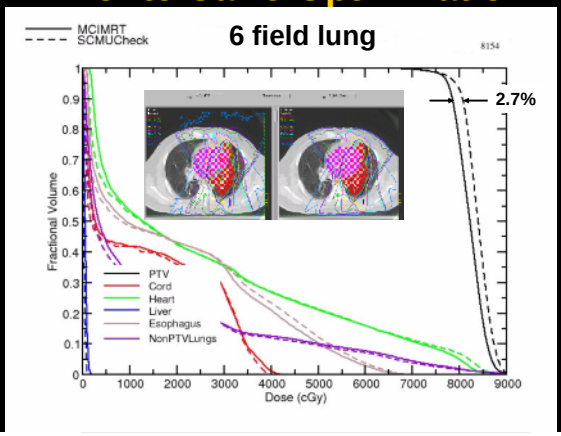
Monte Carlo Optimization



- Optimize with MC
- MU Check (QA) with SC

VCU Virginia Commonwealth University

Monte Carlo Optimization

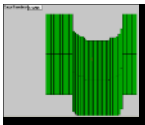


MC times

(OLD CPUs @ VCU, new CPUs 3X faster)

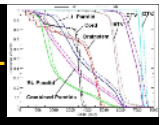
- QA
  - VCU
    - dosxyznrc: 4.1 hours (20*3 Ghz CPU, σ_{Dmax}=0.6%)
    - dosxyznrc: 38 min (20*3 Ghz, σ_{Dmax}=1.5%)
    - VMC++: 25 min (1*3 Ghz CPU, σ_{Dmax}=1.5%)
  - Yamamoto (PMB 52 2007)
    - 15 hrs on 28 CPU cluster
- Optimization
  - Hyperion / CMS (Step-and-shoot)
    - XVMC, < 1 hour (multi-core, multi CPU system)
  - VCU (dynamic MLC)
    - Full MCopt with dosxyznrc: 12.5 hours (1 CPU, σ_{Dmax}=3%)
    - One Correction Hybrid with VMC++: 6 min (Opt, σ_{Dmax}=3%) + 25 min (final calc, σ_{Dmax}=1.5%) (1 CPU)

VCU Virginia Commonwealth University



Summary

MC applications in IMRT



- MC can account for heterogeneities and/or fluence prediction
- MC useful for 3D patient specific QA
- MC optimization is clinically practical
  - Calculation times few minutes
  - Reduces normal structure dose

VCU Virginia Commonwealth University

Thank You for Your Attention

- Acknowledgements / Contributors
  - JJ Gordon
  - J Gardener
  - J Ververs
  - PJ Keall
  - IB Mihaylov
  - W Li
  - I Kawrakow

VCU Virginia Commonwealth University