GPU Based Convolution/Superposition Dose Calculation

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1) Johns Hopkins University

2) Elekta – Research

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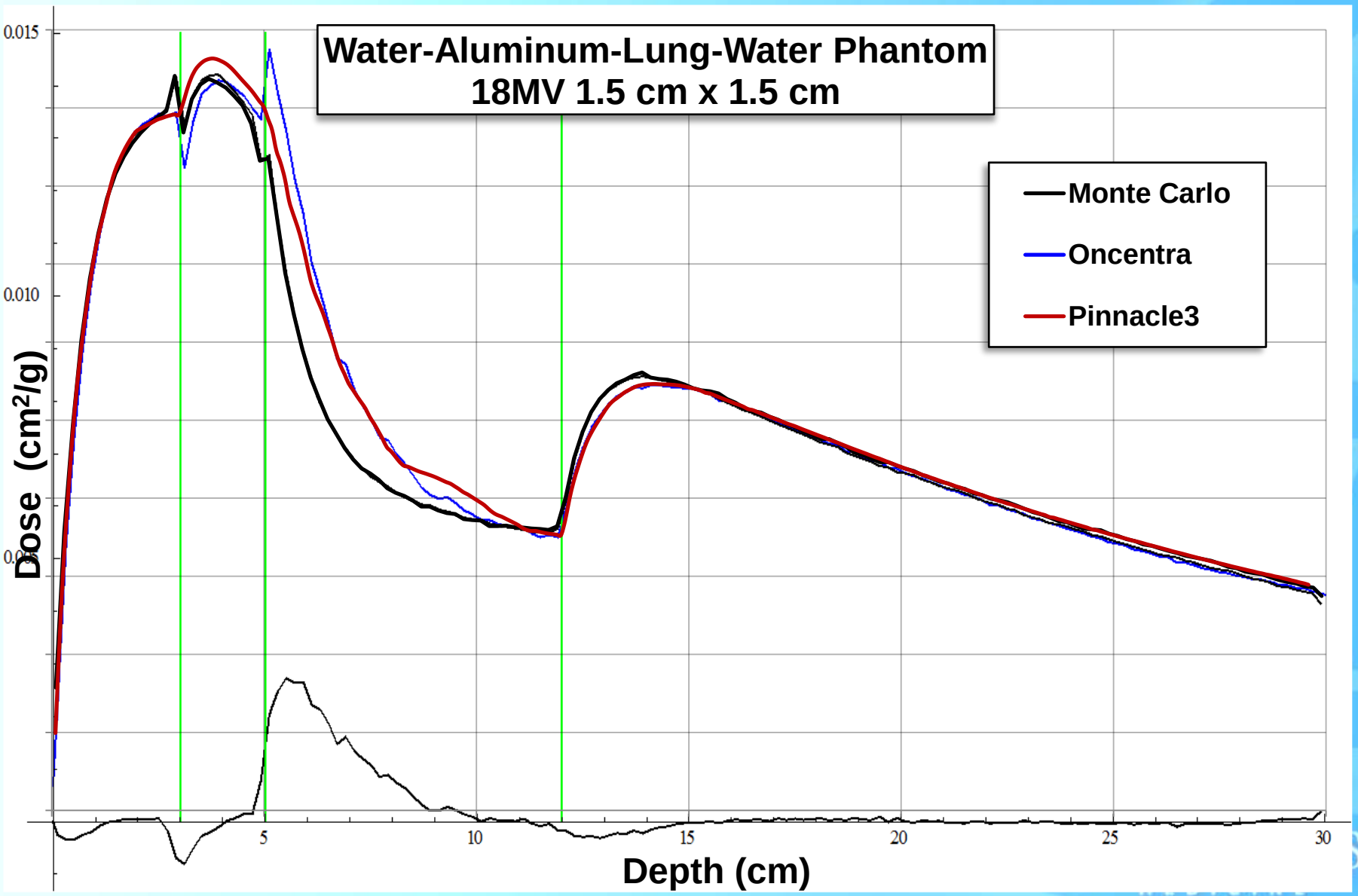
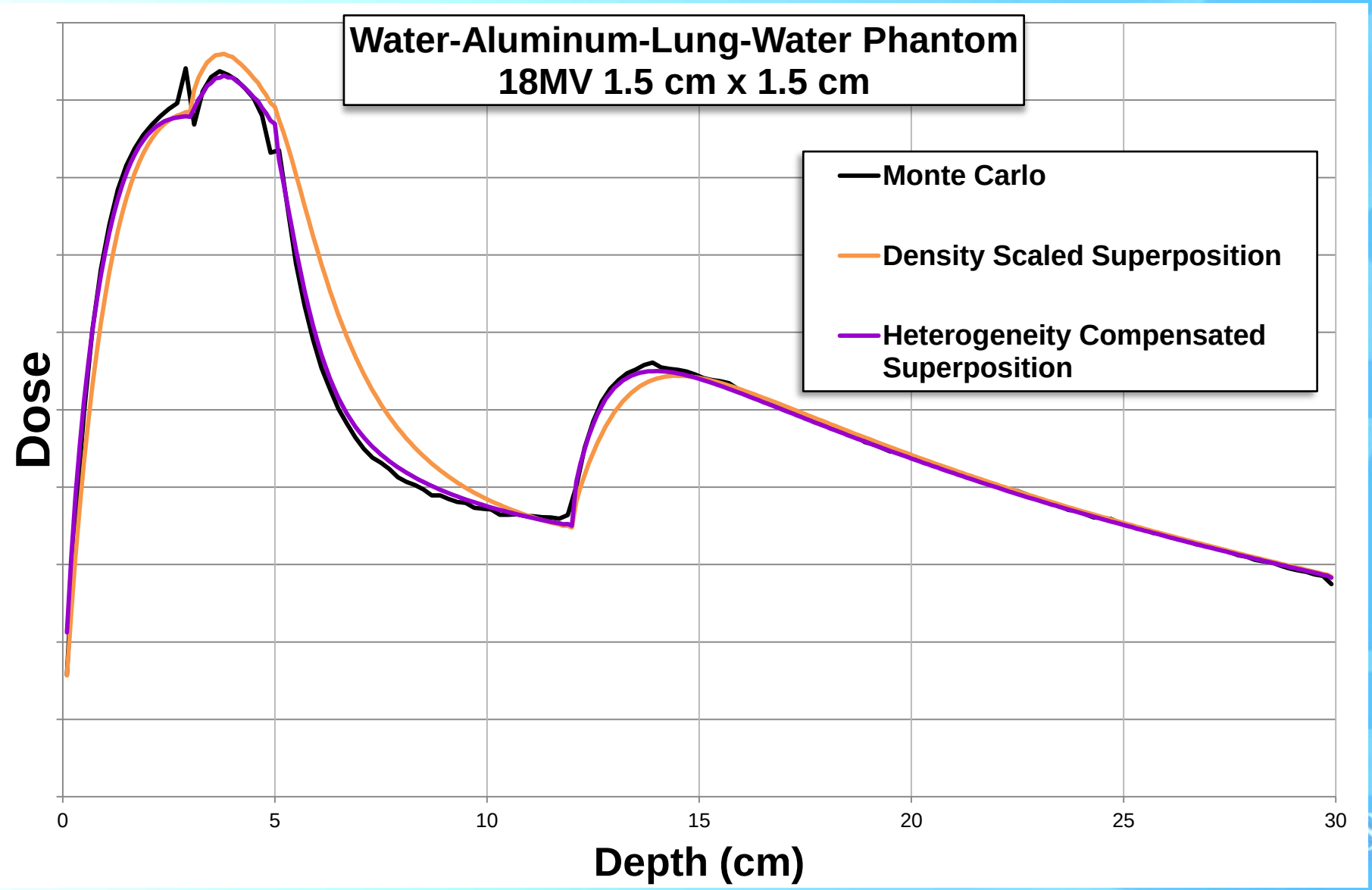
ICCR 2000 Monte-Carlo Photon Benchmark



JHU GPU Superposition



Superposition/Convolution

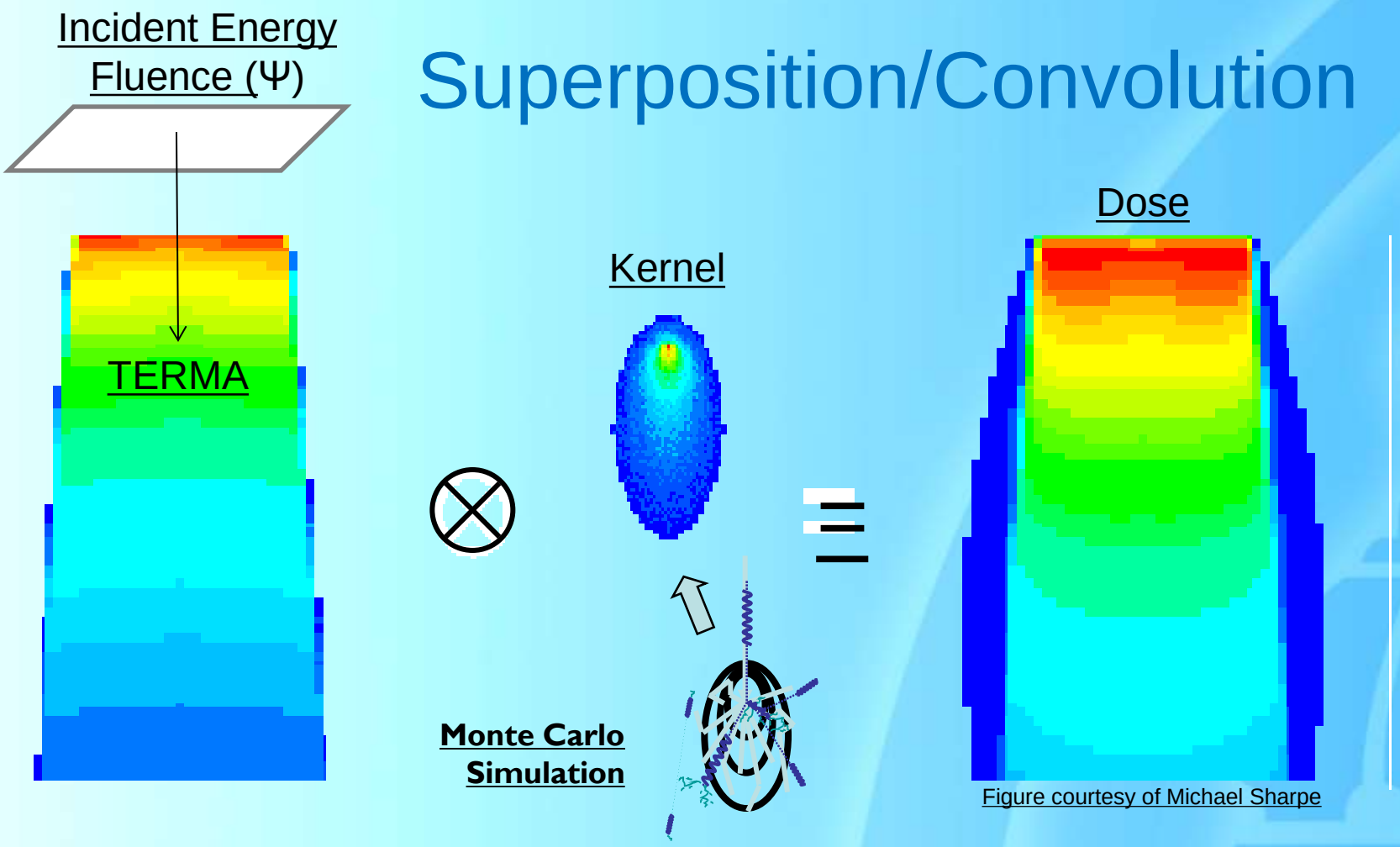


Figure courtesy of Michael Sharpe

$$D(r) = \iiint \sum_E \underbrace{\frac{\mu_E}{\rho(r')} \Psi_{E,0}(r') e^{\int_s^{r'} -\mu_E(t)dt}}_{TERMA} K_E\left(\int_r^{r'} \rho(t)dt, \omega(r,r')\right) \frac{1}{\|r-r'\|^2} dr'$$

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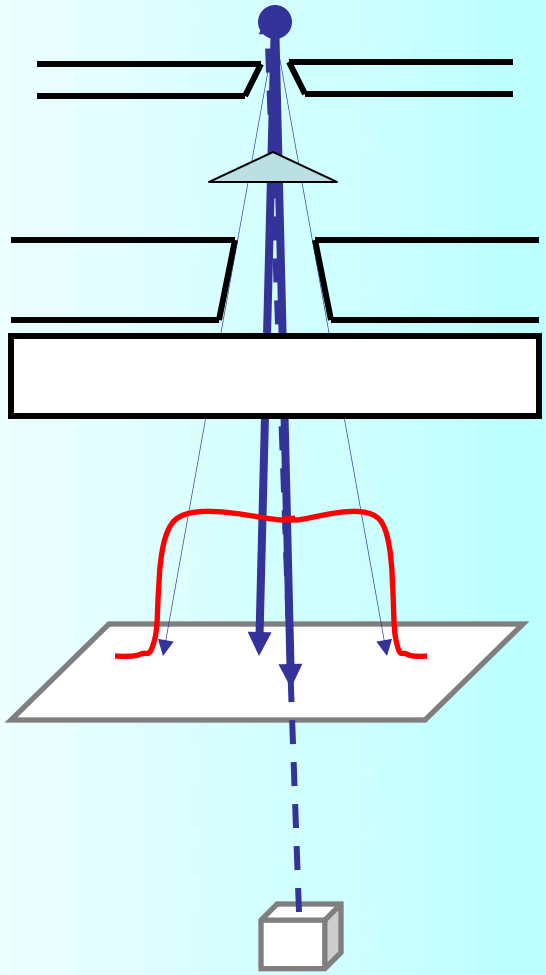
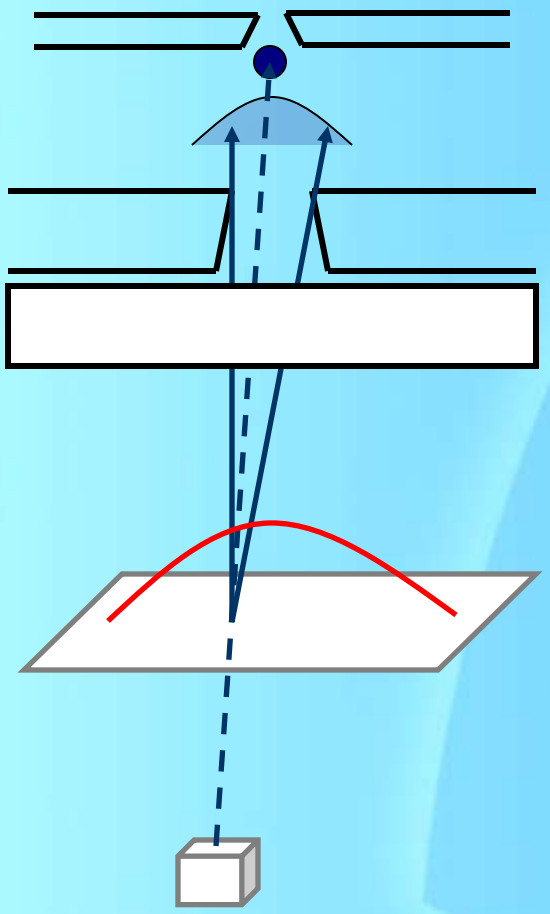
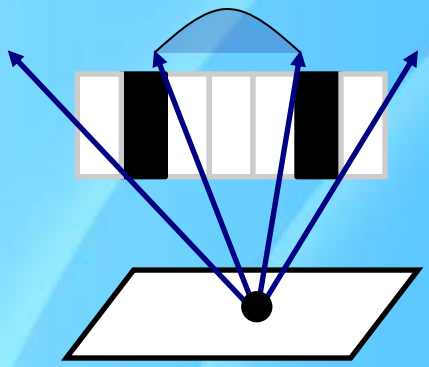
Incident Fluence Generation

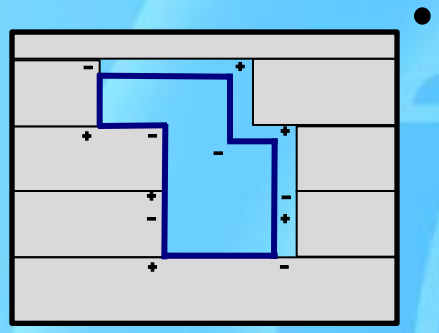
Primary Source

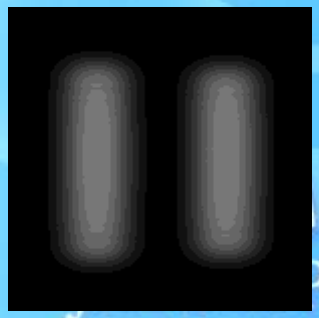


Secondary Scatter Source





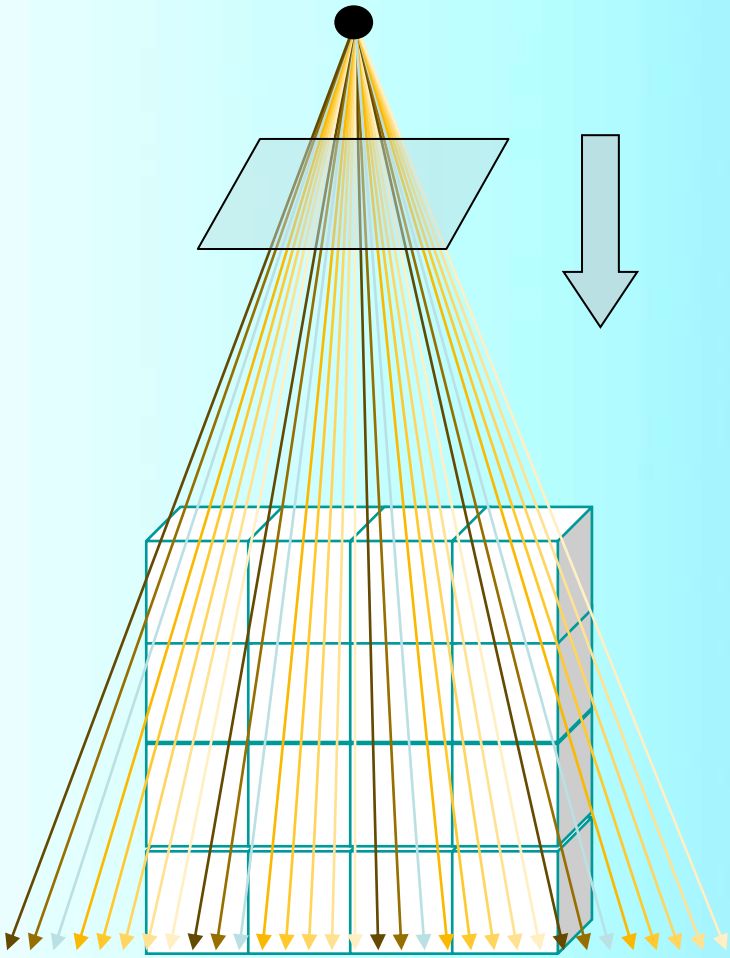




TERMA

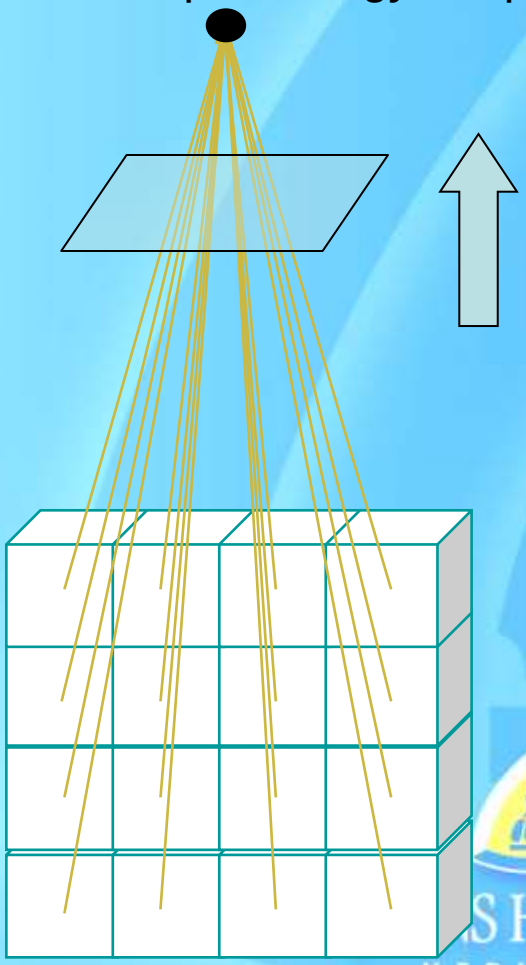
CPU

- # Rays = incident fluence pixels
- Serial processing of each ray
- Requires post processing to remove sampling noise



GPU

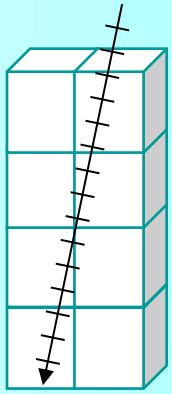
- # Rays = TERMA voxels
- Each voxel is its own process
- Avoids write on write conflicts
- Cache T/Ψ per energy bin per voxel

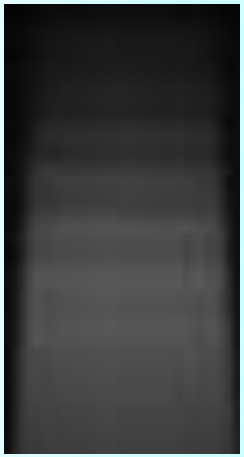


TERMA

CPU

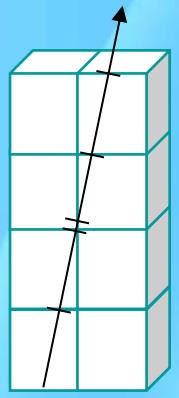
- Pre-compute lookup table for attenuation to avoid exponential
- Fixed step length
- Spectral changes in lookup table

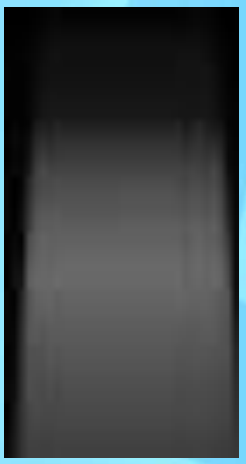


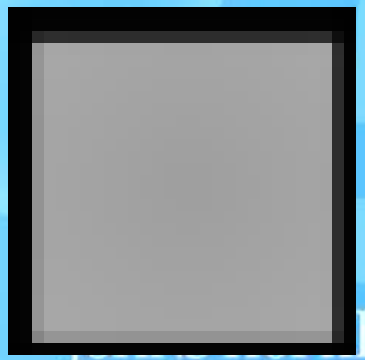


GPU

- Use GPU exponential
- Voxel boundary stepping
- **Attenuate each energy independently!**



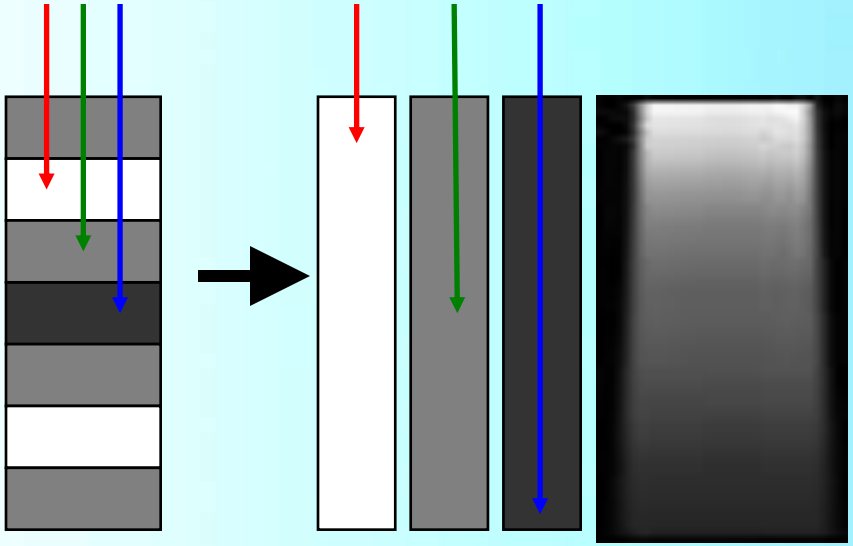




TERMA

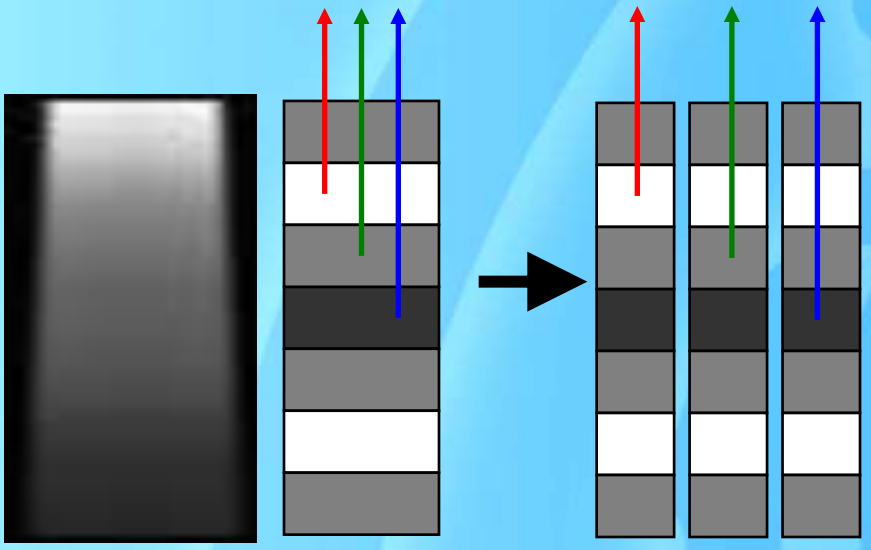
CPU

- Lookup table based attenuation
- Assumes material above is same as current position



GPU

- Exponential evaluation
- Enables correct beam hardening through heterogeneous media



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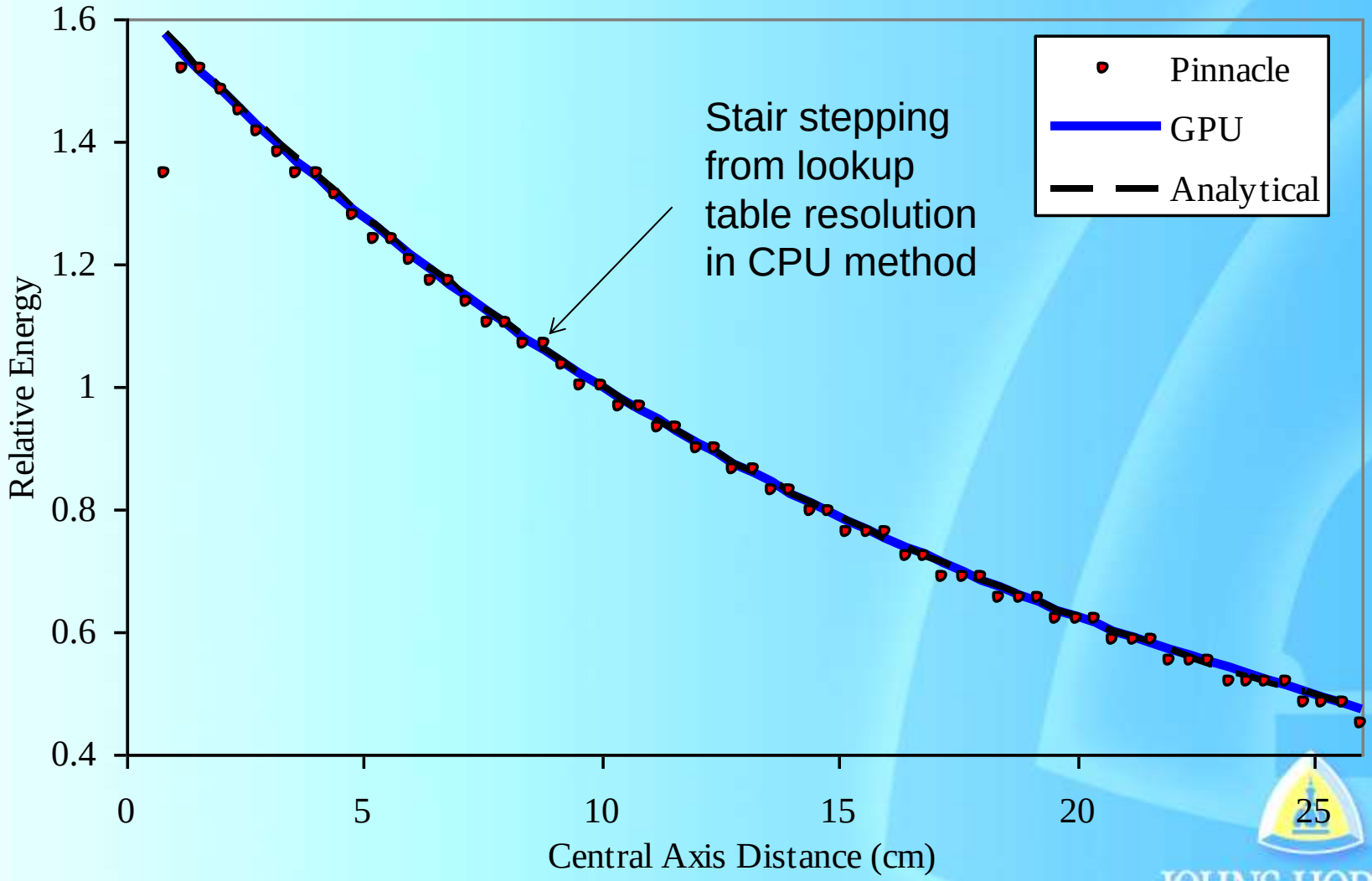
TERMA Accuracy



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TERMA Performance

Size	Forward	Back-projected	Homogenous Approximation	Intensity Modulation
64^3	**44ms**	**4ms**	**2ms**	**<1ms**
128^3	150ms	35ms	27ms	1ms
256^3	1869ms	438ms	363ms	10ms

- Rearranged attenuation equation improves back-projection performance

$$\int_{r'}^{s} -\mu_E(t)\,dt = -\sum_M \frac{\mu_{E,M}}{\rho_M} \int_{r'}^{s} \alpha_M(t)\,\rho(t)\,dt$$

- 'Attenuation' volume caching for Intensity Modulation:

$$A(r') = \sum_E w_E(r') \frac{\mu_E}{\rho(r')} e^{\int_s^{r'} -\mu_E(t)dt}$$

$$T(r') = \Psi_0(r')\,A(r')$$

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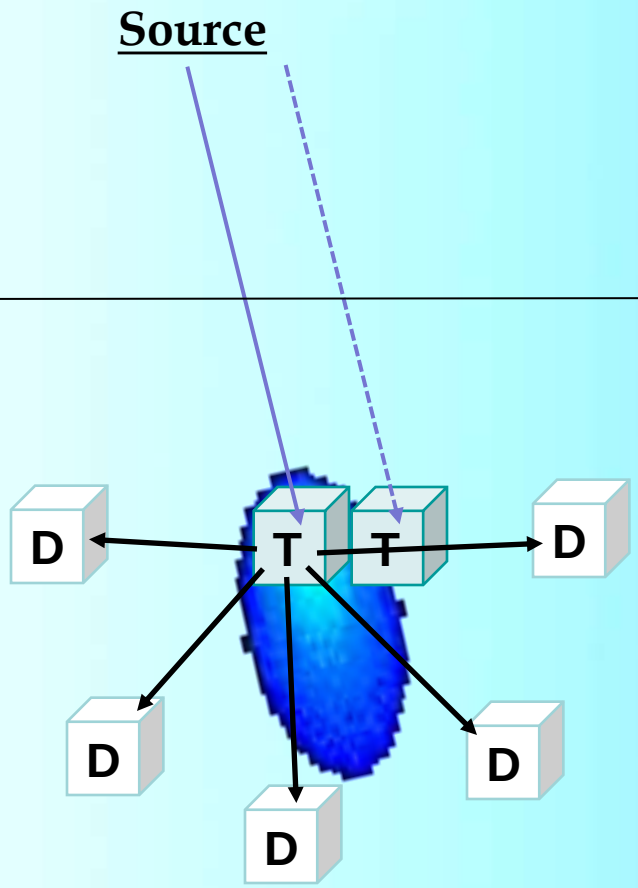
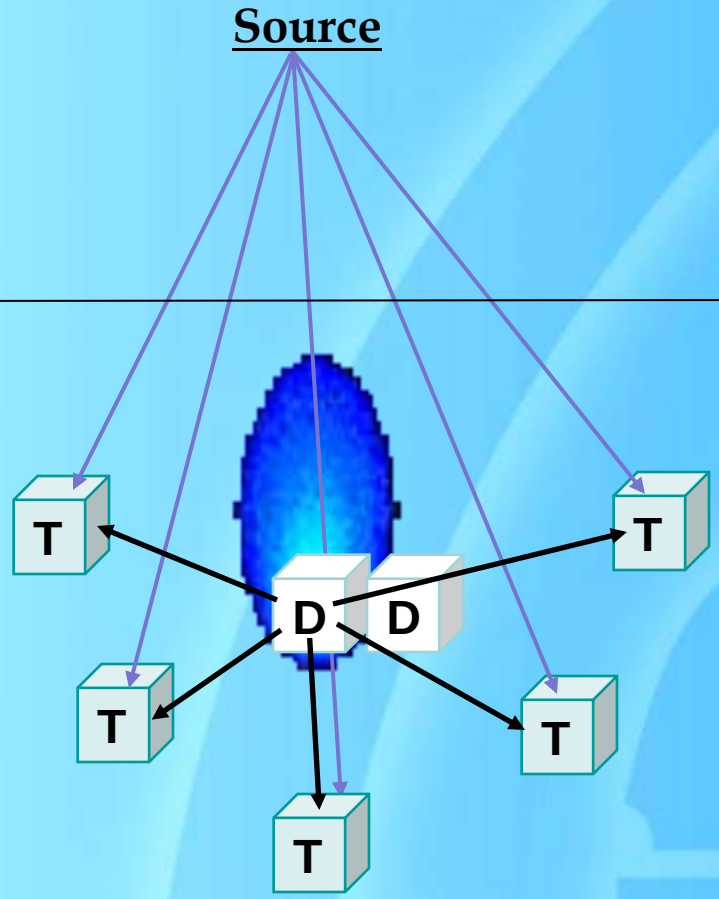
Superposition

CPU



- Each TERMA voxel is a process
- Read once From TERMA
- Write many to Dose
  - Write on Write errors

GPU or CPU



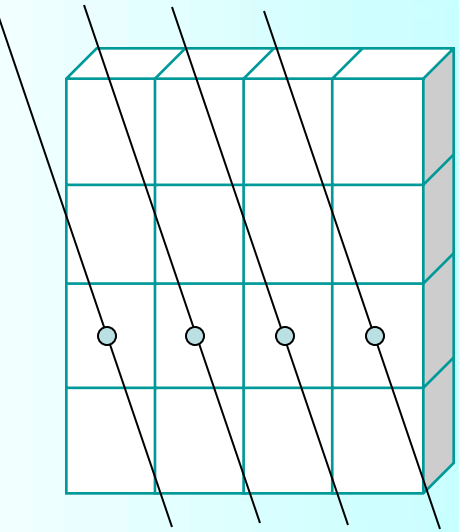
- Each dose voxel is a separate process
- Read many from TERMA
- Write once to Dose
  - No Write on Write errors
- Compute dose to single point

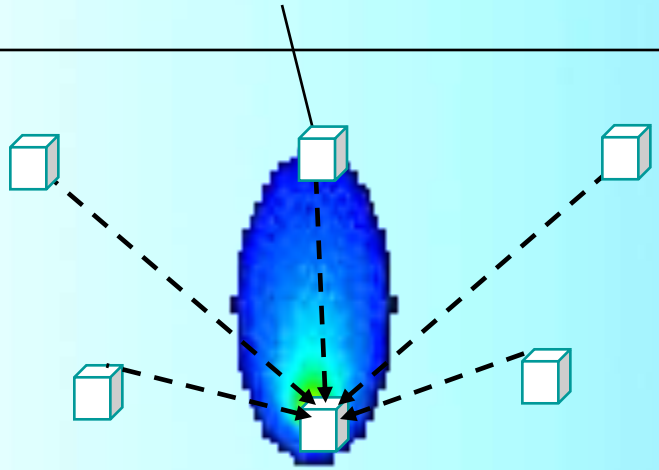
Superposition

CPU

Not Tilted

- Shared ray-tracing
- Process single ray direction for all voxels

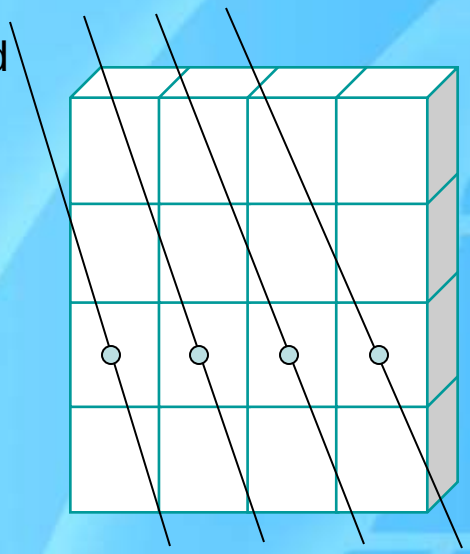


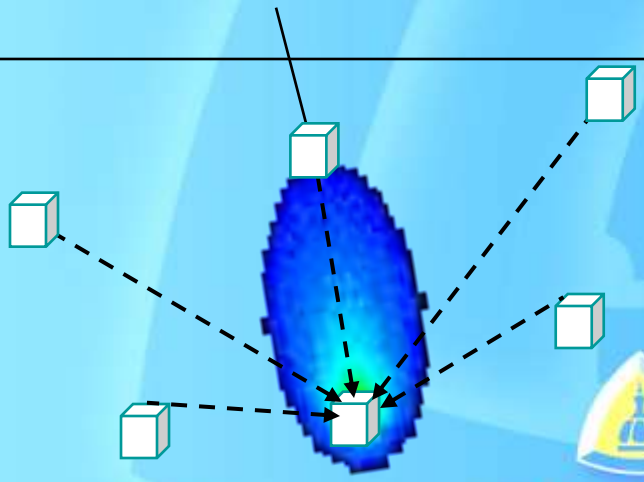


GPU

Tilted

- Each voxel is thread
- Read many write once





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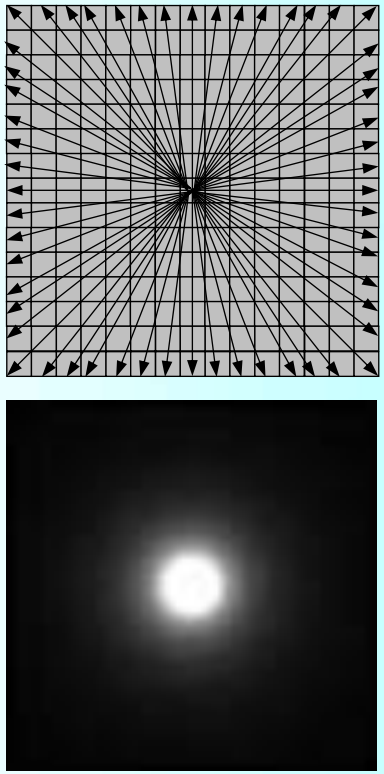
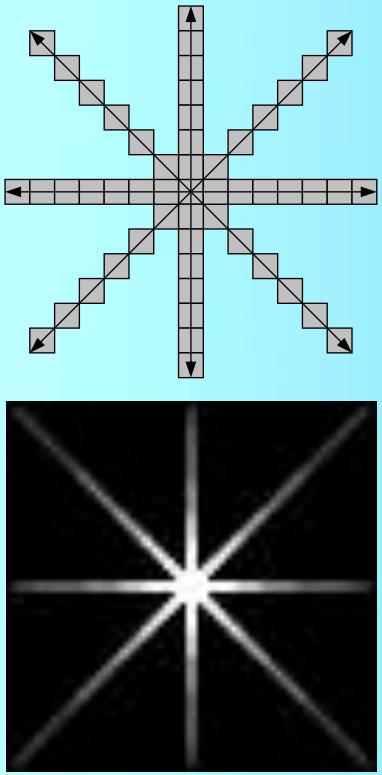
Multi-resolution Superposition

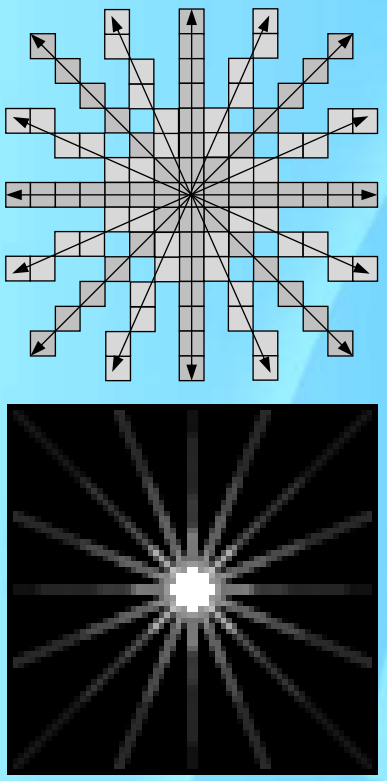
Ideal



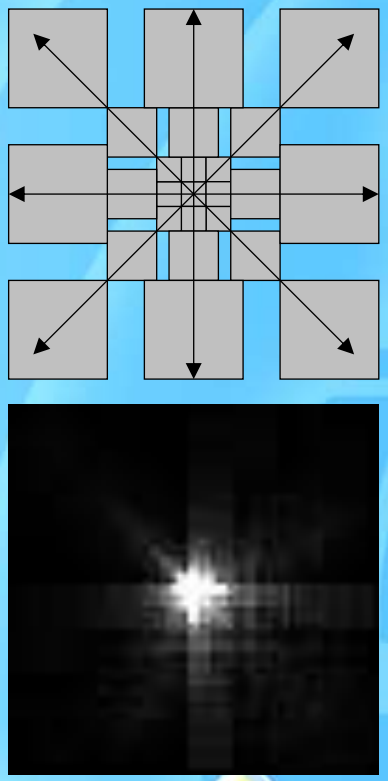
Standard



50% Azimuth Phase



Multi-resolution



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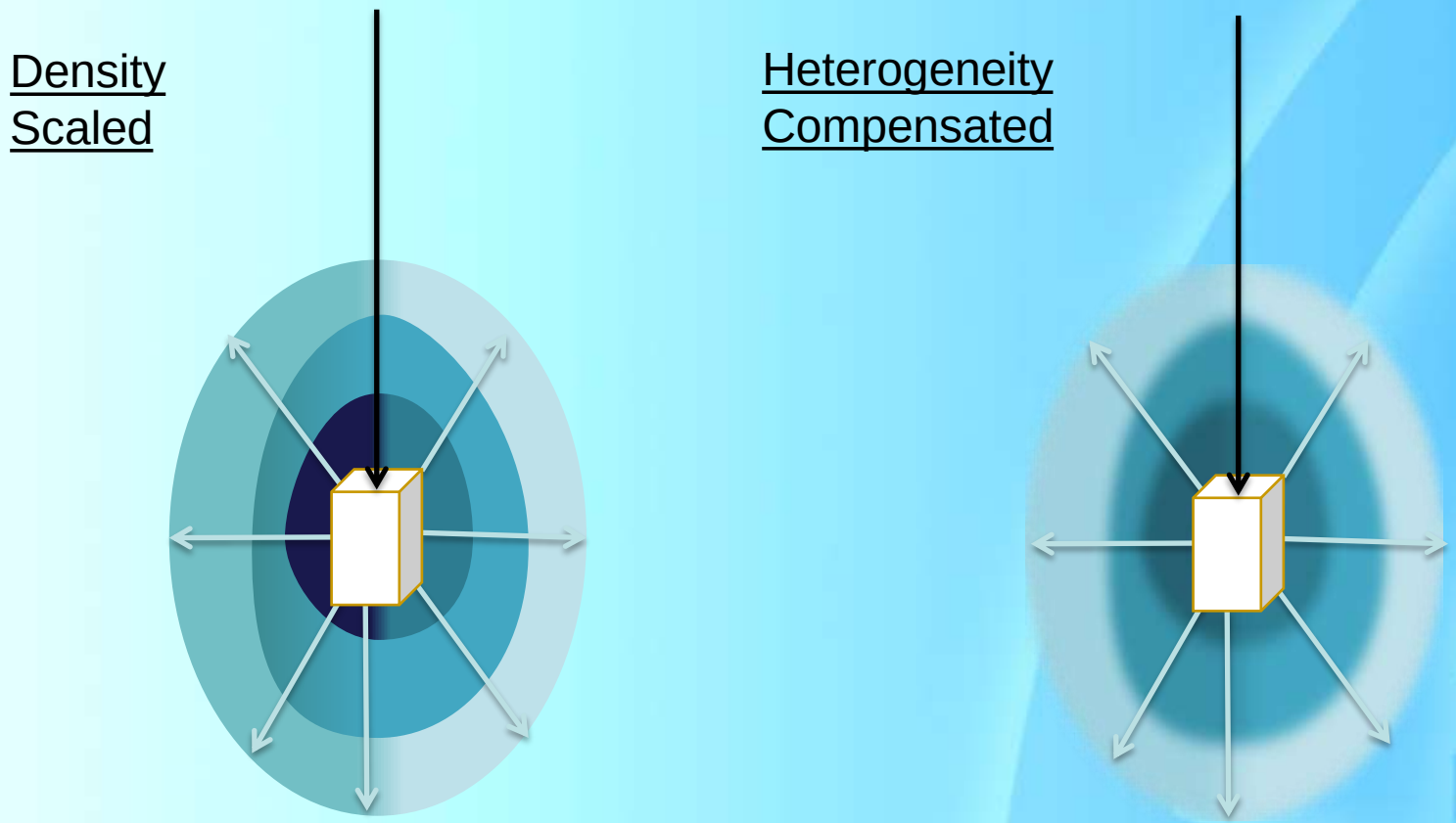
Heterogeneity Compensation



$$D(r) = \iiint \int_E T_E(r')\, K_E(r'-r)\, dE\, dr'$$

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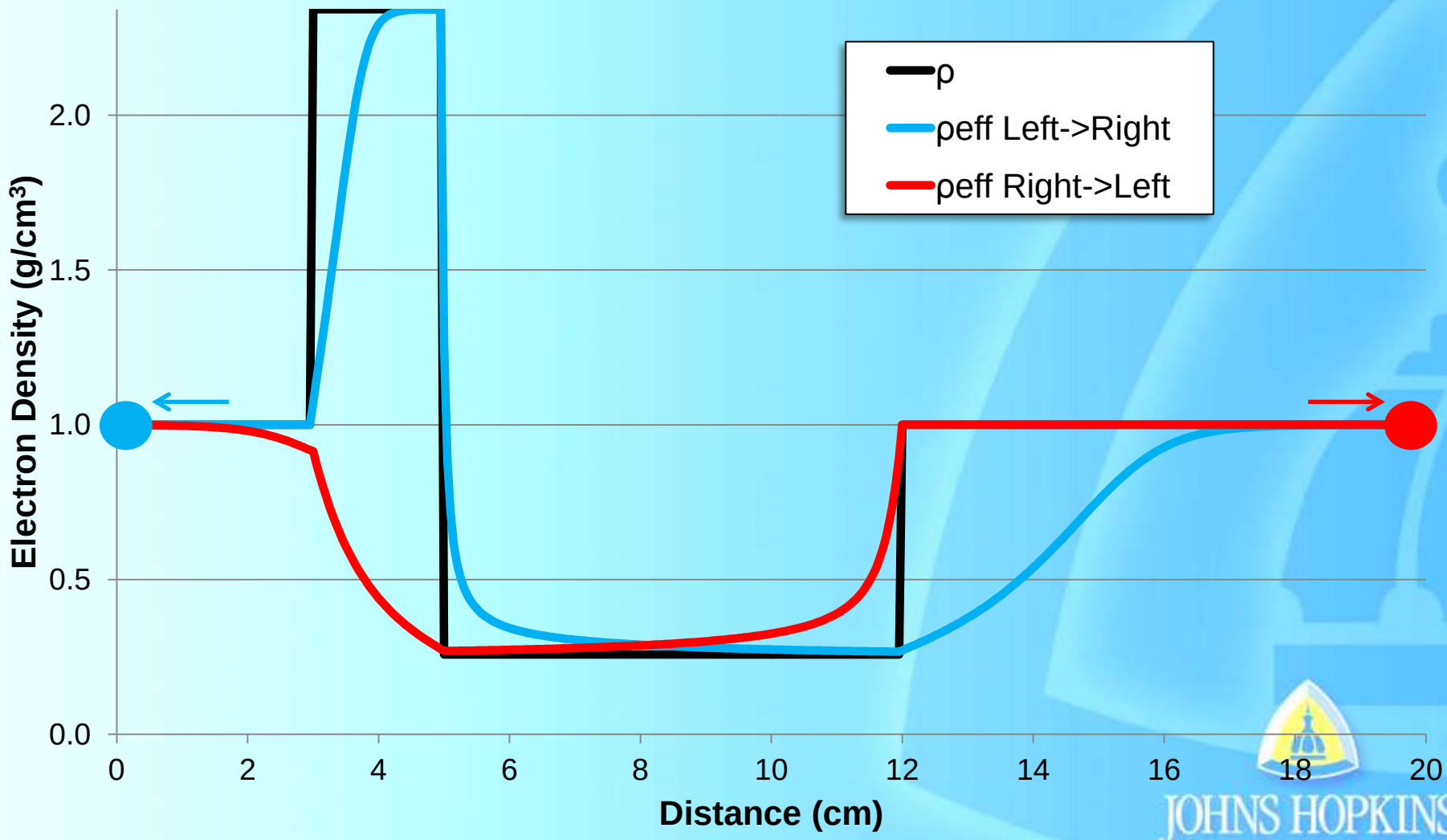
ρ-eff for different locations of dose deposition



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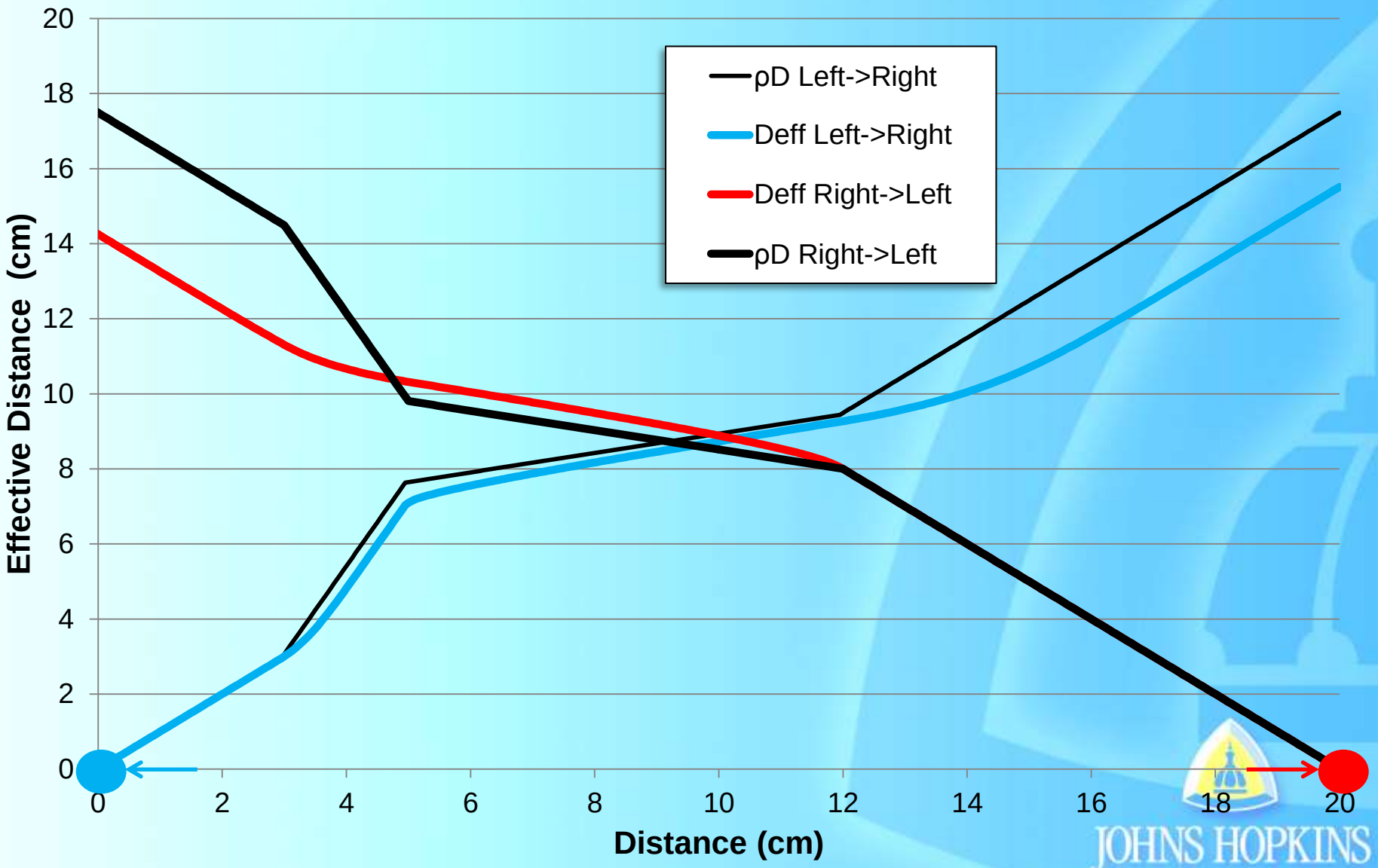
Effective Distance for Kernel Lookup



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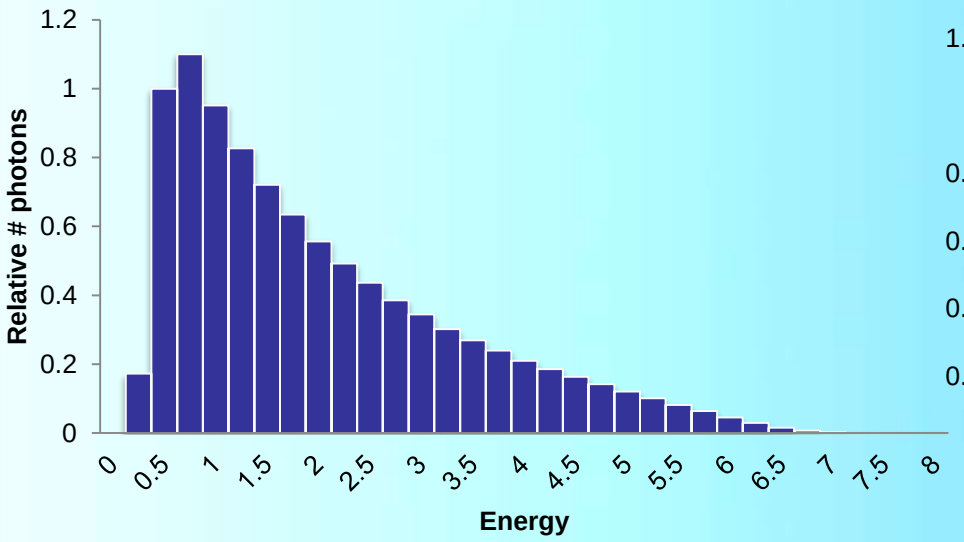
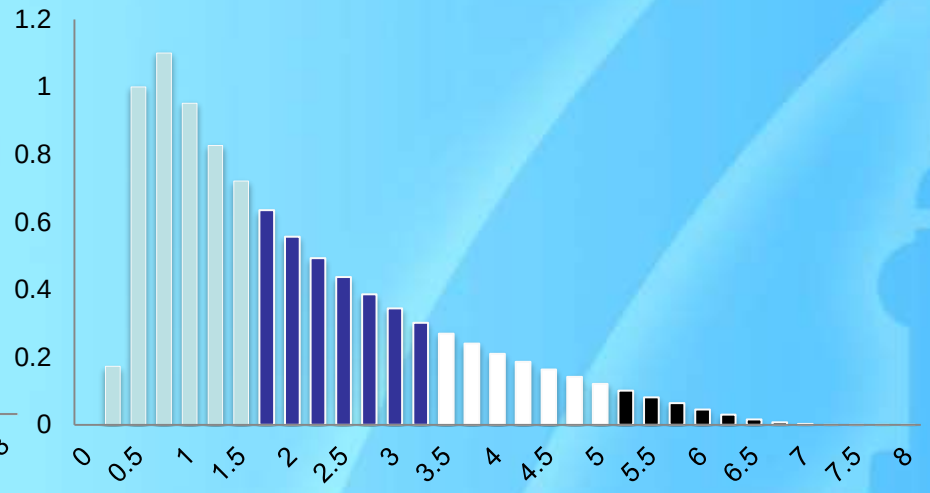
Kernel Hardening





- For each mono-energetic bin there is no hardening
  - Too many calculations
- Solution is to break spectrum up into parts and compute each part separately in parallel as full computation
- QUAD = 4 parts
- DUAL = 2 parts

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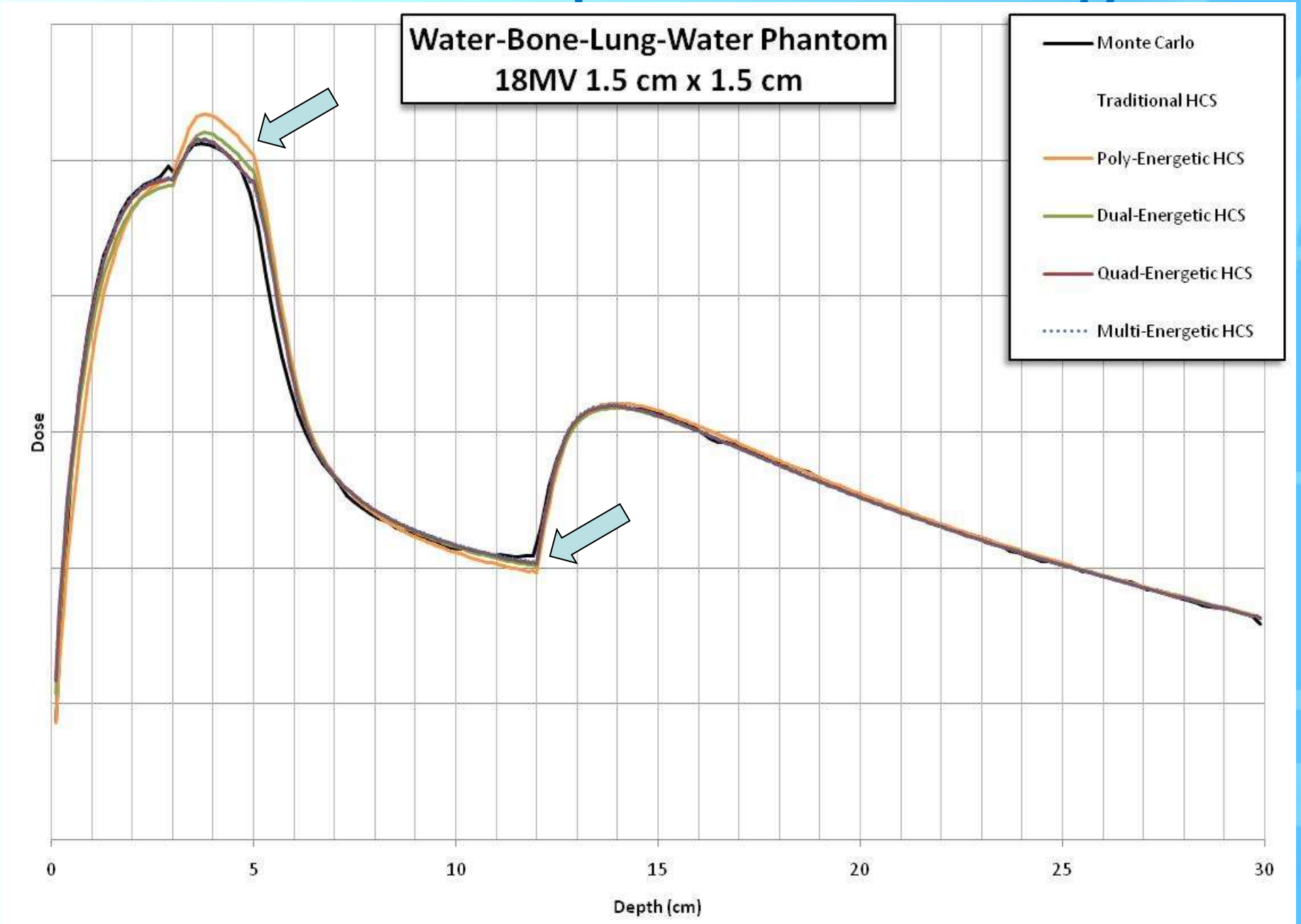
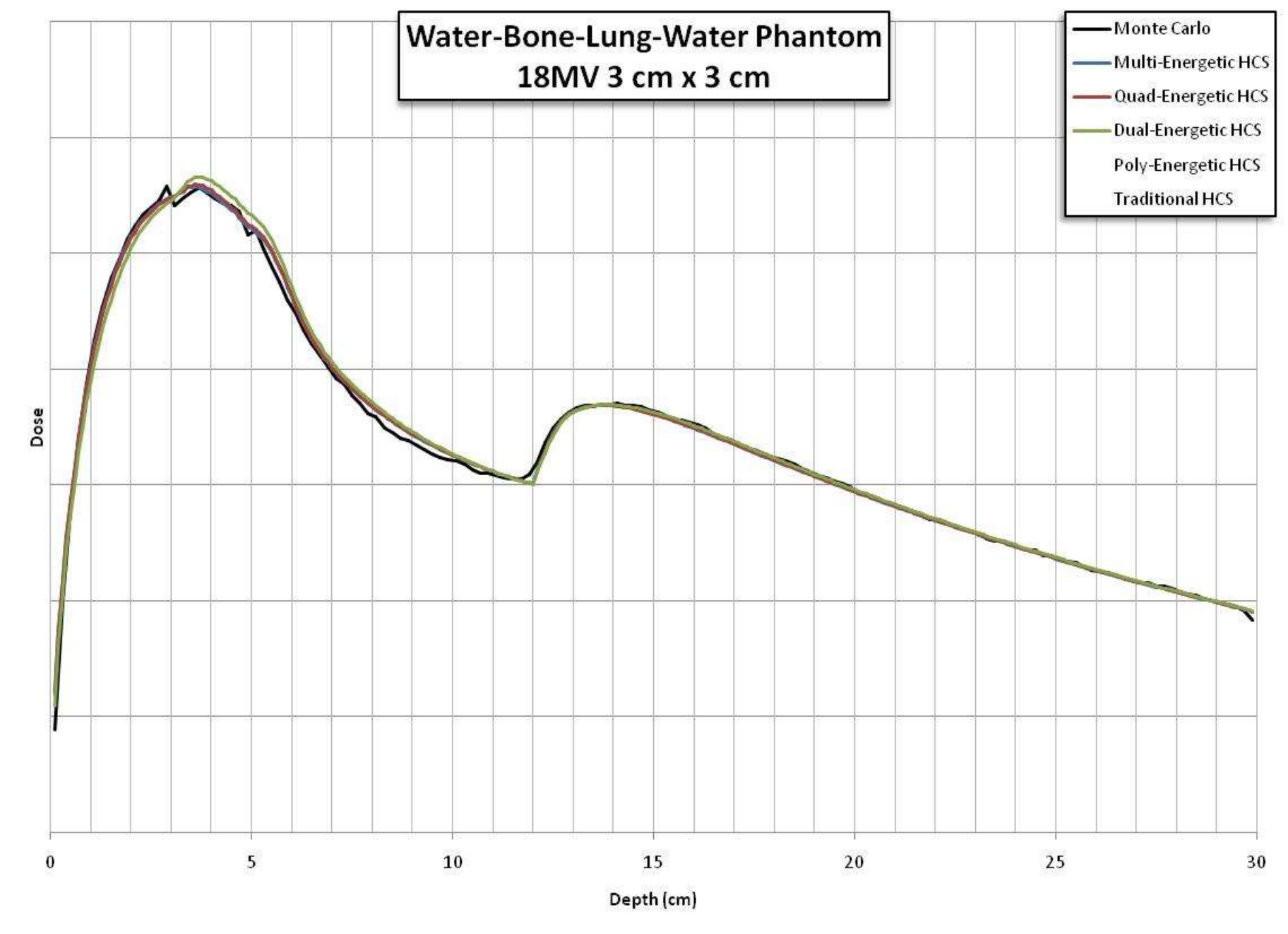
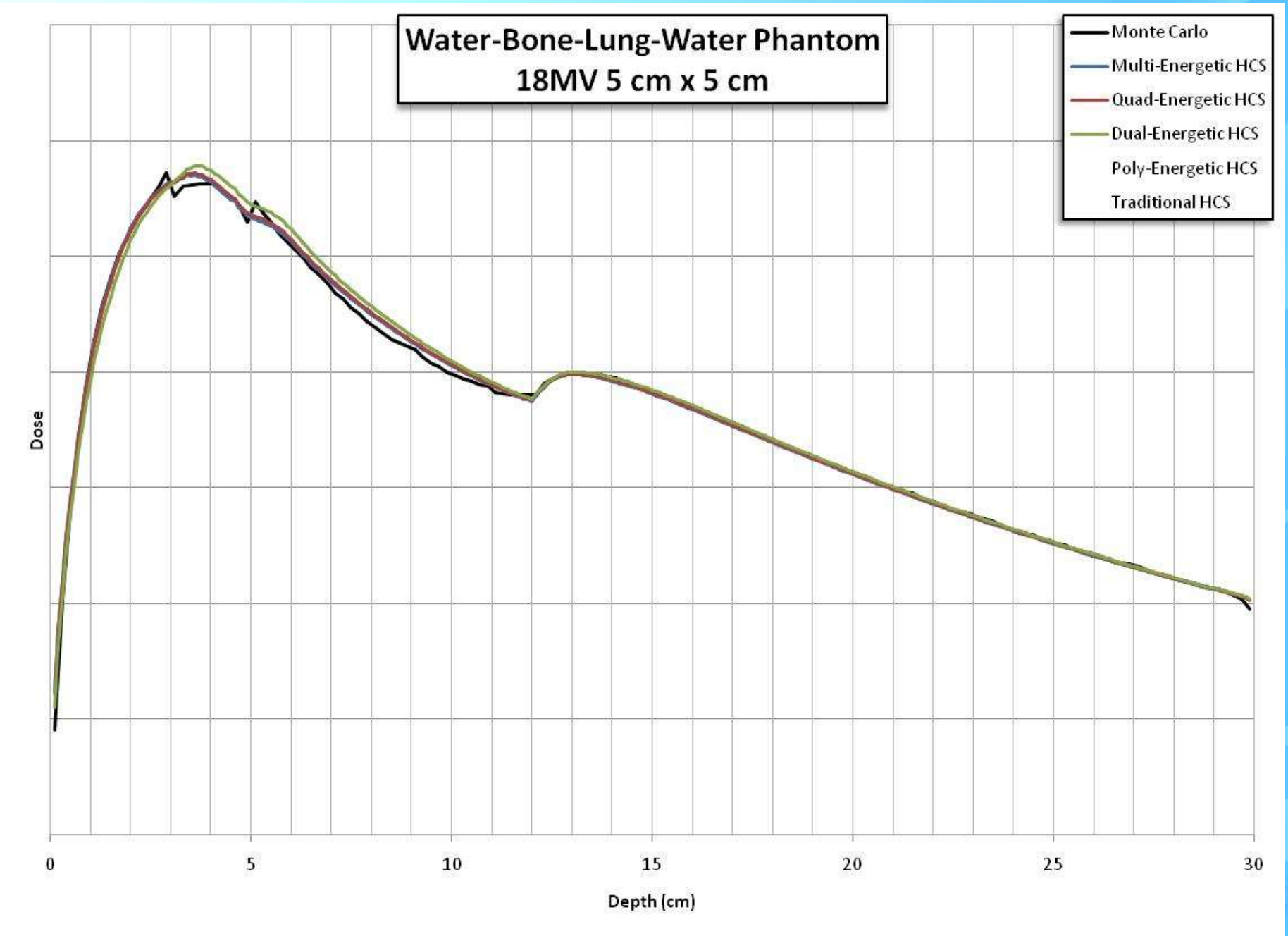
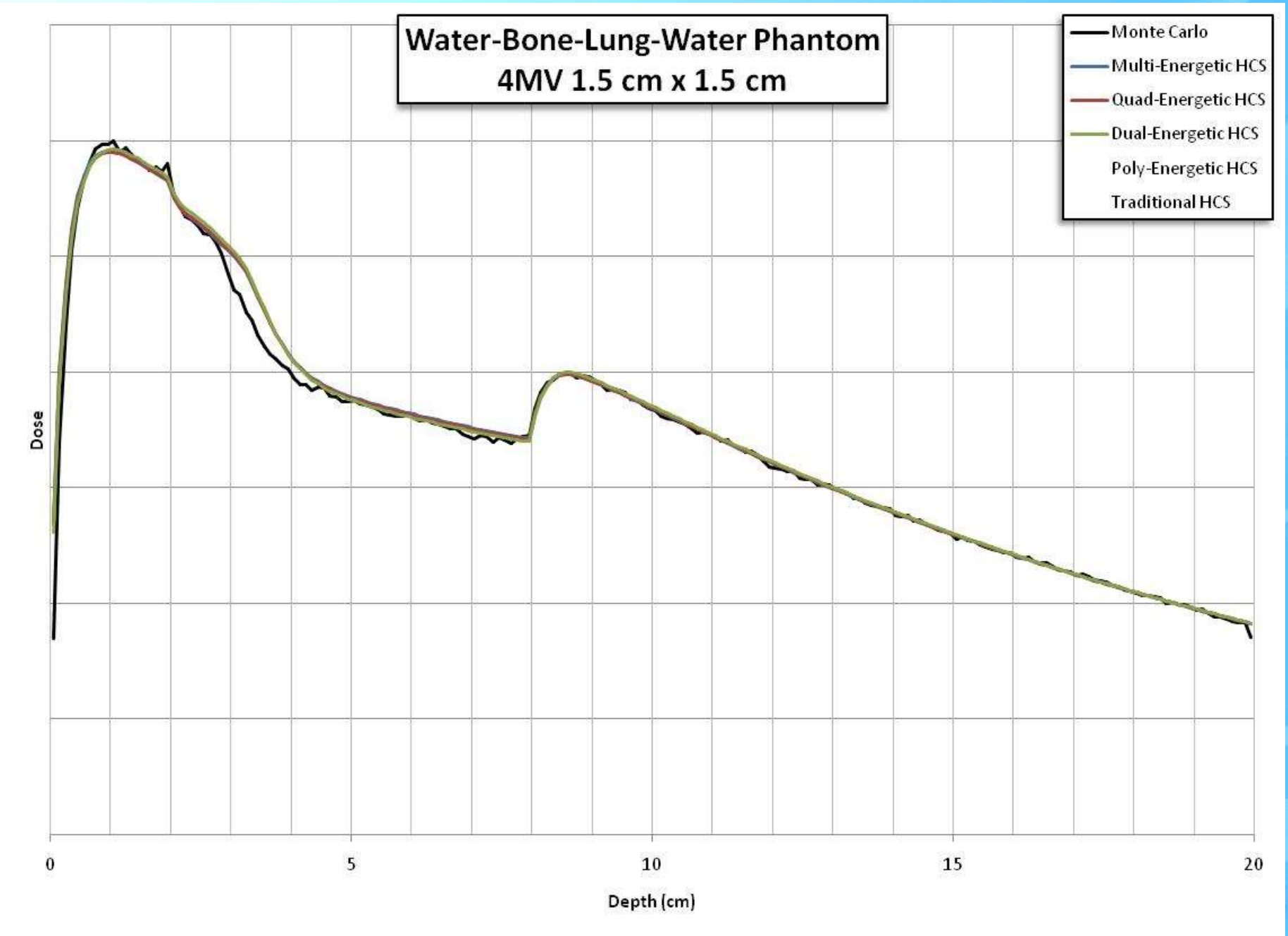
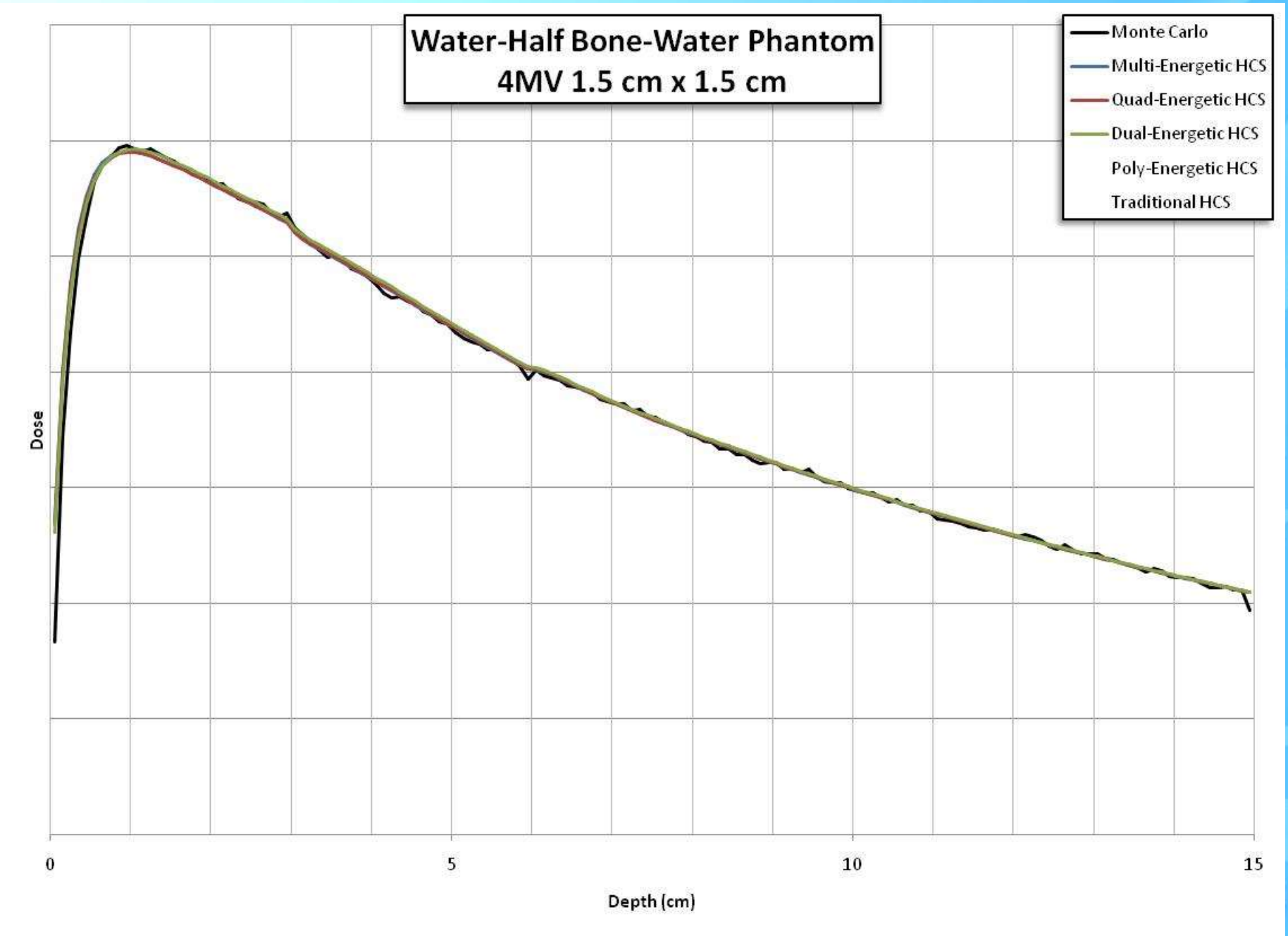
Effect of Spectral Binning

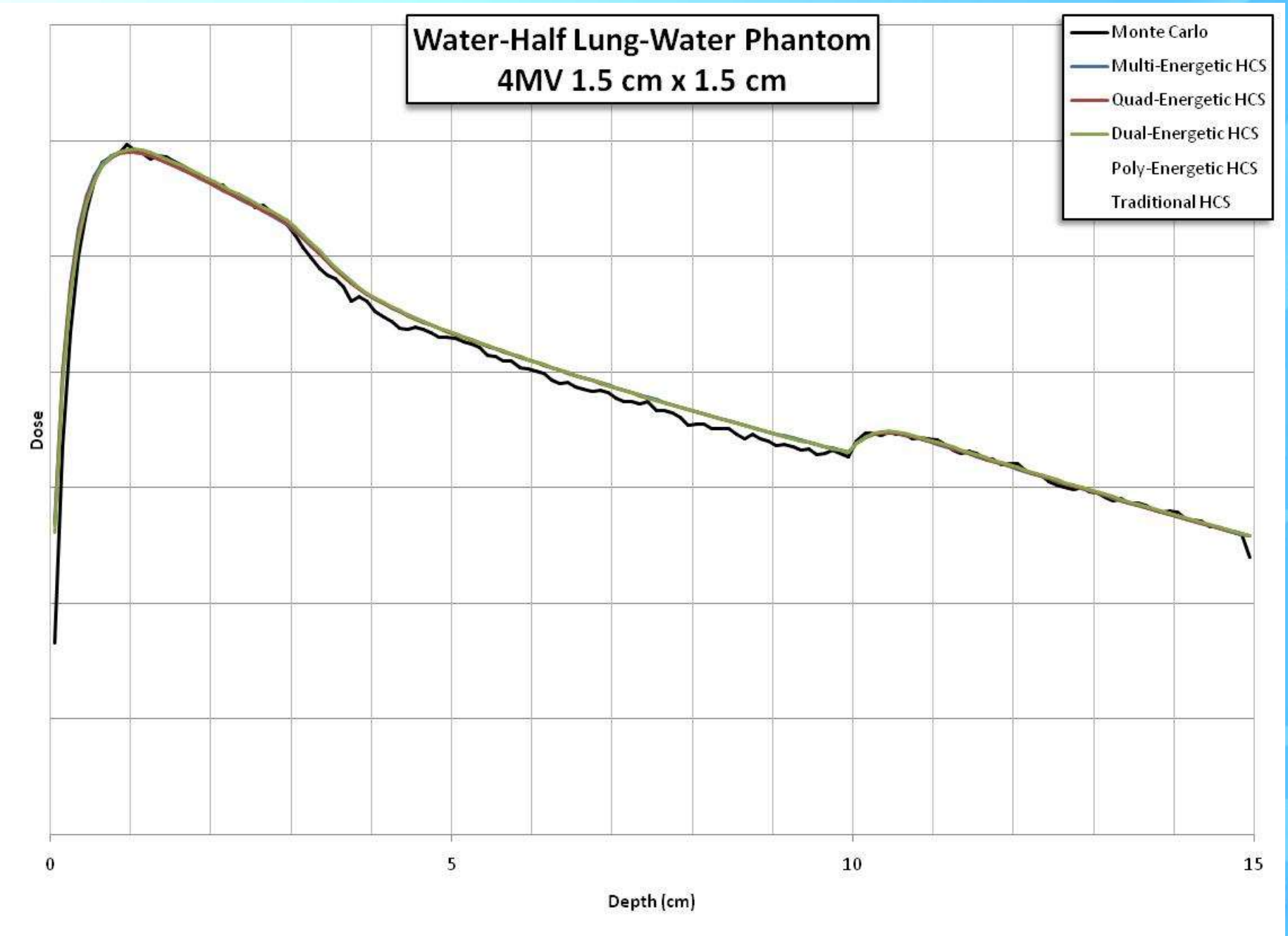


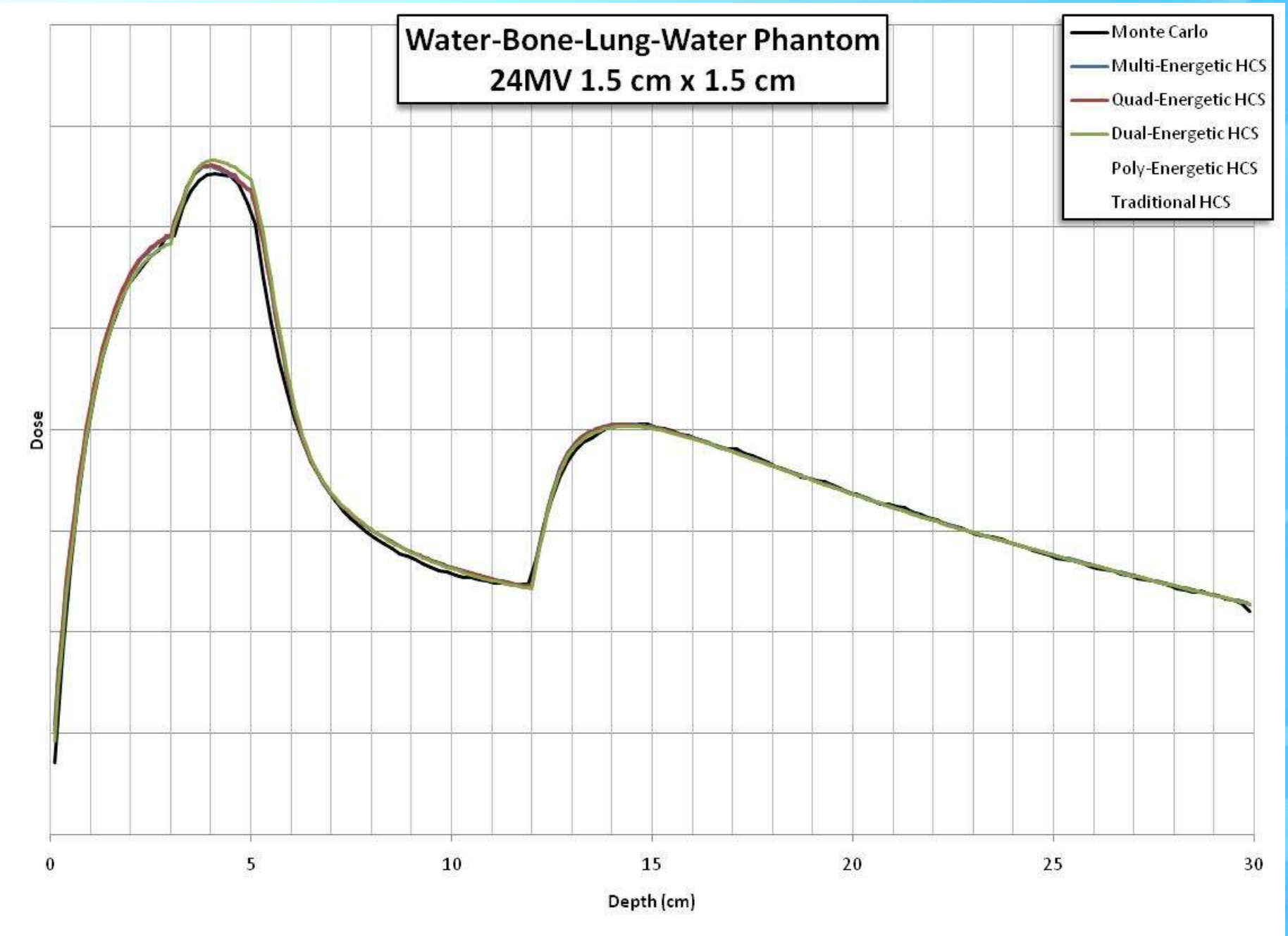

Water-Bone-Lung-Water Phantom
18MV 3 cm x 3 cm
Monte Carlo
Multi-Energetic HCS
Quad-Energetic HCS
Dual-Energetic HCS
Poly-Energetic HCS
Traditional HCS
Dose
0
5
10
15
20
25
30
Depth (cm)

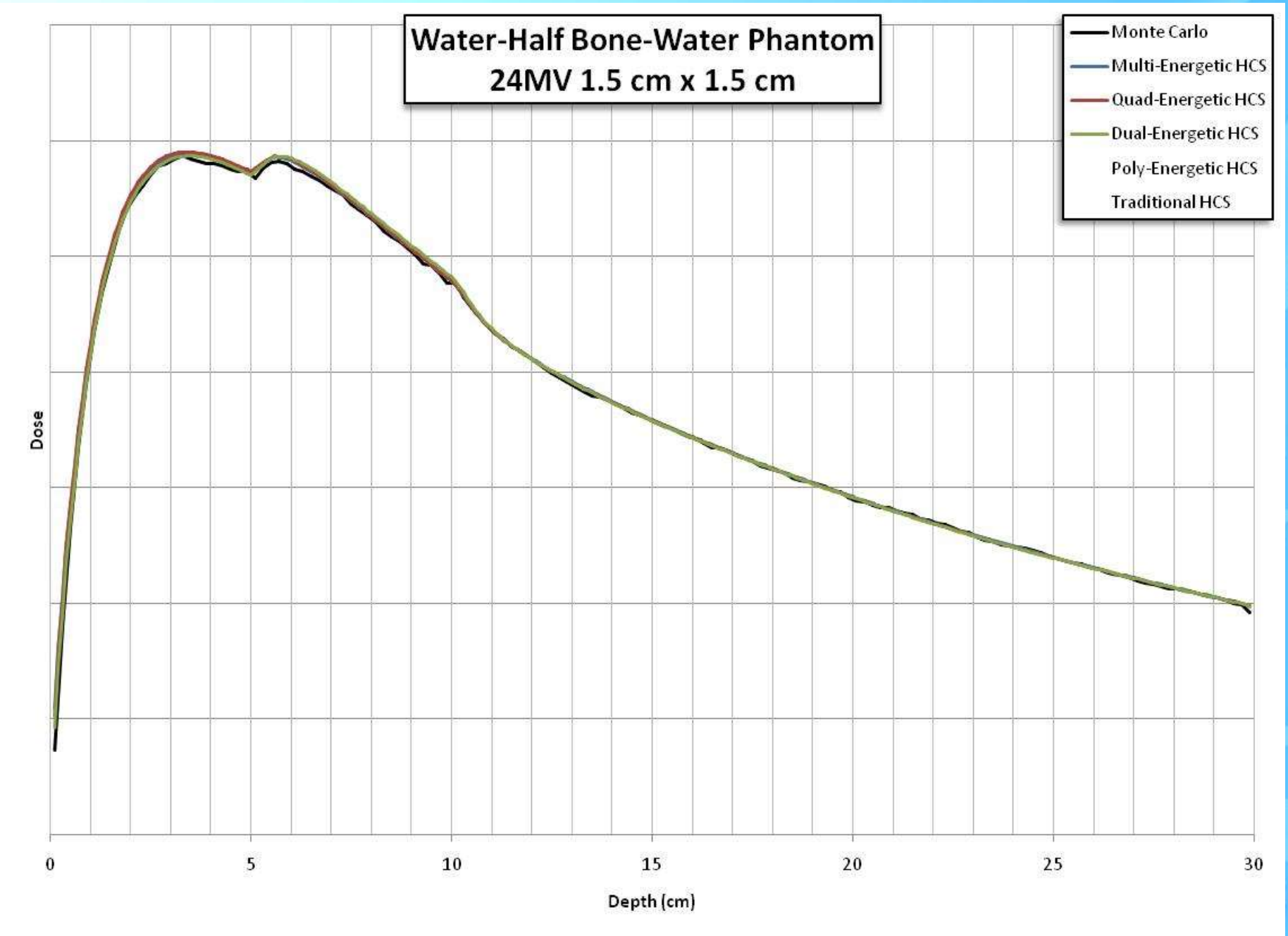

Water-Bone-Lung-Water Phantom
18MV 5 cm x 5 cm
Monte Carlo
Multi-Energetic HCS
Quad-Energetic HCS
Dual-Energetic HCS
Poly-Energetic HCS
Traditional HCS
Dose
0
5
10
15
20
25
30
Depth (cm)

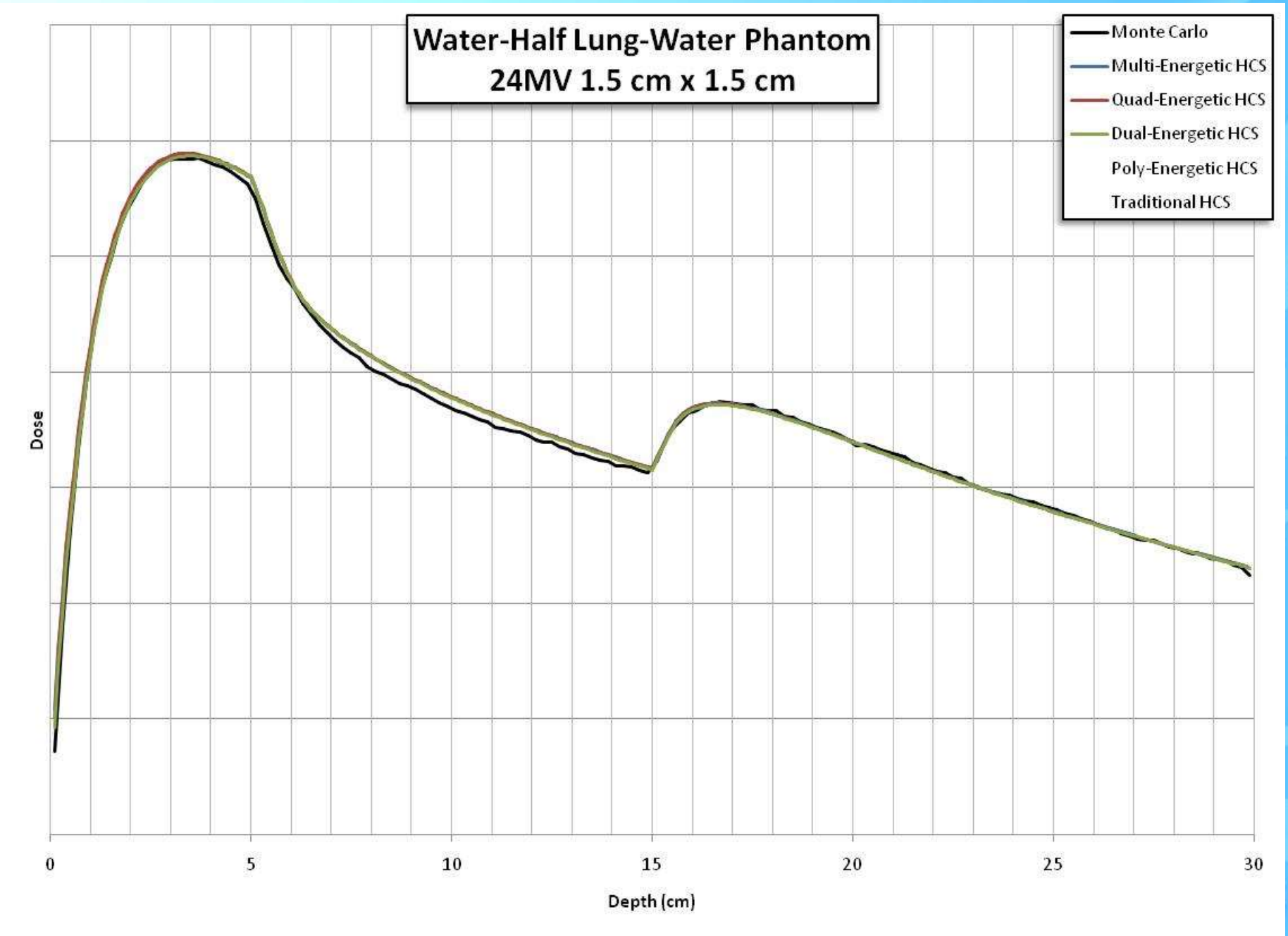

Water-Bone-Lung-Water Phantom
4MV 1.5 cm x 1.5 cm
Monte Carlo
Multi-Energetic HCS
Quad-Energetic HCS
Dual-Energetic HCS
Poly-Energetic HCS
Traditional HCS
Dose
0
5
10
15
20
Depth (cm)


Water-Half Bone-Water Phantom
4MV 1.5 cm x 1.5 cm
Monte Carlo
Multi-Energetic HCS
Quad-Energetic HCS
Dual-Energetic HCS
Poly-Energetic HCS
Traditional HCS
Dose
0
5
10
15
Depth (cm)


Water-Half Lung-Water Phantom
4MV 1.5 cm x 1.5 cm
Monte Carlo
Multi-Energetic HCS
Quad-Energetic HCS
Dual-Energetic HCS
Poly-Energetic HCS
Traditional HCS
Dose
0
5
10
15
Depth (cm)

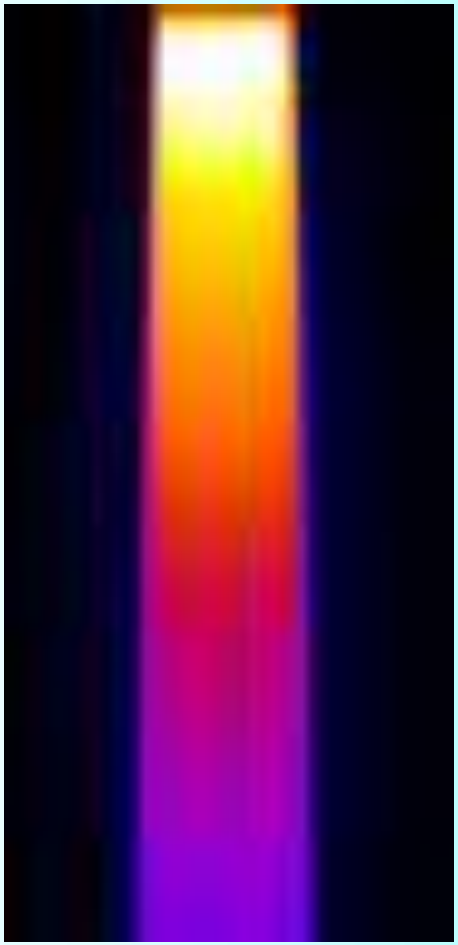

Water-Bone-Lung-Water Phantom
24MV 1.5 cm x 1.5 cm
Monte Carlo
Multi-Energetic HCS
Quad-Energetic HCS
Dual-Energetic HCS
Poly-Energetic HCS
Traditional HCS
Dose
0
5
10
15
20
25
30
Depth (cm)


Water-Half Bone-Water Phantom
24MV 1.5 cm x 1.5 cm
Monte Carlo
Multi-Energetic HCS
Quad-Energetic HCS
Dual-Energetic HCS
Poly-Energetic HCS
Traditional HCS
Dose
0
5
10
15
20
25
30
Depth (cm)

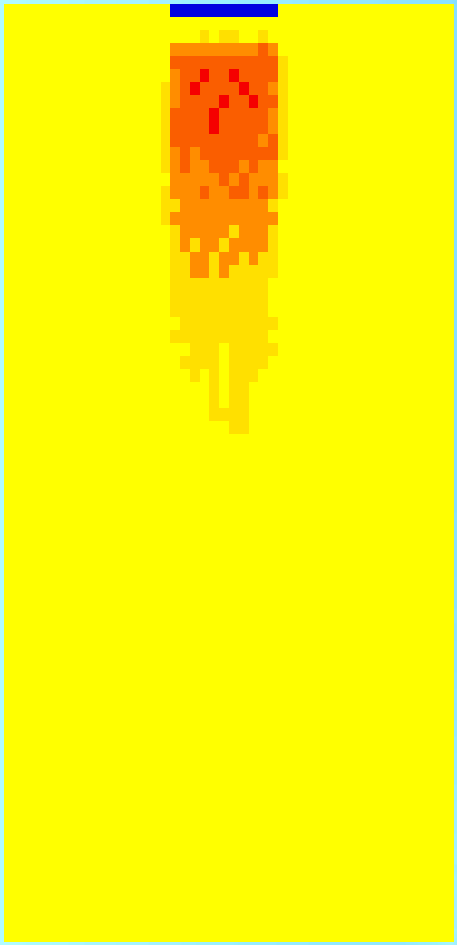

Water-Half Lung-Water Phantom
24MV 1.5 cm x 1.5 cm
Monte Carlo
Multi-Energetic HCS
Quad-Energetic HCS
Dual-Energetic HCS
Poly-Energetic HCS
Traditional HCS
Dose
0
5
10
15
20
25
30
Depth (cm)

HCS, CS vs MC

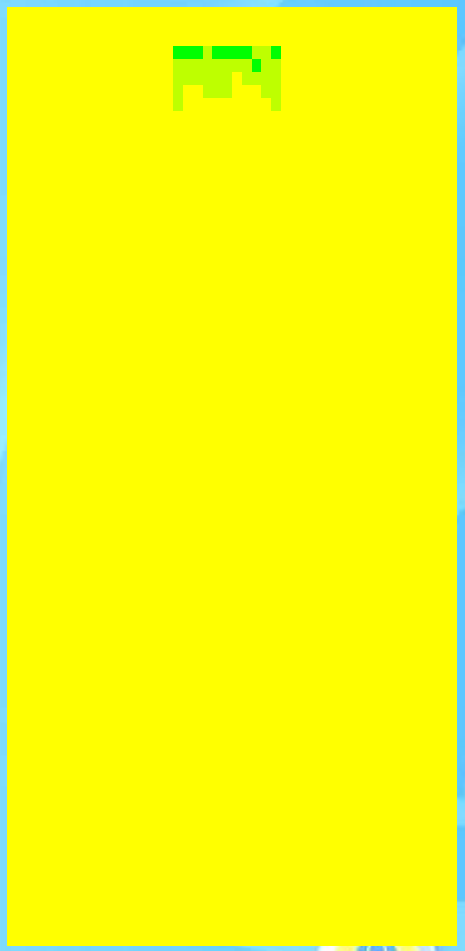
Dose

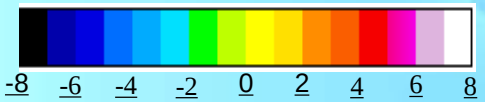


C/S



HCS



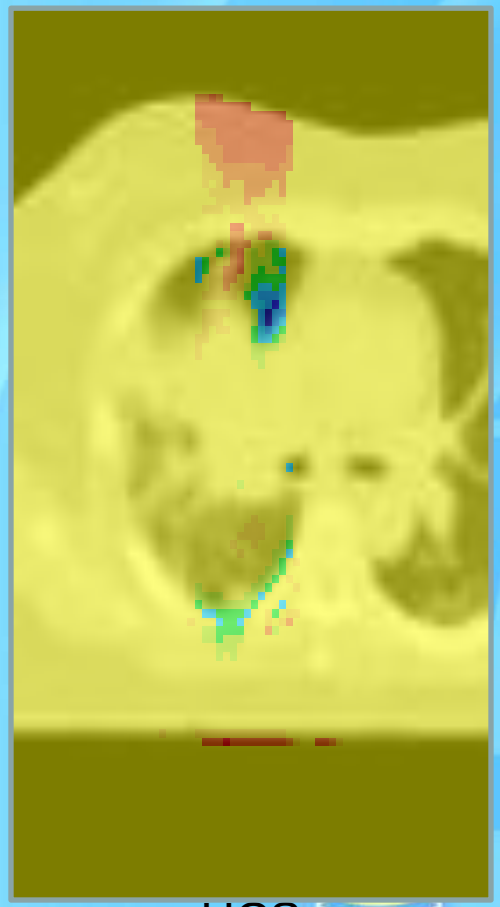


% difference

Heterogeneity Compensation

Dose

C/S



HCS

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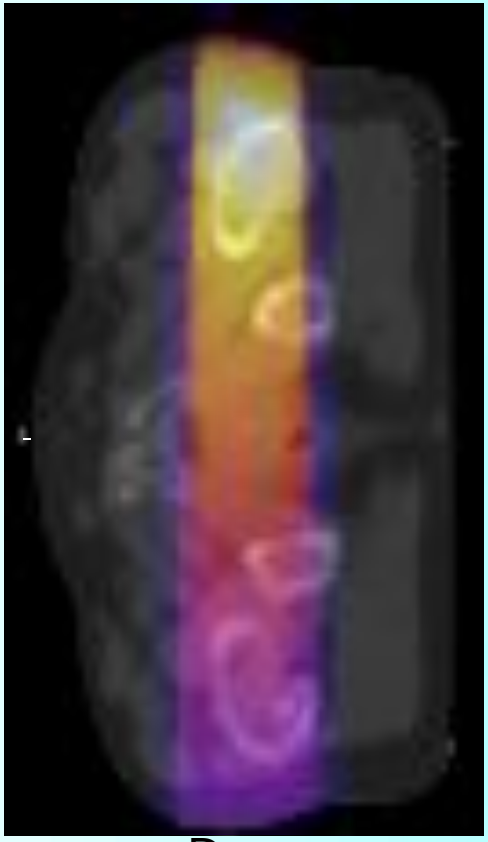
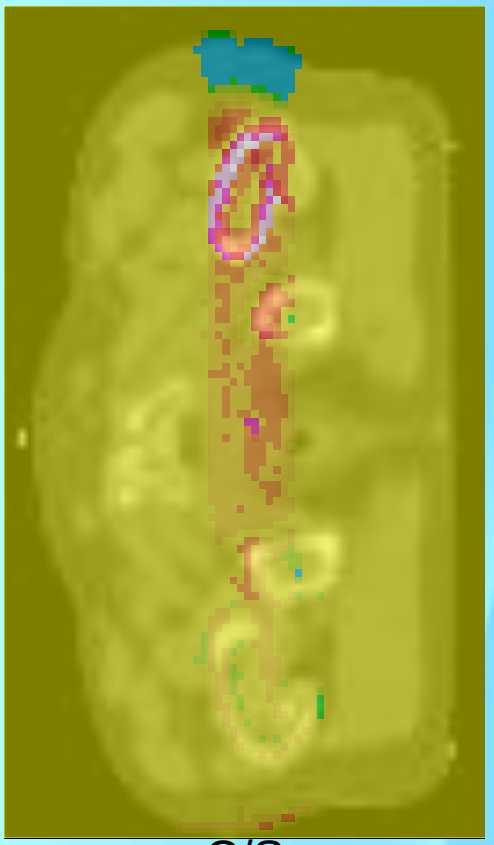
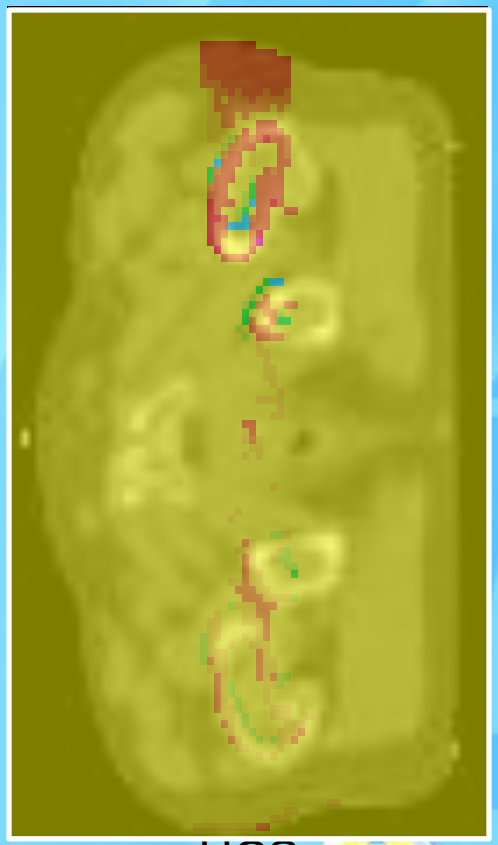
Heterogeneity Compensation



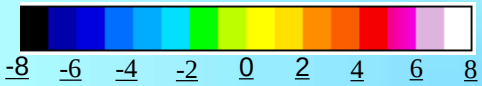
Dose



C/S



HCS



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Performance

Method	Grid^3	# rays	spectra	tilt	kernel	t (ms)	
HCS	64	72	poly	tilted	CCK	277	
HCS	64	72	dual	tilted	CCK	305	Best Balance
HCS	64	72	quad	tilted	CCK	404	Most Accurate
HCS	128	72	poly	tilted	CCK	3913	
HCS	128	72	dual	tilted	CCK	4300	High Res

10x10 field using the ICCR 18 MV spectrum
NVIDIA Tesla GPU C2050 with ECC enabled

- Can achieve interactive rates with 64^3 grid
- 128^3 grid under 4 seconds

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Modeling Tools

Open; Site = JHU; Name = Infinity; Energy = 6 for Monaco release 3.0. VCT - Release 3.0.9.0

Machine Definition | Class Solutions | Spectrum Fitting | Components Fitting | Horn Fitting | PB Fitting | Verify | Conv Superposition | date

Review Beam Data | Spectra | Calculation Parameters | Configurations | Wedges | Additional MLC | Cones | Compensators | Irregular Fields / Blocks | Components Fit | Model Optimization

Weights

Primary Photons	0.950000
Electron Contamination	1.000000
MU Backscatter	0.000000

Primary Source

Collimator Cutoff Angle (rad)	0.242600
Sigma Blur X (mm)	0.500000
Sigma Blur Y (mm)	0.500000
Off Axis Softening	6.300000

Secondary Source

Distance (cm)	15.600000
Virtual Distance (cm)	15.600000
Conic Radius (cm)	18.000000
Source Type	Gaussian
Spectrum Softening Factor	2.000000

Electrons Source

Penetration Depth (cm)	0.00

Machine Parameters

Gray Per MU	1.000000
Source to Axis Distance (cm)	100.000000

Jaw Parameters

	X	Y
ID	X	Y
Orientation	X	Y
Max Size (cm)	40.000000	40.000000
Source Distance (cm)	41.099998	47.000000
Height (cm)	8.000000	8.000000
Density Ratio	0.780000	0.780000
Material	Tungsten	Tungsten

MLC Parameters

ID	
Source Distance (cm)	33.599998
Leaf Radius (cm)	18.000000
Leaf Height (cm)	8.200000
Groove Width (cm)	0.010000
Leaf Width (cm)	1.000000
Circle Vertical Offset (cm)	0.000000
Number of Leaves Per Bank	40
Material	Tungsten
Orientation	X

☐ Focused

Delete All Calculations

Calculate

Modeling Tools

Open; Site = JHU; Name = Infinity; Energy = 6 for Monaco release 3.0. VCT - Release 3.0.9.0

Machine Definition | Class Solutions | Spectrum Fitting | Components Fitting | Horn Fitting | PB Fitting | Verify | Conv Superposition | Validate | Cones

Review Beam Data | Spectra | Calculation Parameters | Configurations | Wedges | Additional MLC | Cones | Compensators | Irregular Fields / Blocks | Components Fit | Model Optimization

Primary | Secondary

Nominal Energy (MV): 6.00 | 6.00

Primary FF Reference Distance (cm) 100.0

Energy Spectrum

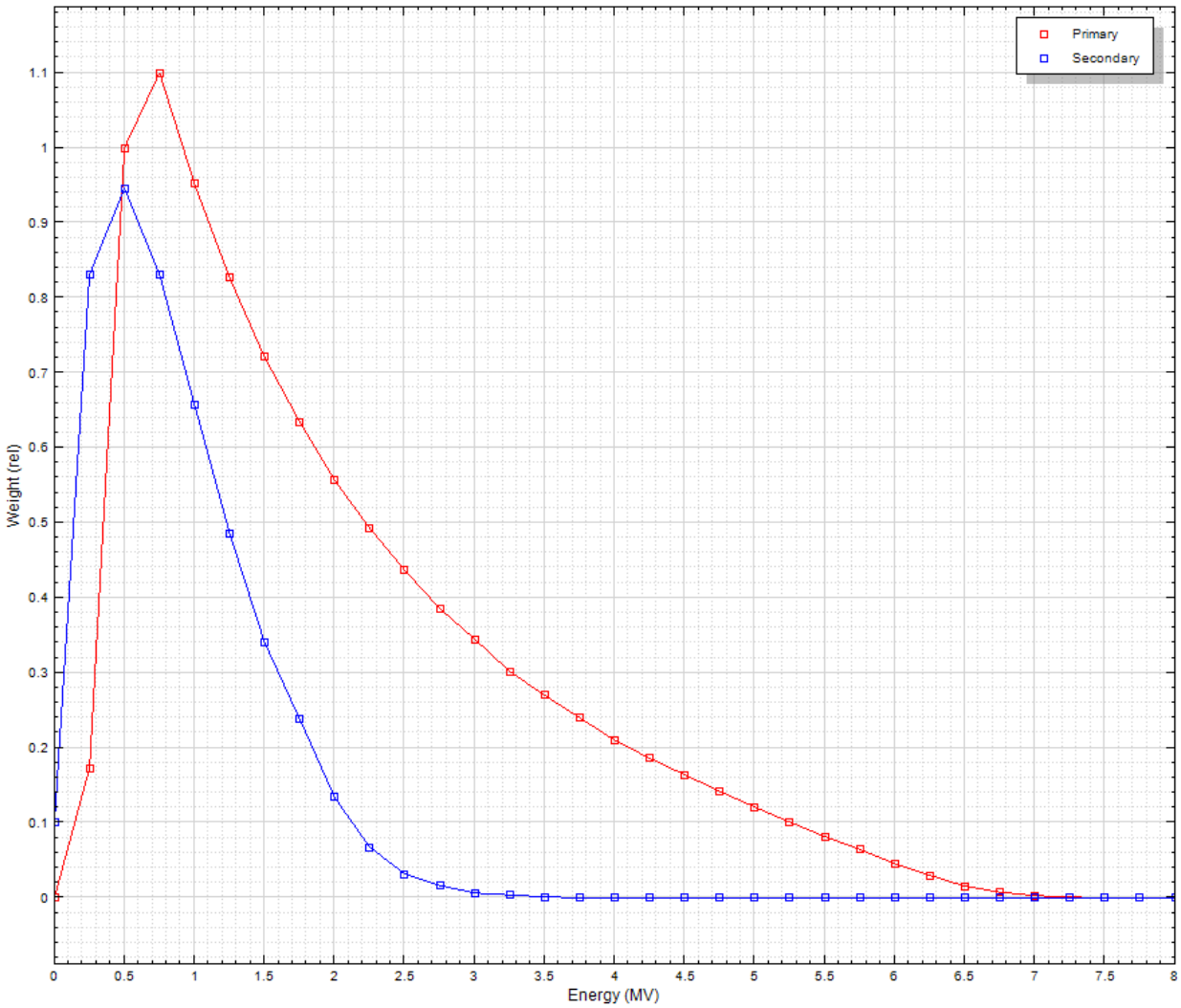
☑ Primary ☑ Secondary

Energy	Weight
0	0
0.25	0.173
0.5	1
0.75	1.1
1	0.952
1.25	0.827
1.5	0.721
1.75	0.635
2	0.557
2.25	0.493
2.5	0.437
2.75	0.386
3	0.345
3.25	0.302
3.5	0.27
3.75	0.24
4	0.21

Energy	Weight
0	0.1
0.25	0.831185590
0.5	0.946102093
0.75	0.831185590
1	0.657533937
1.25	0.486435976
1.5	0.340875035
1.75	0.238726990
2	0.134025253
2.25	0.067629046
2.5	0.031877233
2.75	0.016555023
3	0.006340222
3.25	0.003786522
3.5	0.001232822
3.75	0
4	0

Theta (rad)	Value
0	1
0.009...	1
0.019...	1
0.029...	1.005
0.039...	1.007
0.049...	1.005
0.059...	1.005
0.069...	1.005
0.079...	1.011
0.089...	1.011
0.099...	1.014

X (cm)	Y
0	1
15	0



-- Clone -->

☐ Use Primary

Calculate

Progress

BDT Ranges... | Calculation Summary... | Print | Save | Exit

Modeling Tools

Open; Site = JHU; Name = Infinity; Energy = 6 for Monaco release 3.0. VCT - Release 3.0.9.0

Machine Definition | Class Solutions | Spectrum Fitting | Components Fitting | Horn Fitting | PB Fitting | Verify | Conv Superposition | Validate

Review Beam Data | Spectra | Calculation Parameters | Configurations | Wedges | Additional MLC | Cones | Compensators | Irregular Fields / Blocks | Components Fit | Model Optimization

Kernel Parameters

Number of Azimuth Angles	8
Number of Zenith Angles	10
Maximum Zenith Angle (rad)	0.000000
Phase Ratio	0.25000
Phase Offset Ratio	0.50000
Hardening Depth (cm)	10.00000
Hardening Density (g/ccm)	1.00000
Number of MeV Bins	16
☐ Use Energetic Weighting	0.92500
☑ Add Forward Axis Ray	
☐ Boost First Ring	
☐ Use Bin Look Ahead	
☑ Add Backward Axis Ray	

Superposition Parameters

Angles Per CUDA Call	1
ms Between CUDA Calls	50
Energetic Type	Dual
☑ Use Tilted Kernels	
☑ Use CCK	
☑ Use MS Attenuation	
☐ Multi Resolution	
☐ Truncated	
☐ Use Projected Fluence	
☑ Compute Profiles Only	
☐ Point Dose Mode	

	MeV Divisions
*	

Calculate

Modeling Tools

Open; Site = JHU; Name = Infinity; Energy = 6 for Monaco release 3.0. VCT - Release 3.0.9.0

Machine Definition | Class Solutions | Spectrum Fitting | Components Fitting | Horn Fitting | PB Fitting | Verify | Conv Superposition | Validate | Cones

Review Beam Data Table | Select Calculation Parameters | Evaluate OF and Graphs | Statistics

Results

OF %Diff @ depth (cm): 10

MC Data | PB Data | Conv / Sup | Import Data

Field AB(mm)	Field GT(mm)	% Diff	Measure Value	Calcul Value
20	20	0	0.526...	1.332..
40	40	0	0.588...	1.456..
50	50	0	0.608...	1.494..
50	200	0	0.653...	1.566..
100	100	0	0.674...	1.607..
120	120	0	0.692...	1.640..
150	150	0	0.713...	1.676..
200	50	0	0.653...	1.567..
200	200	0	0.740...	1.726..
250	250	0	0.754...	1.760..
300	300	0	0.772...	1.786..
400	400	0	0.786...	1.829..

MC Calc Scaling 1.0000 Reset

PB Calc Scaling 1.0000 Reset

Conv Sup Scaling Force All Reset

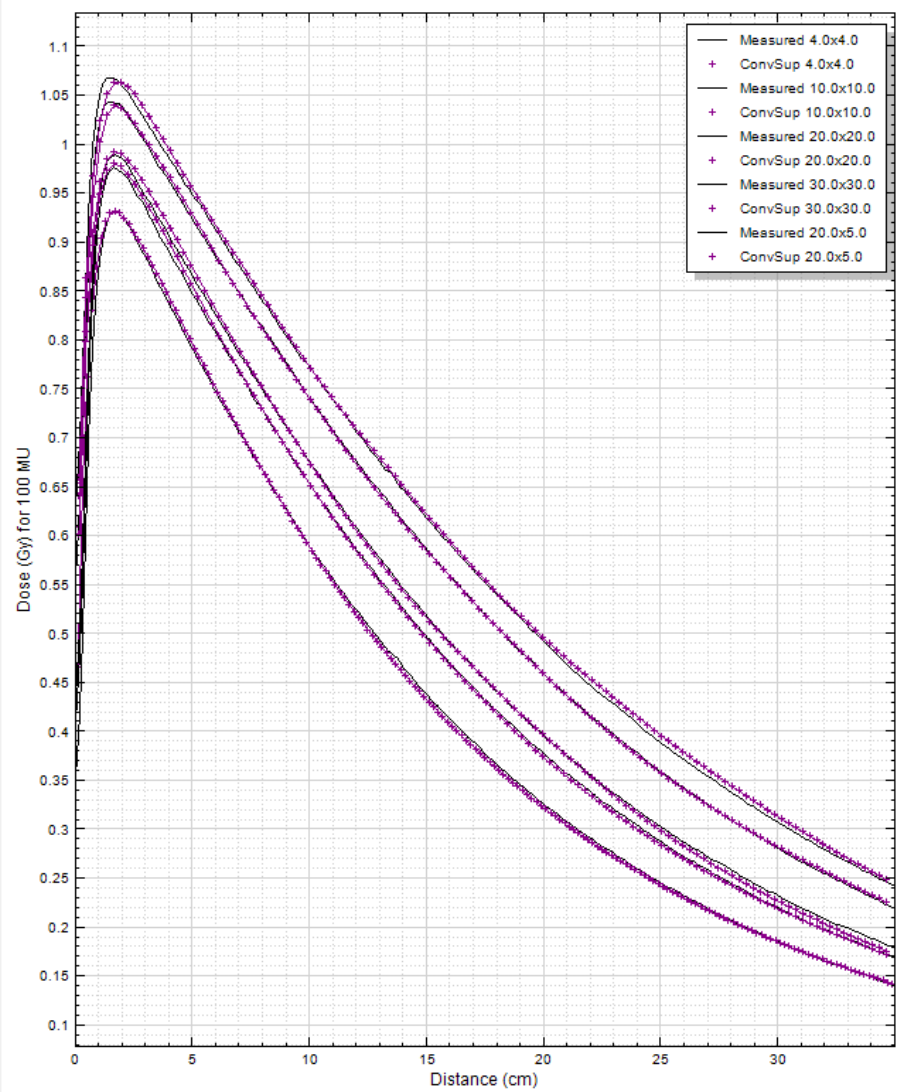
Import Scaling 0.4227 Reset

Force agreement @ ref. Field Size and Depth

Show normalized dose

Force Symmetrical Profiles

Select Graph to View PDD | Create Report... | Callibrate...



Save As Imported

Calculated Profiles Available

Field AB(mm)	Field GT(mm)	SSD (mm)
150	150	1000
200	200	1000
300	300	1000
400	400	1000
200	50	1000
50	200	1000

Show data points

Show Meas. Data

Show MC Calc. Data

Denoised MC Calc.

Show PB Calc. Data

Show Conv / Sup Data

Show Import. Data

Show difference

Show Interpolated PDD's

Calc. Details... | Denoising...

Quadratic

0.00100 | 3

0.50 | 0.050

Progress | BDT Ranges... | Calculation Summary... | Print | Save | Exit

Modeling Tools

Open; Site = JHU; Name = Infinity; Energy = 6 for Monaco release 3.0. VCT - Release 3.0.9.0

Machine Definition | Class Solutions | Spectrum Fitting | Components Fitting | Horn Fitting | PB Fitting | Verify | Conv Superposition | Validate | Cones

Review Beam Data Table | Select Calculation Parameters | Evaluate OF and Graphs | Statistics

Results

OF %Diff @ depth (cm): 15

MC Data | PB Data | Conv / Sup | Import Data

Field AB(mm)	Field GT(mm)	% Diff	Measure Value	Calcul Value
20	20	0	0.386...	0.981..
40	40	0	0.437...	1.070..
50	50	0	0.456...	1.101..
50	200	0	0.497...	1.187..
100	100	0	0.518...	1.228..
120	120	0	0.534...	1.258..
150	150	0	0.556...	1.307..
200	50	0	0.496...	1.187..
200	200	0	0.586...	1.363..
250	250	0	0.603...	1.401..
300	300	0	0.618...	1.437..
400	400	0	0.634...	1.477..

MC Calc Scaling 1.0000 Reset

PB Calc Scaling 1.0000 Reset

Conv Sup Scaling Force All Reset

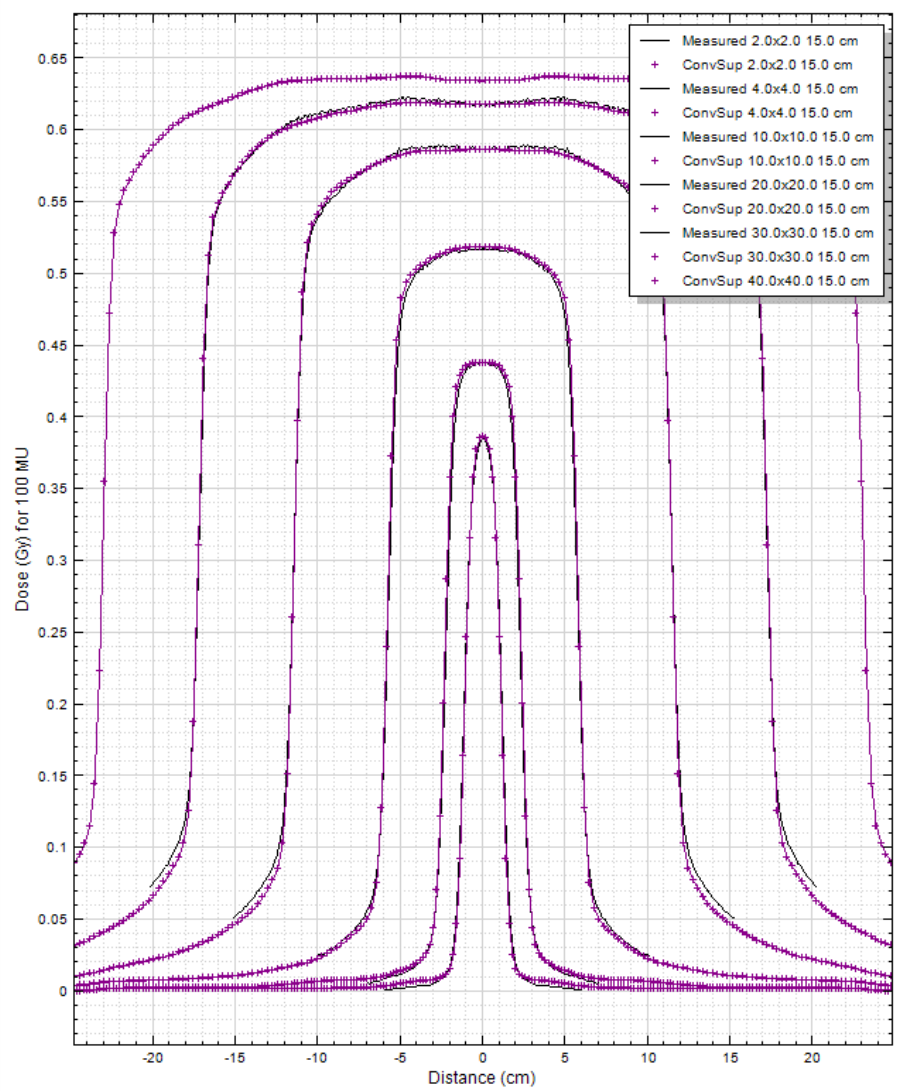
Import Scaling 0.4227 Reset

Force agreement @ ref. Field Size and Depth

Show normalized dose

Force Symmetrical Profiles

Select Graph to View AB | Create Report... | Callibrate...



Save As Imported

Calculated Profiles Available

Field AB(mm)	Field GT(mm)	SSD (mm)
150	150	1000
200	200	1000
300	300	1000
400	400	1000
200	50	1000
50	200	1000

Depth (mm)
300
200
150
100
50
15

Show data points

Show Meas. Data

Show MC Calc. Data

Denoised MC Calc.

Show PB Calc. Data

Show Conv / Sup Data

Show Import. Data

Show difference

Trim Calc

Calc. Details... | Denoising...

Quadratic

0.00100 | 3

0.50 | 0.050

Progress | BDT Ranges... | Calculation Summary... | Print | Save | Exit

Modeling Tools

Open; Site = JHU; Name = Infinity; Energy = 6 for Monaco release 3.0. VCT - Release 3.0.9.0

Machine Definition | Class Solutions | Spectrum Fitting | Components Fitting | Horn Fitting | PB Fitting | Verify | Conv Superposition | Validate | Cones

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50	50	0	0.608...
50	200	0	0.653...
100	100	0	0.674...
120	120	0	0.692...
150	150	0	0.713...
200	50	0	0.653...
200	200	0	0.740...
250	250	0	0.754...
300	300	0	0.772...
400	400	0	0.786...

MC Calc Scaling 1.0000 Reset

PB Calc Scaling 1.0000 Reset

Conv Sup Scaling Force All Reset

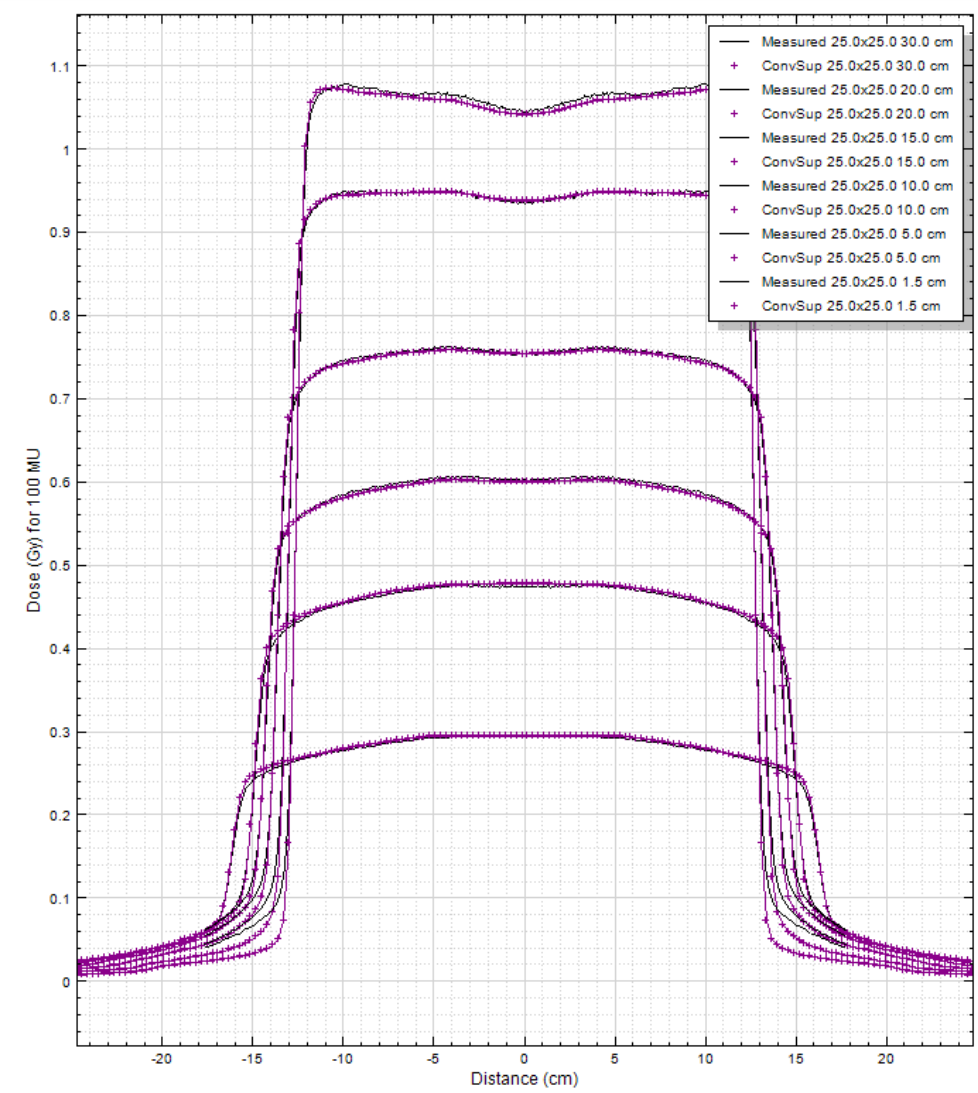
Import Scaling 0.4227 Reset

Force agreement @ ref. Field Size and Depth

Show normalized dose

Force Symmetrical Profiles

Select Graph to View AB | Create Report... | Callibrate...



Save As Imported

Calculated Profiles Available

Field AB(mm)	Field GT(mm)	SSD (mm)
300	300	1000
400	400	1000
200	50	1000
50	200	1000
120	120	1000
250	250	1000

Depth (mm)
300
200
150
100
50
15

Show data points

Show Meas. Data

Show MC Calc. Data

Denoised MC Calc.

Show PB Calc. Data

Show Conv / Sup Data

Show Import. Data

Show difference

Trim Calc

Calc. Details... | Denoising...

Quadratic

0.00100 | 3

0.50 | 0.050

Progress | BDT Ranges... | Calculation Summary... | Print | Save | Exit

Summary - Algorithm

- Reworked the C/S method from first principles for the GPU
- Significant accuracy gains by avoiding performance approximations used in CPU methods
- Able to obtain Monte Carlo accuracy with improvements in the heterogeneity compensation and kernel hardening methods
- Obtain performance in the 100-300 ms range for a typical beam calculation

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Robert Allan Jacques

(July 25,1982 - June 18, 2013)

Thank you! Robert

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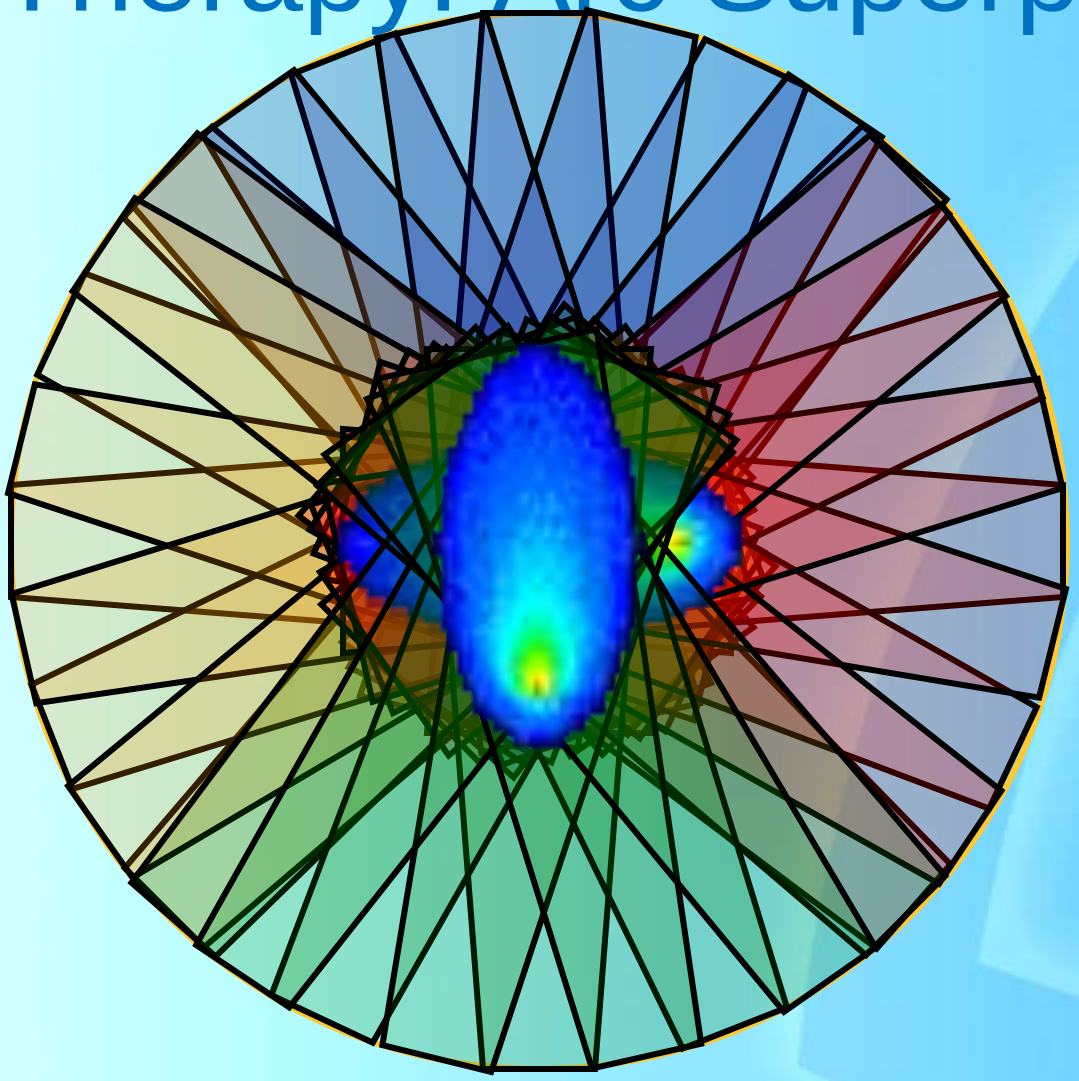
Arc Therapy: Arc Superposition



Arc Therapy

		Arc Superposition				*Standard Superposition*				
	Rays	*6x12*	*4x8*	*4x8*	*4x8*	*10x8*	*6x12*	*4x8*	*4x8*	*4x8*
	Tilt	✓	✓	✓	✗	✗	✓	✓	✓	✗
Multi-resolution		✗	✗	✓	✓	✗	✗	✗	✓	✓
# of ∠'s	Δ∠	*High Dose Region*								
∞	0°	0.12%	0.28%	0.99%	1.12%	0.27%	0.12%	0.28%	0.99%	1.12%
360	0.5°	0.12%	0.28%	0.99%	1.12%	0.32%	0.18%	0.32%	1.01%	1.14%
180	1°	0.12%	0.28%	0.99%	1.12%	0.40%	0.29%	0.40%	1.05%	1.18%
36	5°	0.27%	0.31%	1.02%	1.16%	2.73%	2.66%	2.69%	3.07%	3.18%
18	10°	0.50%	0.44%	1.12%	1.25%	7.05%	6.95%	6.96%	7.21%	7.30%
9	20°	1.07%	0.92%	1.48%	1.60%	14.05%	13.90%	13.88%	14.07%	14.19%
		Gradient Region $(\lvert\nabla D\rvert > 0.3D)$								
∞	0°	0.14%	0.31%	0.88%	1.12%	0.47%	0.14%	0.31%	0.88%	1.12%
360	0.5°	0.16%	0.31%	0.88%	1.14%	1.30%	1.07%	1.17%	1.62%	1.81%
180	1°	0.18%	0.32%	0.89%	1.14%	2.16%	1.99%	2.05%	2.40%	2.56%
36	5°	0.63%	0.61%	1.07%	1.25%	7.63%	7.54%	7.53%	7.59%	7.69%
18	10°	1.24%	1.08%	1.42%	1.52%	11.86%	11.77%	11.74%	11.75%	11.83%
9	20°	2.31%	2.25%	2.30%	2.33%	17.08%	16.98%	16.91%	16.92%	17.01%