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Monte Carlo for CyberKnife® Radiosurgery with the Incise™ Multileaf Collimator

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DISCLOSURES

- Eight of the authors are employees of Accuray, Inc.
- Portions of this work were completed through a contract between the Fox-Chase Cancer Center and Accuray, Inc.

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CyberKnife® with InCise™ Multileaf Collimator

- The CyberKnife is an image-guided therapeutic radiation delivery system with a linear accelerator mounted on a robot
- Beams are collimated with fixed cones, the Iris™ variable aperture collimator, or the InCise multileaf collimator (MLC)
- The MLC has a 11.5 x 10.0cm field size with 26 0.385cm leaf pairs
- Full interdigitation and 100% overtravel are provided

Overview

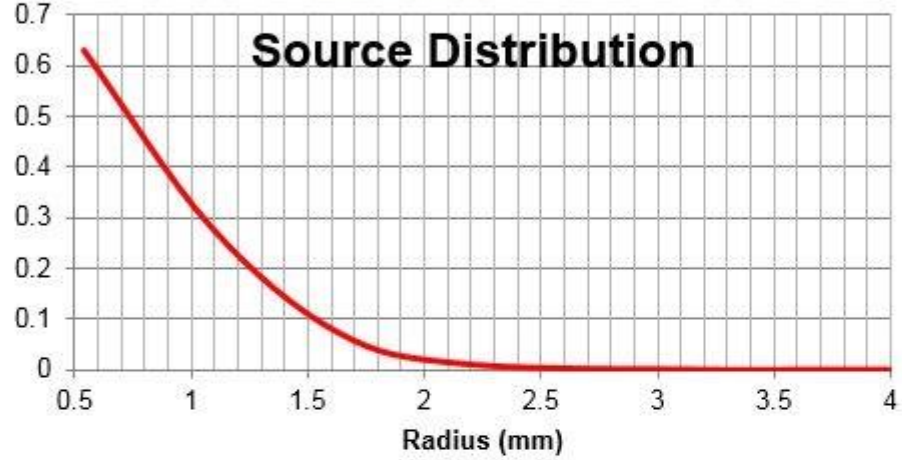
- Monte Carlo dose model
  - Source model and sampling
  - Transport through the MLC
  - Transport through and dose deposition in the patient
- Accuracy testing
  - Planar single beam comparisons with measurement
  - Point dose comparisons with measurements of composed plans
- Implemented dose calculation times

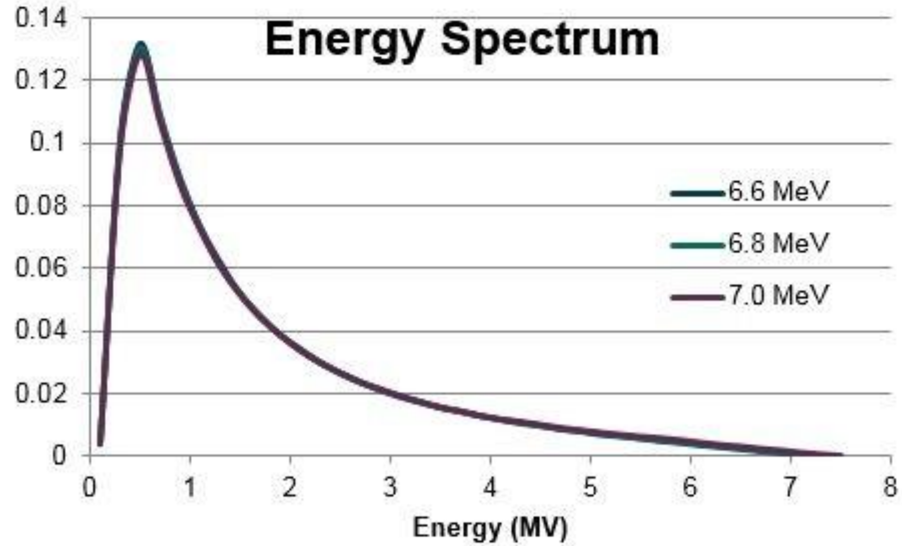
Source model

- A virtual source model with a single source coincident with the Linac target is defined

- Three probability distribution recreate the photon phase space for the linac
  - Source position distribution: a Gaussian with user set full width half-max
  - Fluence distribution:
    - Measure 0, 45, 90, 135 degree open field profiles with MLC removed
    - Planar distribution interpolates profiles in polar coordinates
  - Energy distribution: user selects Geant pre-calculated spectrum based on linac energy rating

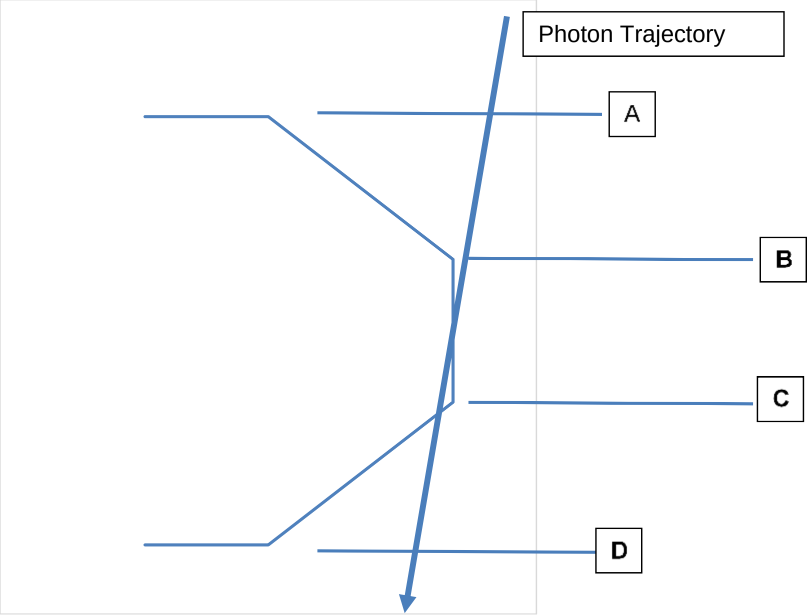
- Gaussian FWHM and Energy spectrum settings are optimized iteratively by comparing MC dose calculations with commissioning beam data measurements





Transport through the MLC

- Leaves are flat sided and move on linear trajectories
- To reduce leakage, the collimator bank is 9cm high and is tilted 0.5^o
- Leaf tip has a trapezoidal edge
- Particle transmission is checked in 4 planes that define the trapezoid
  – Set transmission probability based on planes intersected by particle trajectory
- Collimator scatter is not modelled

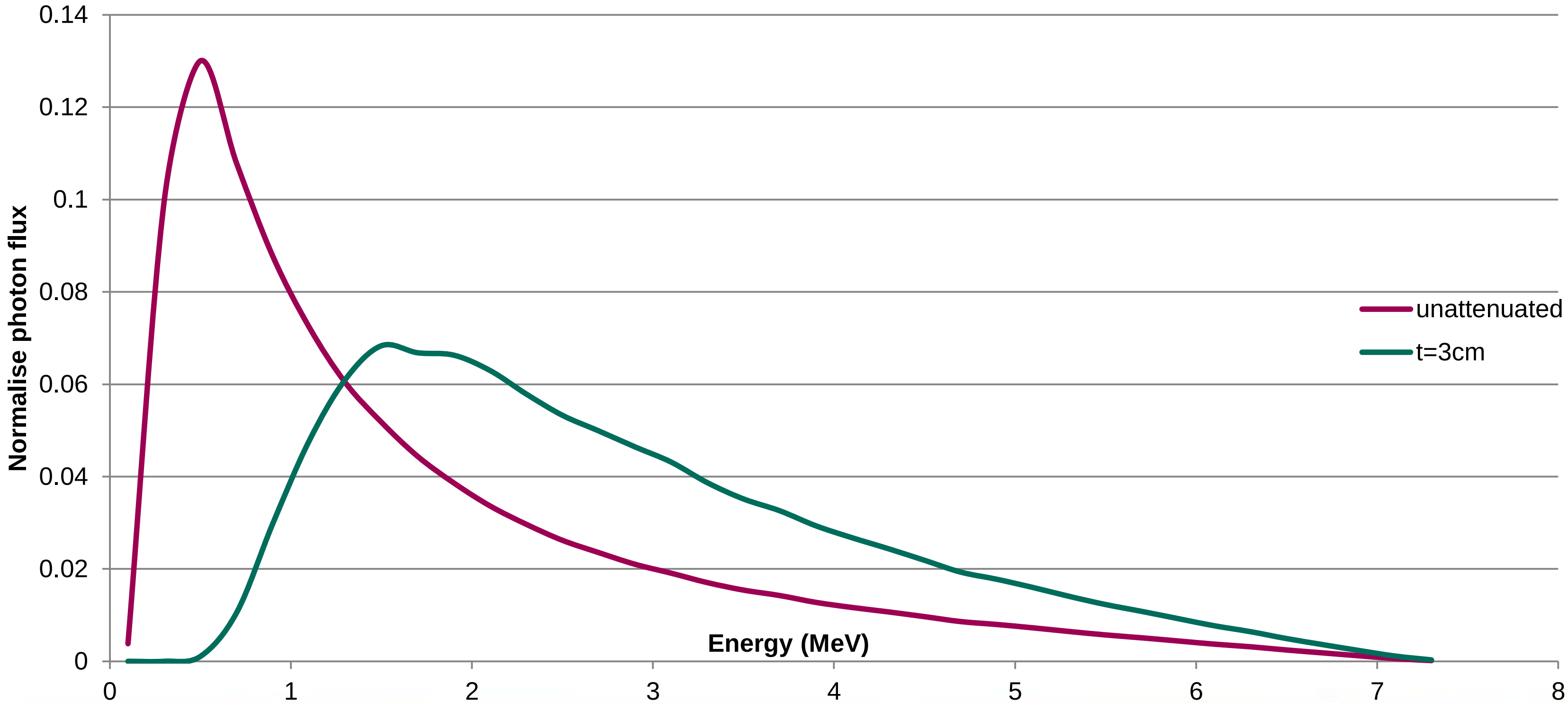


PLANE				Transmission Probability
A	B	C	D	
X				0.32
			X	0.32
	X	X		0.01
	X			0.20
		X		0.20
X	X			0.003
X	X	X		0.003
	X	X	X	0.003
		X	X	0.003
				1.0

Transport through the collimator

Beam Hardening

- Energy for photons that intersect the MLC leaves are sampled from a hardened energy spectrum
- The hardened energy spectrum is calculated from the open spectrum, by assuming 3cm of transmission through tungsten



Transport through the patient or phantom

- Particle transport uses pre-simulated electron track data for mono-energetic photons that interact with water
  - Energy bins range from 25 keV to 7.7 MeV
  - 1000 to 10000 photon simulations in each energy bin
  - Track lengths scaled proportionally based on local density
- Variance reduction techniques include:
  - Electron track repeating
  - Forced photon interactions
  - Photon splitting
  - Russian roulette on collimator attenuated and patient scattered photons
  - Energy cutoffs (10 keV for photons, 700 keV for electrons and positrons)

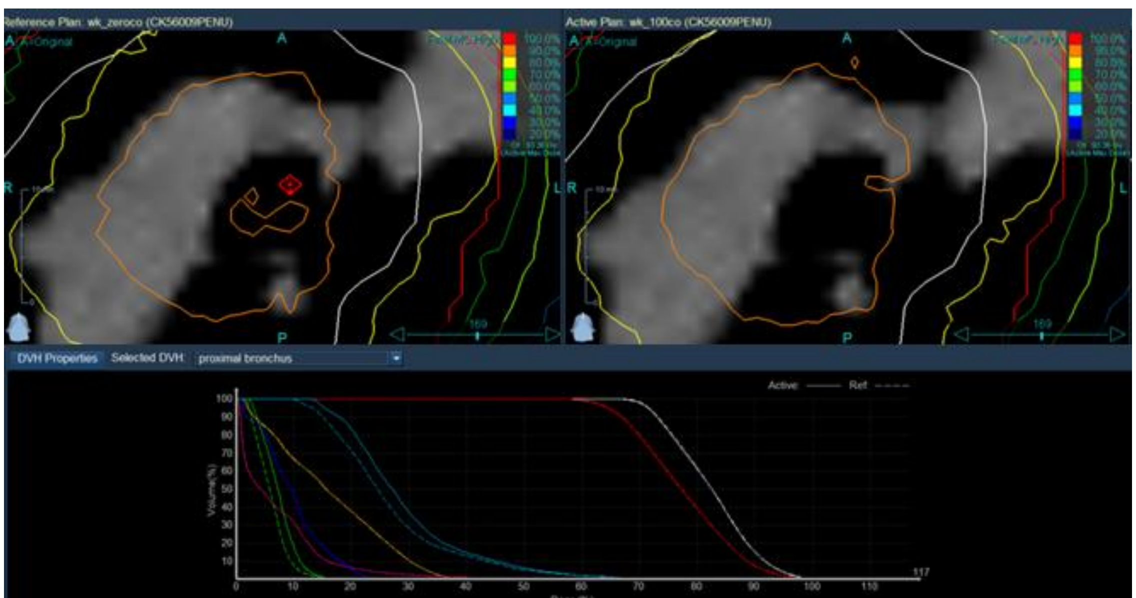
- Ma, et al, “Implementation of Monte Carlo dose calculation for CyberKnife treatment planning”, J. of Physics: Conf. Series 102 (2008)
- Li, et al, “Validation of a Monte Carlo dose calculation tool for radiotherapy”, Phys. Med. Biol. 45: 2969-85 (2000)

Transport through the patient or phantom

Handling electrons and positrons below E_{cut}

- For the original implementation, if the particle energy falls below E_{cut} during the final step of the pre-generated particle track then the remaining energy is deposited in the current voxel
- For the new version, linearly extrapolate the final track step using stopping-power ratio and local density to attenuate the energy
  - Prevents artificial high-dose sparkles in low density

Original



New

Accuracy Tests

Comparisons of calculated and measured dose

- Single beam tests
  - PDD in homogeneous and heterogeneous phantoms
  - Planar analysis of rectangular and irregularly shaped beams in homogeneous and heterogeneous phantoms

- Composed plans in homogeneous and heterogeneous phantoms

Comparison of PDD in water phantoms

PTW60018 diode vs. PTW μDiamond detector

- Both detectors give good agreement for field sizes greater than 2 x 2 cm
- μDiamond has better agreement for small field sizes and deeper depths
- Tabulate ratio of measured to calculated dose

PTW60018 Diode

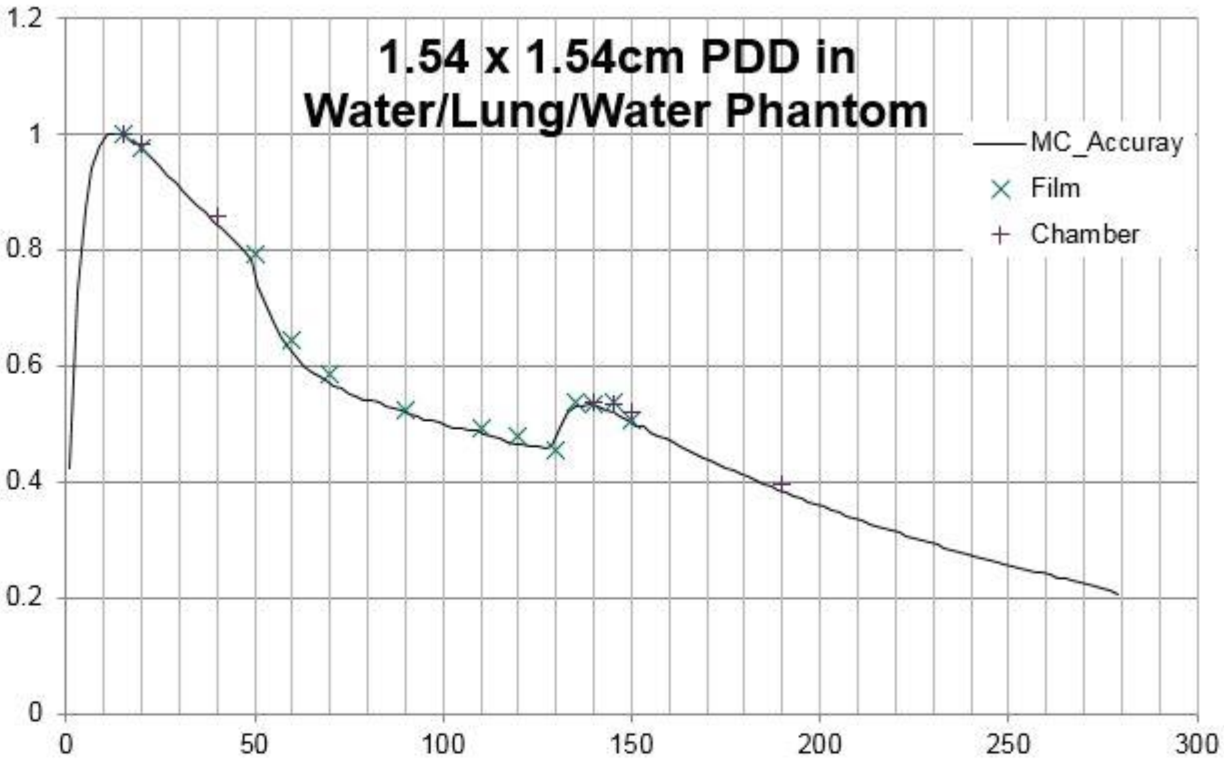
Field Size (cm)	5cm Depth	10cm Depth	20cm Depth	29.5cm Depth
0.76 x 0.77	0.995	0.989	0.969	0.957
1.54 x 1.54	0.999	0.994	0.980	0.973
2.30 x 2.31	0.996	0.998	0.993	0.993

μDiamond Detector

Field Size (cm)	5cm Depth	10cm Depth	20cm Depth	29.5cm Depth
0.76 x 0.77	1.007	1.005	1.008	0.988
1.54 x 1.54	1.002	1.007	0.999	0.996
2.30 x 2.31	1.008	1.008	1.010	1.004

Dose Accuracy Tests

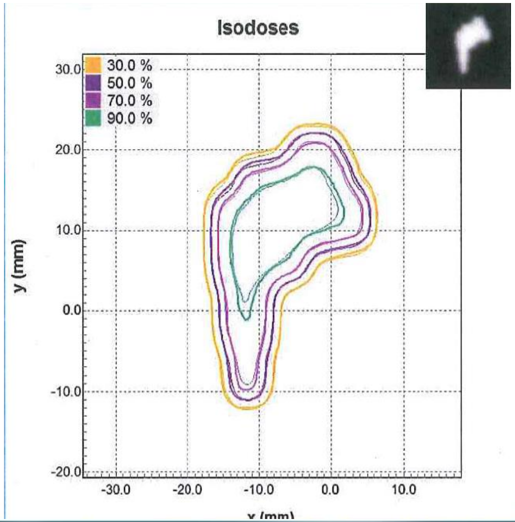
PDD in a Water / Lung / Water phantom

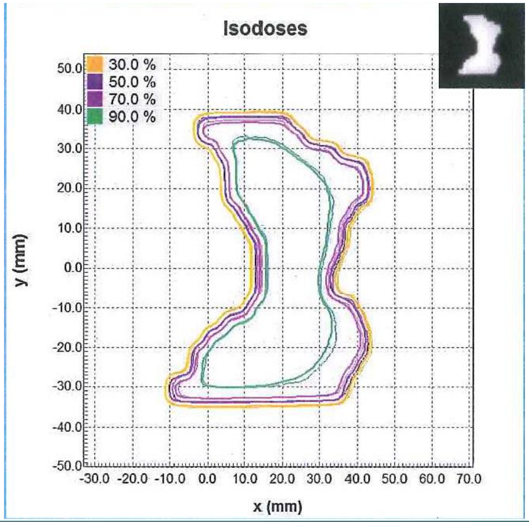


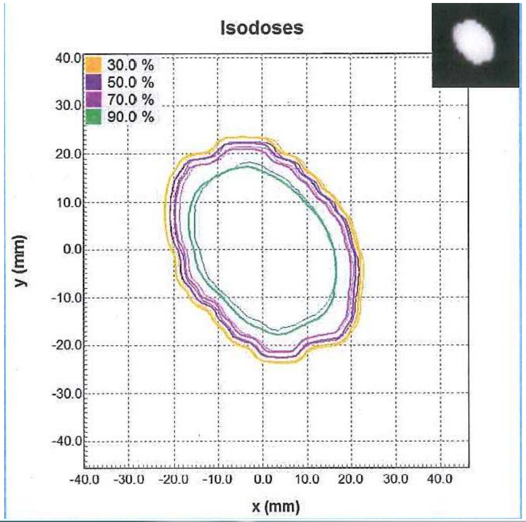
Dose Accuracy Tests

Planar gamma analysis of film in Water / Lung / Water phantom

- 3 rectangular shapes (0.76x0.77cm, 1.54x1.54cm, and 4.62x4.62cm) and 9 irregular shapes
- Same water / lung / water phantom as the PDD measurement
- Film measurements recorded 9cm (mid-lung), 13.5cm (0.5cm of buildup), and 14.0cm (1.0cm of buildup) deep
- Gamma analysis at 2% dose difference and 0.2cm distance to agreement for all pixels in the plane with dose 50% or more of the maximum dose







Dose Accuracy Tests

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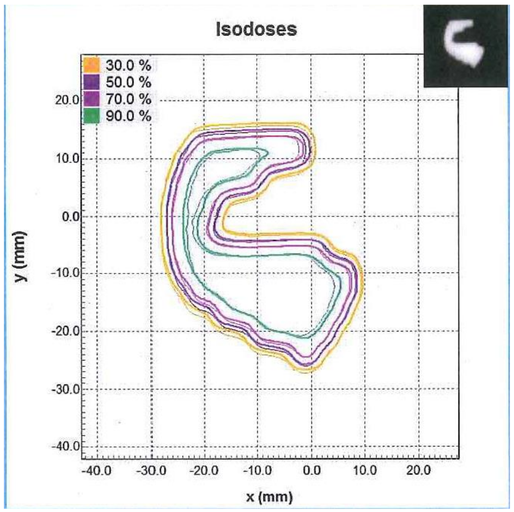
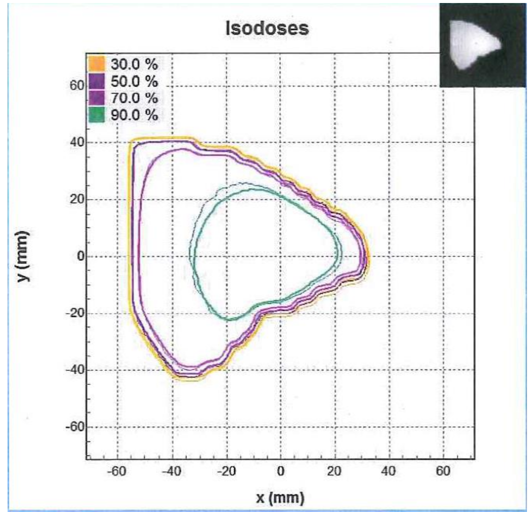
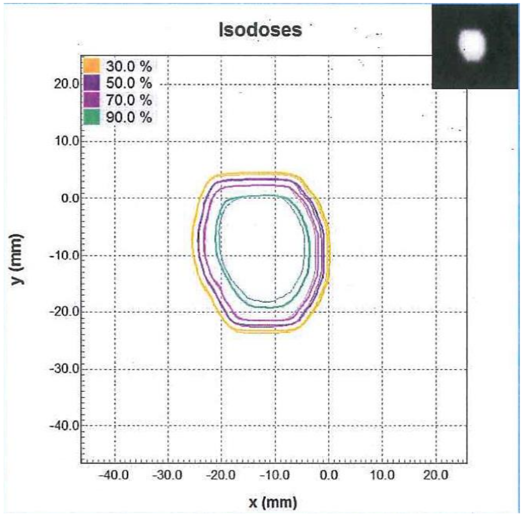
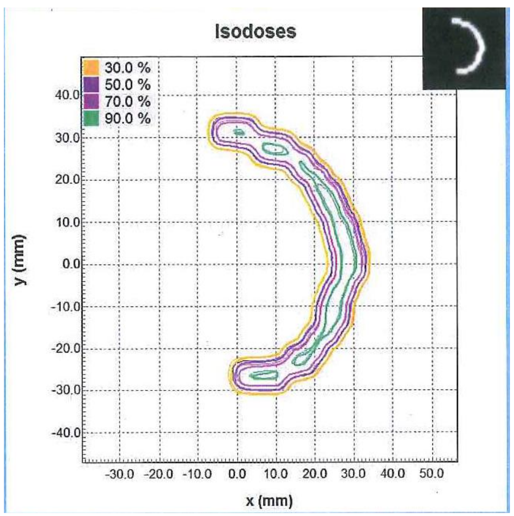
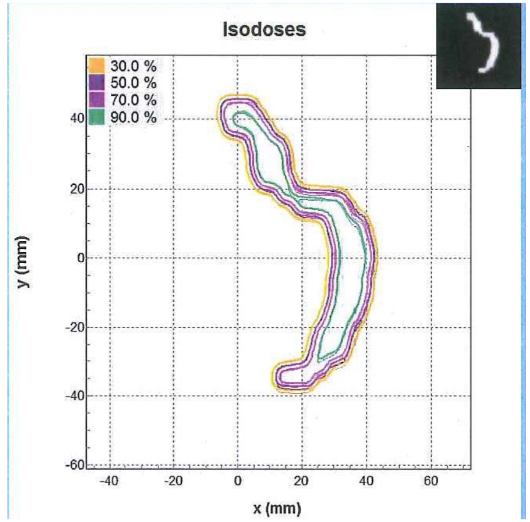
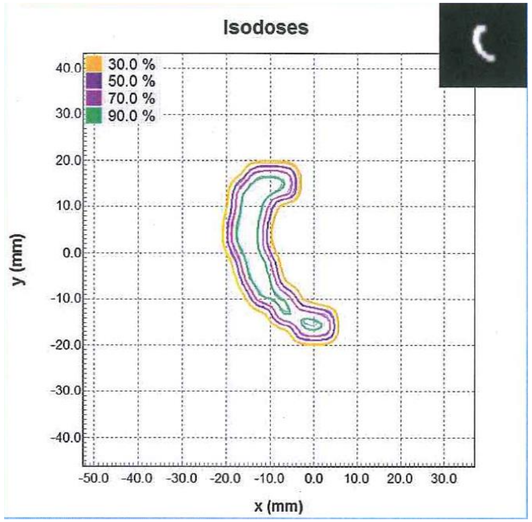












Dose Calculation Tests

Planar gamma analysis (2.0% / 0.2cm) with film measurement

Shape	9 cm	13.5 cm (2.0mm voxel)	13.5 cm (0.5mm voxel)	14.0 cm
0.76 x 0.77 cm	100%	86.7%	97.7%	91.3%
1.54 x 1.54 cm	94.8%	69.9%	95.7%	100.0%
4.62 x 4.62 cm	100%	97.8%		100.0%
HN Ring	98.1%	69.3%	95.7%	100.0%
HN Random	100%	99.3%		99.8%
HN Conf. Avoid	100%	95.8%		100.0%
Lung Ring	100%	71.5%	90.2%	99.1%
Lung Random	100%	53.0%	81.5%	100.0%
Lung Conformal	100%	100.0%		100.0%
Prostate Ring	95.4%	75.2%	94.4%	95.7%
Prostate Random	100%	63.9%	97.0%	98.7%
Prostate Conf. Avoid	100%	75.0%	100.0%	100.0%

Composed Plans

Point dose comparisons of measurement and calculation

- 3 relatively homogeneous phantoms (9 plans)
- 2 anthropomorphic chest heterogeneous phantoms with low density regions (3 plans)

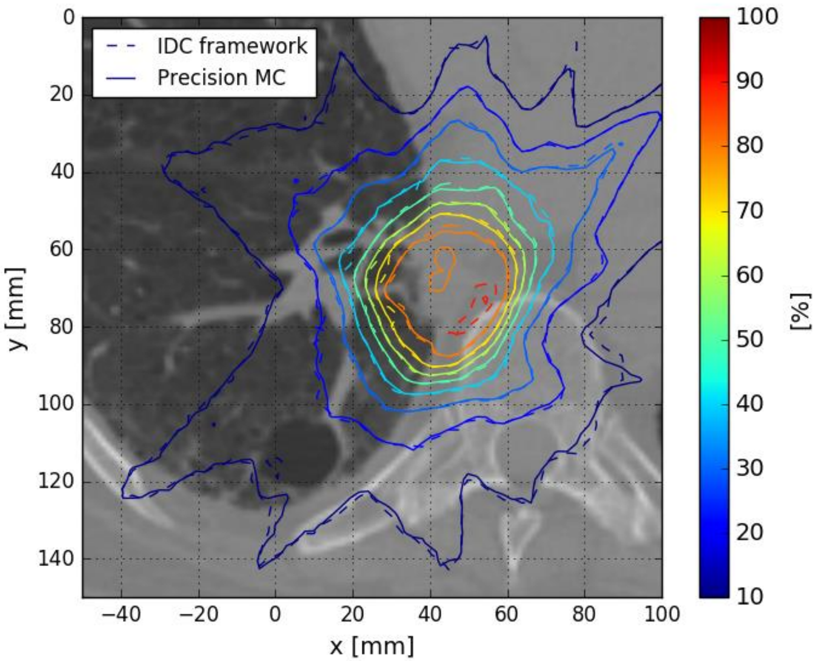
Phantom	Treatment Plan Segment Types	Measure (cGy)	Monte Carlo (cGy)	MC Diff
Head	A 30, Conf	408.3	403.7	-1.1%
Head	B 30, Conf	4085.4	4033.8	-1.3%
Head	C 35, Conf	406.7	402.8	-1.0%
Head	D 114, Many	393.4	389.9	-0.9%
Head	E 88, Many	393.3	393.5	+0.1%
DQAA16	F 13, Conf	414.6	405.7	-2.1%
DQAA16	G 55, Many	400.0	390.4	-2.4%
DQA	H 13, Conf	414.1	408.9	-1.3%
Cheese ++	I 37, Conf	715.1	694.3	-2.9%
Heterogeneous Phantom Measurements				
XLT Lung	J 22, Conf	341.3	341.0	-0.1%
XLT Lung	K 100, Many	338.7	342.4	+1.1%
RPC Lung (*)	L 126, Many	562.3	568	+1.0%
RPC Lung (*)	M 126, Many	550.4	562	+2.1%

(*) TLD measurement, otherwise ion chamber measurement

Comparison with EGSnrc

- Composed plan comparisons performed by Inselspital – University Hospital Bern, using an independently developed MC dose calculation framework (IDC)[1]
- 7 lung SBRT cases evaluated
  - Mean dose difference (EGSnrc-Precision)/Precision
  - 2% / 0.1cm gamma comparison for voxels greater than 10.0% of maximum dose

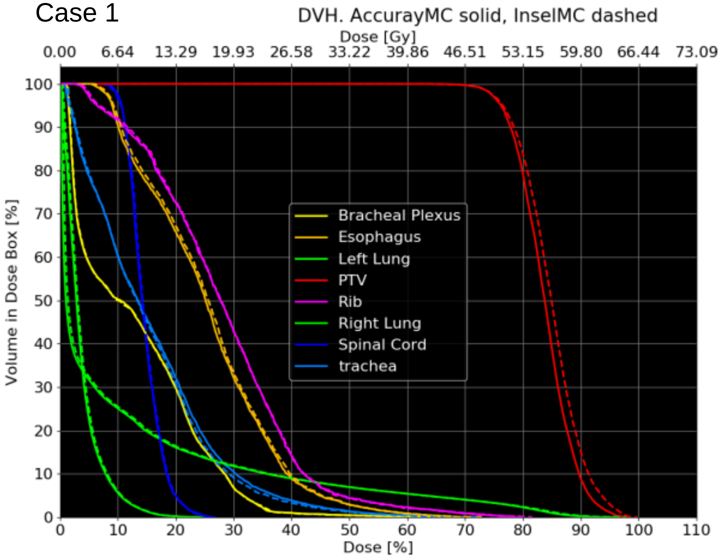
Case	PTV mean dose diff (%)	Lung V20 (%)	3D gamma passing rate (%)
1	1.4	1.5	99.7
2	-0.4	-1.5	97.9
3	0.0	0.0	99.5
4	2.3	0.0	99.1
5	-1.0	0.9	97.6
6	0.4	0.3	99.1
7	0.9	0.0	99.5



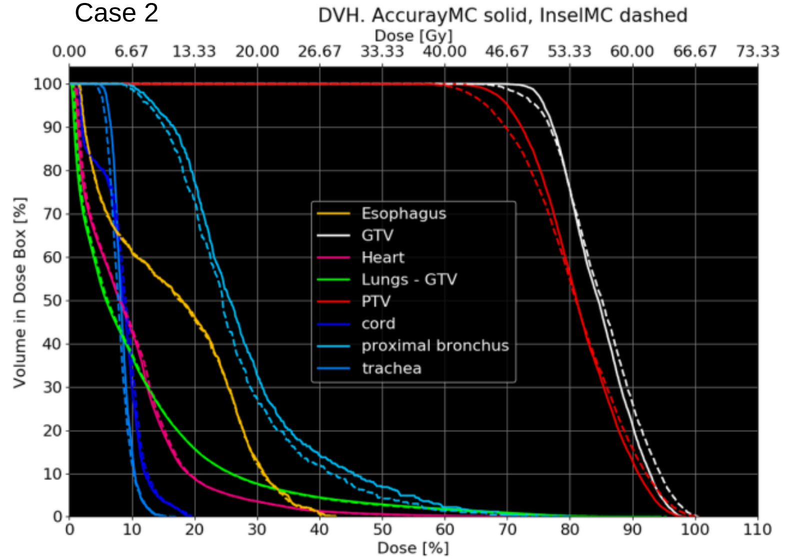
1. P.-H. Mackeprang, … M.K. Fix, P. Manser, (submitted to PMB)

Results

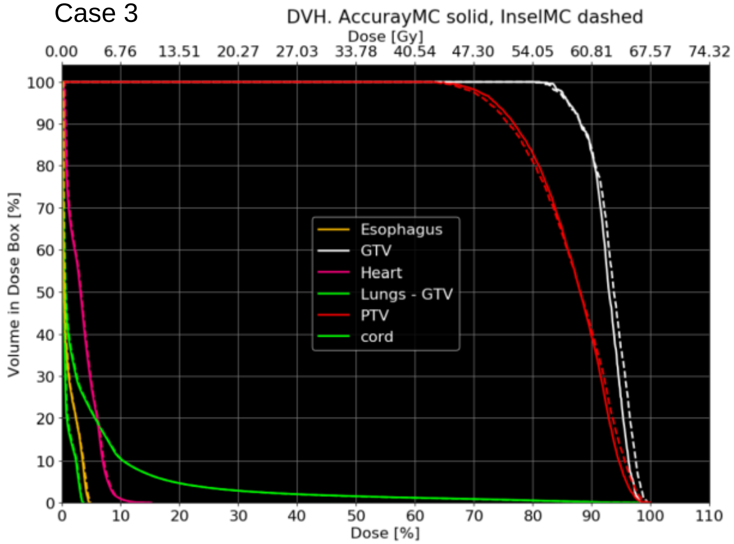
Case 1



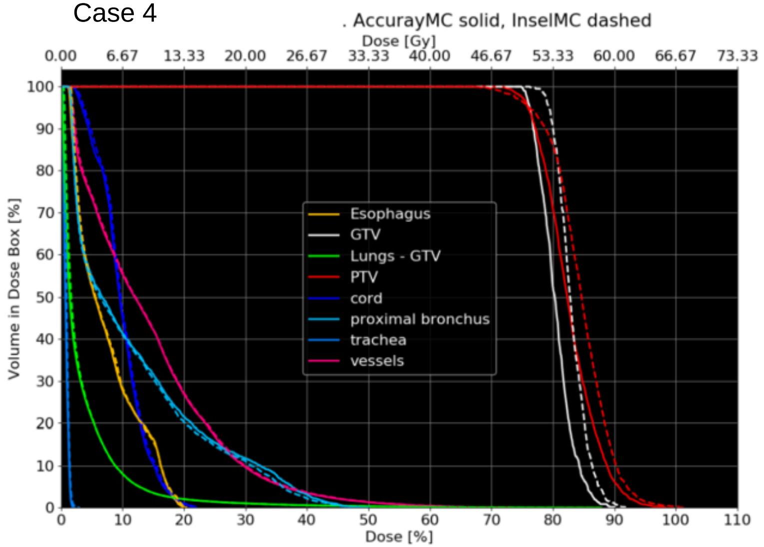
Case 2



Case 3



Case 4



Calculation Time Analysis

- In the Accuray Precision™ Treatment Planning System, Monte Carlo runs in 23 parallel threads on dual 6-core hyper-threaded CPUs
- Calculation times depend on the number of photons sampled
- The number of photons sampled (n_{hist}) is calculated from:
  - The number of voxels
  - The desired calculation uncertainty (u)
  - The mean equivalent square size of the MLC shapes ($\overline{EQS}$)

$$n_{hist} = H_{ref}{}' \left(\frac{1}{u}\right)^2 \left(\frac{V}{v}\right)^{2/3} \frac{1}{\overline{\overline{(EQS^2)}}}$$

  - $H_{ref'}$ = 1.4E6, V = target volume, v = voxel volume

This algorithm is implemented in Accuray Precision v1.1.1

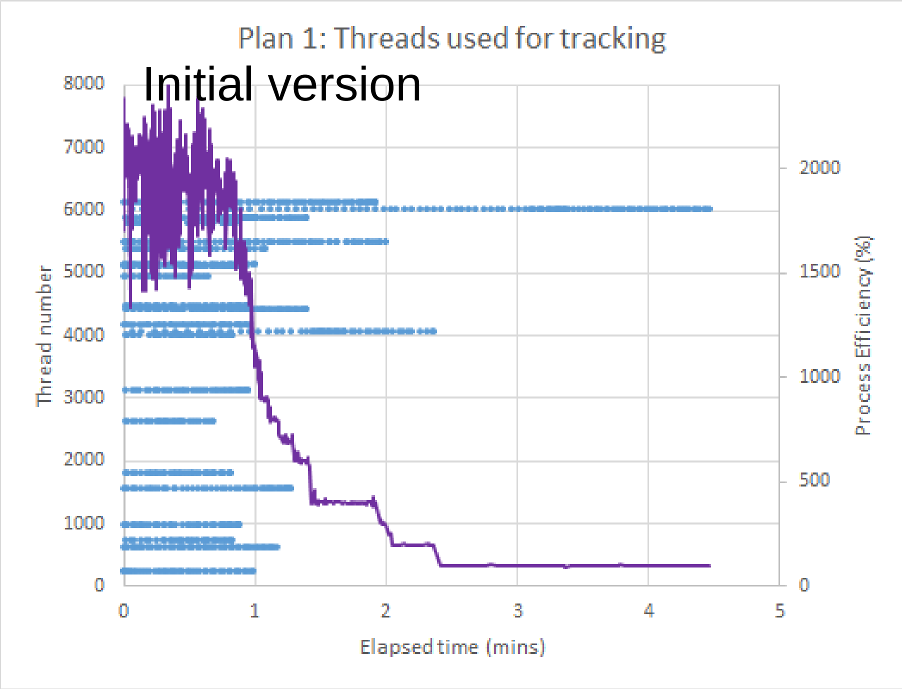
Sample Calculation Times

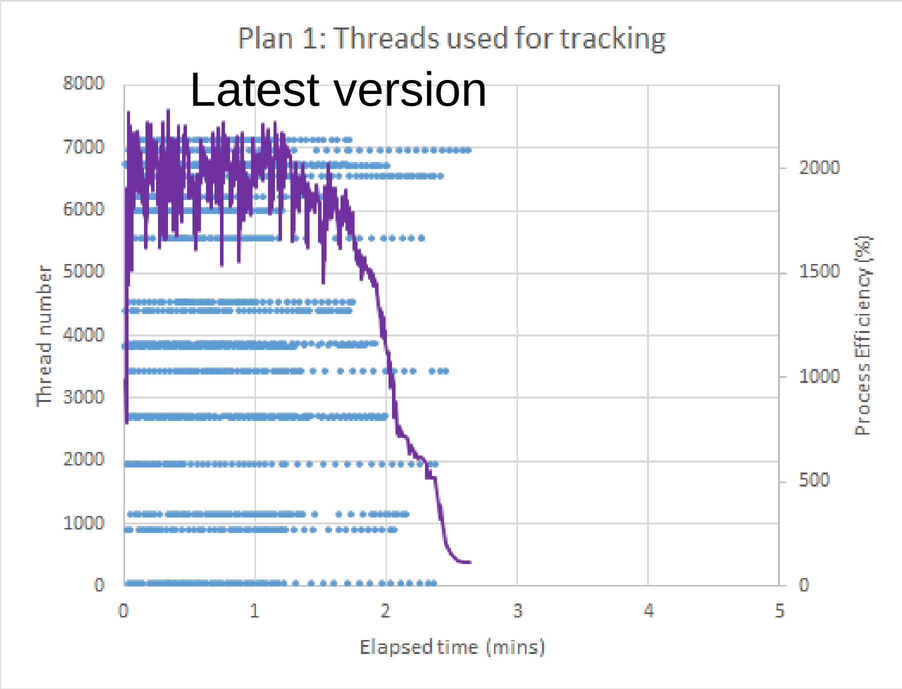
- All plans are lung SBRT using actual patient CT and volumes
- All cases calculated at medium resolution (256 x 256 x number of slices) with a requested uncertainty of 2.0%
- Time is from calculation button clicked to display of isodoses and DVH

Case	PTV (cm^3)	Voxel size at medium res (mm)	Number of Beams	Achieved Uncertainty (%)	Calculation Time (s)
1	93	2.2 x 1.0 x 2.2	23	1.9	142
2	14	1.7 x 1.5 x 1.7	24	2.1	61
3	22	2.2 x 1.3 x 2.2	22	1.8	57
4	22	2.3 x 1.5 x 2.3	19	2.2	52
5	30	1.7 x 1.0 x 1.7	21	1.9	101
6	39	2.0 x 2.5 x 2.0	24	1.7	44
7	83	2.0 x 1.3 x 2.0	21	1.9	140

Calculations performed using Precision v1.1.1 on a Dell T7910, 2 x 2.40Gz CPU, 64 GB RAM

Multi-Threading





- Initial version allocated equal numbers of beams to each thread
- Latest version allocates equal number of sampled photons to each thread
- Thread balancing has improved significantly, but further improvement is possible by balancing based on estimated number of transported photons

Calculations performed using Accuray Precision v1.1.0 (left) vs. v1.1.1 (right)

Conclusion

- Most recent version of Accuray Precision treatment planning system includes a Monte Carlo dose calculation algorithm that can calculate dose for MLC collimated beams

- The algorithm computes dose with clinically acceptable agreement with measurement in both homogeneous and heterogeneous media

- The algorithm has a balanced parallel implementation and takes advantage of multiple variance reduction techniques that lead to clinically realizable calculation times