Validation of Monte Carlo Simulations For Medical Imaging

Experimental validation and the AAPM Task Group 195 Report

Ioannis Sechopoulos, Ph.D., DABR
Diagnostic Imaging Physics Lab
Department of Radiology and Imaging Sciences
Emory University

Disclosure

Institutional Research Collaborations:
- Hologic, Inc.
- Barco, Inc.
- Koning, Corp.

Consulting Agreement:
- Fujifilm Medical Systems USA, Inc.

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You finished writing your MC code…

Congratulations! Now what???

Let's start doing science!

…not quite yet….

3

Your code needs to be validated!

Are simulation results accurate?

To what level?

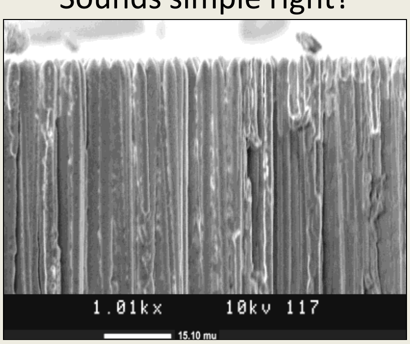
Experimental Monte Carlo Validation

Perform physical measurement

Replicate conditions in MC simulation

Compare results

Sounds simple right?



Courtesy of RMD Inc., Watertown, MA

EXPERIMENTAL VALIDATION

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Experimental Validation Methods

Perform same measurement with different methods

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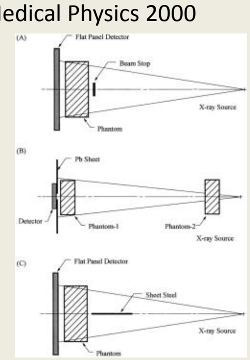
Scatter Simulations Experimental Validation
Boone and Cooper – Medical Physics 2000

1. Edge spread method
2. Beam stop method
3. Scatter medium reposition method
4. Slat method



Boone and Cooper, Medical Physics 27(8), 2000.

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Beam Stop Method

Thickness (cm)	Physical SPR	MC SPR	MC / SPR
2	0.2	0.227	1.14
4	0.41	0.411	1.00
6	0.58	0.586	1.01
6	0.63	0.594	0.94
8	0.73	0.77	1.05

Boone and Cooper, Medical Physics 27(8), 2000.

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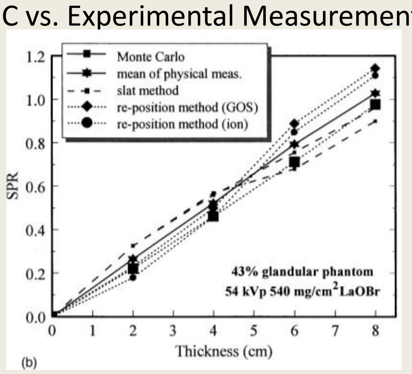
MC vs. Experimental Measurements



Boone and Cooper, Medical Physics 27(8), 2000.

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MC vs. Experimental Measurements

15.2% MC vs. mean of reposition methods

2.6% MC vs. slat method

Overall: **8.4%** MC vs. all four experimental methods

Boone and Cooper, Medical Physics 27(8), 2000.

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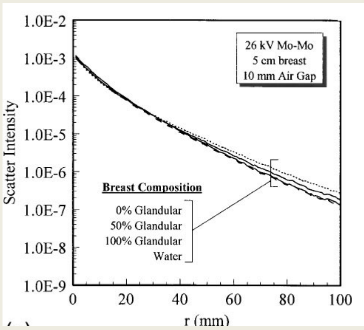
Scatter has its advantages



Boone et al, Medical Physics 27(8), 2000.

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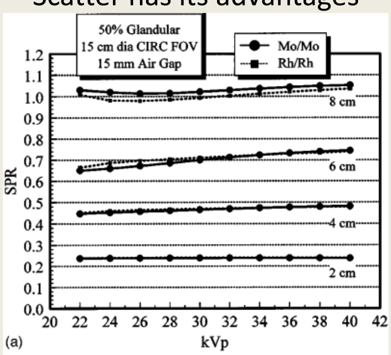
Scatter has its advantages



Boone et al, Medical Physics 27(8), 2000.

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Understand the Experimental Conditions

Build your own hardware

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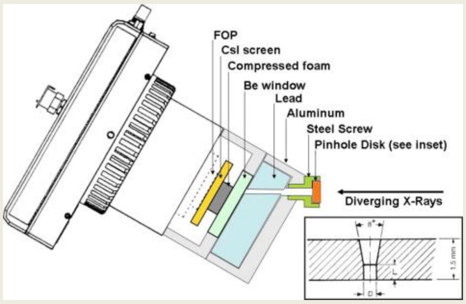
Detector Point Spread Function



Freed et al, Medical Physics 36(11), 2009.

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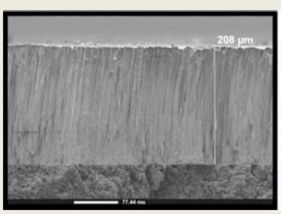
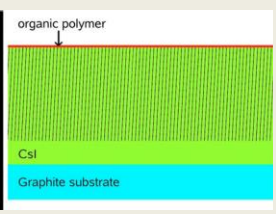
Sometimes although you know what is there doesn't mean you can describe it





Freed et al, Medical Physics 36(11), 2009.

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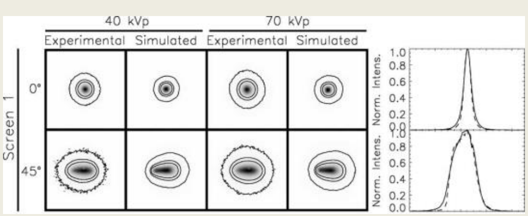
Point Spread Functions



Freed et al, Medical Physics 36(11), 2009.

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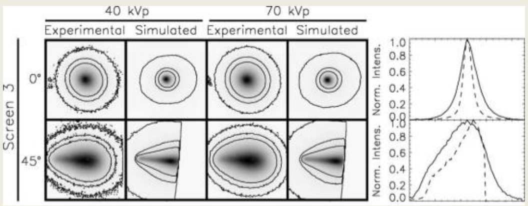
Point Spread Functions



Freed et al, Medical Physics 36(11), 2009.

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What is the task?

PSFs were obtained to investigate something else:

- Geometry optimization?
- Detector optimization?

How much does the PSF inaccuracy affect the actual final task?

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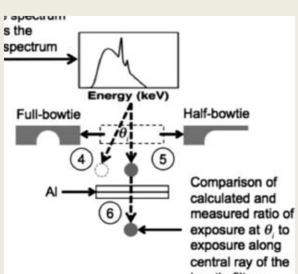
Measurement Results as part of the Simulation



McMillan et al, Medical Physics 40(11), 2013.

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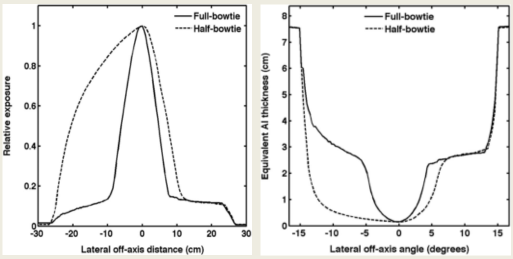
Bowtie Filter Characterization



McMillan et al, Medical Physics 40(11), 2013.

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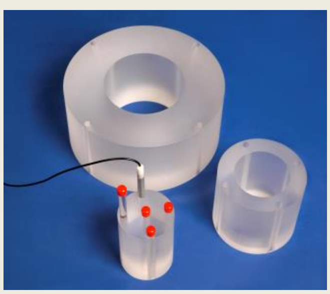
But this is a validation talk…



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Dose Comparison between MC and Measurements (% difference)

Location	AP Pelvis	AP Head		CBCT Pelvis	CBCT Head
1	−1.36	−0.54		-2.19	-4.17
2	−3.46	−4.59		-3.66	-5.31
3	−3.61	−1.00		-3.63	-3.51
4	−4.61	−3.27		-4.07	-1.35
5	−5.14	−3.15		-3.16	-3.14
Average	**−3.64**	**−2.51**		**-3.34**	**-3.50**

McMillan et al, Medical Physics 40(11), 2013.

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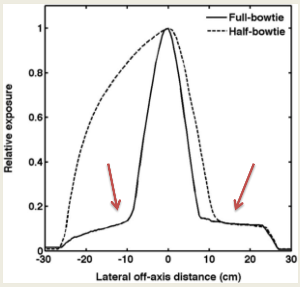
You know what they say when you assume things…



McMillan et al, Medical Physics 40(11), 2013.

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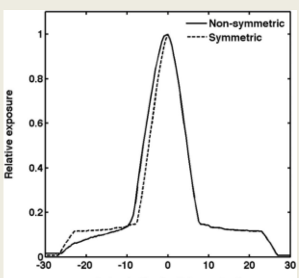
Assuming a symmetric bowtie filter…



McMillan et al, Medical Physics 40(11), 2013.

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…leads to this: AP Head Dose Differences (%)

Location	Actual	Assumption
1	−0.54	-3.25
2	−4.59	-6.42
3	−1.00	-5.23
4	−3.27	-4.58
5	−3.15	-25.23
Average	**−2.51**	**-8.94**

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Experimental MC Validation

Don't assume!

Build it yourself

Obtain component information

Measure! (maybe using different methods)

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Experimental MC Validation

Don't expect to fall within the MC statistical uncertainty

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When replicating an experiment, which of the following simulation conditions needs to be accurately replicated?

12%	1.	Source description
6%	2.	Geometry definitions
35%	3.	Material definitions
29%	4.	Scoring details
18%	5.	All of the above

When replicating an experiment, which of the following simulation conditions needs to be accurately replicated?

- Source description
- Geometry definitions
- Material definitions
- Scoring details

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Another Alternative…

Take advantage that somebody else already did all the work!

… actually this is not easy either

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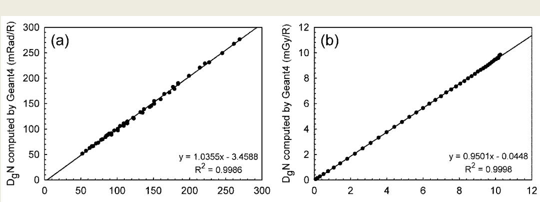
Replicate results from previously published Monte Carlo results



Sechopoulos et al, Medical Physics 34(1), 2007

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Replication of Previous Studies

No need to perform experiments

May span more parameter values

Enough details to replicate are frequently lacking

Graphical results

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Monte Carlo Reference Data Sets for Imaging Research

AAPM TASK GROUP 195

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American Association of Physicists in Medicine Task Group #195

Ioannis Sechopoulos, Emory University, Chair
Elsayed S. M. Ali, Carleton University*
Andreu Badal, Food and Drug Administration
Aldo Badano, Food and Drug Administration
John M. Boone, University of California, Davis
Iacovos S. Kyprianou, Food and Drug Administration
Ernesto Mainegra-Hing, National Research Council of Canada
Michael F. McNitt-Gray, University of California, Los Angeles
Kyle L. McMillan, University of California, Los Angeles
D. W. O. Rogers, Carleton University
Ehsan Samei, Duke University
Adam C. Turner, University of California, Los Angeles**

*Present address: The Ottawa Hospital Cancer Centre
**Present address: Arizona Center for Cancer Care

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Our report…

Provides complete simulation details of a set of simulations

Includes results from widely used MC codes
- EGSnrc
- Geant4
- MCNPX
- Penelope

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Our report…

All simulation conditions:
- Geometry
- Source
- Material composition
- Energy spectra
- Scoring
- etc

(A lot of) Tabulated results and variance

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With our report…

Future work needs only mention TG report case number and degree of agreement.
- Recommended language is included in the report.

Teaching tool for students and trainees

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Simulations Developed

Half-value layers
Radiography (including tomosynthesis):
- Dose
- X-ray scatter

Mammography (including tomosynthesis):
- Dose
- X-ray scatter

CT:
- Dose in simple solids
- Dose in voxelized phantom

Production of x-rays

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Common Parameters/Definitions

Material compositions:
- NIST
- ICRU 46
- Hammerstein et al, Radiology, 1979

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Common Parameters/Definitions

X-ray spectra definition:
- IPEM Report 78
- IEC 61267

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Common Parameters/Definitions

Mass energy absorption coefficients:

IPEM Report 78

Material Compositions

Elemental mass fractions (%) and material densities (g/cm3) for all materials used in all Monte Carlo cases of AAPM TG Report 1

		1	6	7	8	11	13	15	16	17	18
Material	**Density (g/cm3)**	**H**	**C**	**N**	**O**	**Na**	**Al**	**P**	**S**	**Cl**	**Ar**
Air	0.001205	0	0.0124	75.5268	23.1781	0	0	0	0	0	1.2
Aluminum	2.699	0	0	0	0	0	100	0	0	0	
Breast Adipose	0.93	11.2	61.9	1.7	25.1	0	0	0.025	0.025	0	
Breast Glandular	1.04	10.2	18.4	3.2	67.7	0	0	0.125	0.125	0	
Breast Skin	1.09	9.8	17.8	5.0	66.7	0	0	0.175	0.175	0	
Molybdenum	10.22	0	0	0	0	0	0	0	0	0	
PMMA	1.19	8.0541	59.9846	0	31.9613	0	0	0	0	0	
Soft Tissue	1.03	10.5	25.6	2.7	60.2	0.1	0	0.2	0.3	0.2	
Tungsten	19.30	0	0	0	0	0	0	0	0	0	
Water	1.000	11.1898	0	0.0	88.8102	0	0	0	0	0	

(*) ICRU Report 46

(**) Hammerstein et al, Radiology, 1979

(***) NIST: http://physics.nist.gov/PhysRefData/XrayMassCoef/tab2.html

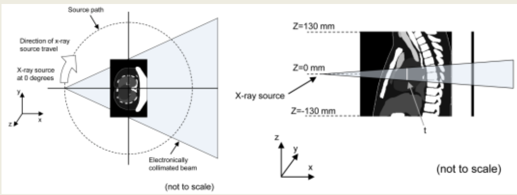
Case 5: Computed Tomography with Voxelized Solid

Aim

This case aims to verify the accuracy of voxel-based x-ray transport and interaction characteristics in computed tomography, in addition to x-ray source rotation, resulting in the validation of estimates of absorbed dose in a complex, voxelized CT phantom. Even though this simulation uses a relatively thin fan beam, this case may also be useful for verification of dosimetry simulations involving voxelized solids in other modalities such as radiography and body tomosynthesis. For this, comparison of the results for a single or a limited number of projection angles may be sufficient.

Case 5: Computed Tomography with Voxelized Solid

Geometry



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Case 5: Computed Tomography with Voxelized Solid

Geometry

1. Geometry is exactly the same as that defined for Case #4, but with a voxelized box replacing the cylindrical body phantom. The box has dimensions of thickness (x-direction) 320 mm, width (y-direction) 500 mm and height (z-direction) 260 mm, containing 320 x 500 x 260 voxels. This voxelized volume contains the description of the torso portion of a human patient. Each voxel is 1.0 mm x 1.0 mm x 1.0 mm.

Materials

1. The three dimensional (3D) image with the information for the material content of the voxelized volume is available for download in the electronic resources included with this report. This reference case is a XCAT model, courtesy of Ehsan Samei and Paul Segars of the Duke University, to serve as a reference platform for Monte Carlo simulations. Care should be taken in using this volume with the correct orientation in the Monte Carlo simulation. The voxels in the image contain values ranging from 0 to 19 that correspond to material definitions also available for download in the electronic resources included with this report.
2. The rest of the geometry is filled with air.

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Case 5: Computed Tomography with Voxelized Solid

Radiation source

1. Isotropic x-ray point source collimated to a fan beam with dimensions, measured at the center of the voxelized volume, of width (y-direction) equal to the voxelized volume (500 mm) and thickness (z-direction) of 10 mm.
2. The rotation radius of the x-ray source about the isocenter, located at the center of the body phantom, is 600 mm.
3. The 0° position of the x-ray source is located at coordinates x=-600 mm and y = z = 0, as shown in Figure 17, and increasing angle projections are in the direction marked in the same figure.
4. Two different source types are simulated:
    a. Source rotated 360° about the isocenter in 45° increments, with 8 evenly spaced simulations performed.
    b. Angular position of source is randomly sampled for each x-ray emitted from the continuous distribution of 360° about the isocenter.
5. Simulations are performed for the W/Al 120 kVp spectrum and for monoenergetic photons with energy 56.4 keV (equivalent to the mean energy of the spectrum).

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Case 5: Computed Tomography with Voxelized Solid

Scoring

The scoring is the energy deposited in all the voxels with values 3 to 19, separated by organ/material.

Statistical Uncertainty

The number of simulated x rays is such that the statistical uncertainty is 1% or lower on dose scored in all organ/materials except for the adrenals (voxel value = 12).

Projection Angles (deg)	Number	Minimum	Maximum	Increment
Discrete	8	0	345	45
Random	∞	0	360	-

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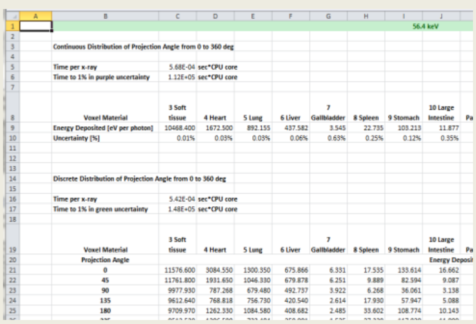
Results



56.4 keV

Continuous Distribution of Projection Angle from 0 to 360 deg

Time per x-ray 5.68E-04 sec*CPU core

Time to 1% in purple uncertainty 1.12E+05 sec*CPU core

Voxel Material	3 Soft tissue	4 Heart	5 Lung	6 Liver	7 Gallbladder	8 Spleen	9 Stomach	10 Large Intestine	Pa
Energy Deposited [eV per photon]	10468.400	1672.500	892.155	437.582	3.545	22.735	103.213	11.877	
Uncertainty [%]	0.01%	0.03%	0.03%	0.06%	0.63%	0.25%	0.12%	0.35%	

Discrete Distribution of Projection Angle from 0 to 360 deg

Time per x-ray 5.42E-04 sec*CPU core

Time to 1% in green uncertainty 1.48E+05 sec*CPU core

Voxel Material	3 Soft tissue	4 Heart	5 Lung	6 Liver	7 Gallbladder	8 Spleen	9 Stomach	10 Large Intestine	Pa
Projection Angle								Energy Deposi	
0	11576.600	3084.550	1300.350	675.866	6.331	17.535	133.614	16.662	
45	11761.800	1931.650	1046.330	679.878	6.251	9.889	82.594	9.087	
90	9977.930	787.268	679.480	492.737	3.922	6.268	36.061	3.138	
135	9612.640	768.818	756.730	420.540	2.614	17.930	57.947	5.088	
180	9709.970	1262.330	1084.580	408.682	2.485	33.602	108.774	10.143	

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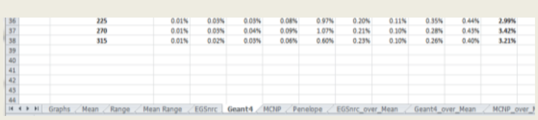
I did say a LOT of tabulated results!



225	0.01%	0.03%	0.03%	0.08%	0.97%	0.20%	0.11%	0.35%	0.44%	2.99%
270	0.01%	0.03%	0.04%	0.09%	1.07%	0.21%	0.10%	0.28%	0.43%	3.42%
315	0.01%	0.02%	0.03%	0.06%	0.60%	0.23%	0.10%	0.26%	0.40%	3.21%

Graphs / Mean / Range / Mean Range / EGSnrc / Geant4 / MCNP / Penelope

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Comparison Among Codes

Continuous Distribution of Projection Angle from 0 to 360 deg

Time per x-ray	0.10 - 1.90	sec*CPU core
Time to 1% in purple uncertainty	0.57 - 1.43	sec*CPU core

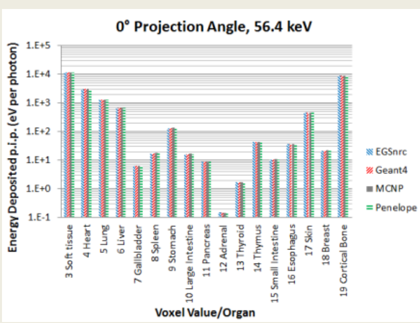
Voxel Material	3 Soft tissue	4 Heart	5 Lung	6 Liver	7 Gallbladder	8 S
Energy Deposited [eV per photon]	0.994 - 1.006	0.999 - 1.001	0.998 - 1.002	0.998 - 1.002	0.994 - 1.006	0.99

Discrete Distribution of Projection Angle from 0 to 360 deg

Time per x-ray	0.12 - 2.52	sec*CPU core
Time to 1% in green uncertainty	0.51 - 1.70	sec*CPU core

Voxel Material	3 Soft tissue	4 Heart	5 Lung	6 Liver	7 Gallbladder	8 S
Projection Angle						
0	0.999 - 1.002	0.996 - 1.008	0.997 - 1.006	0.995 - 1.010	0.994 - 1.014	0.99
45	0.999 - 1.002	0.996 - 1.008	0.997 - 1.005	0.995 - 1.010	0.988 - 1.023	0.99
90	0.999 - 1.002	0.993 - 1.014	0.995 - 1.008	0.995 - 1.012	0.994 - 1.012	0.99
135	0.994 - 1.003	0.997 - 1.005	0.998 - 1.002	0.997 - 1.005	0.996 - 1.006	0.99

And some graphs...



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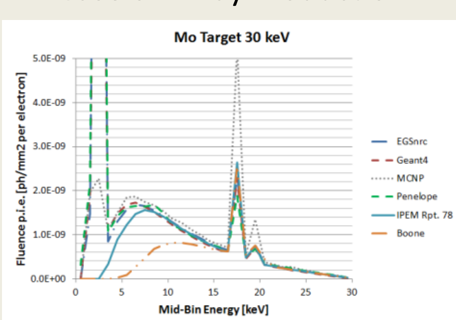
Case 6: X-Ray Production



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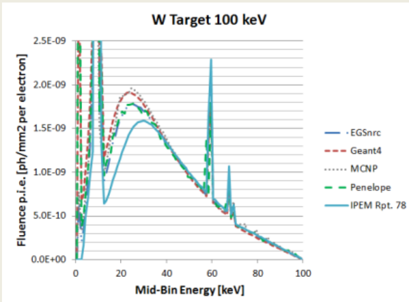
Case 6: X-Ray Production



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Results Comparison Among Monte Carlo Packages

In most cases, differences within statistical uncertainty.

- Especially for x-ray only simulations
- A few results <5%, almost all <10%

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Results Comparison Among Monte Carlo Packages

X-ray production simulations had larger differences

- More sensitive to electron transport physics

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Given the correct replication of conditions, what difference should be expected when performing the same **x-ray** based simulations with different Monte Carlo software packages?

16% 1. Always within the statistical uncertainty of the simulations

12% 2. Mostly within the statistical uncertainty, and a few results within <10% of each other

8% 3. All results within <20% of each other

36% 4. All results within <50% of each other, if you're lucky!

Given the correct replication of conditions, what difference should be expected when performing the same **x-ray** simulations with different Monte Carlo software packages?

- Mostly within the statistical uncertainty
  - Especially for x-ray dosimetry simulations
- And a few results within <10% of each other
  - Some scatter characterization results
- Simulations involving electrons show larger differences

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Lessons Learned

Most of them sound obvious....

... it is easy to think that you are clear in your descriptions when you are not.

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Source Description

"Uniform" vs. "isotropic"

Electronic collimation?

Collimated to a plane or a spherical surface?

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Geometry Description

In which direction is positive rotation?

Does the x-ray source rotate or translate in tomosynthesis?

- Body: translate
- Breast: rotate

Is there air defined in the rest of the geometry?

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Material Definitions

Is the chemical composition and densities of all materials correct?

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Scoring

What are the units? (e.g. x-rays in ROI or x-rays/mm^2)

Binning: Does the value provided for each bin represent the floor, middle, or top of the bin?

“Per photon history” normalization

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Validation with Previous MC Results

Avoids burdensome (and expensive) experiments

Allows for validation against wider span of parameter values

Is not necessarily enough!

- Are your simulations a lot more complicated than the previous results?

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Validation with Previous MC Results

Difficult to obtain all simulation conditions

Graphical results?

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AAPM TG 195

Simulating exactly the same conditions is challenging

Once this is achieved, results are very consistent

Electron physics result in larger variations

We believe this will be a very useful tool for researchers and educators involved in x-ray based imaging simulations

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Report Availability

- Approved by SC a few days ago
- Will be posted in AAPM Task Group Reports website:
  http://www.aapm.org/pubs/reports/
- Summary will be published in *Medical Physics*
- Look for it in a few weeks (?)

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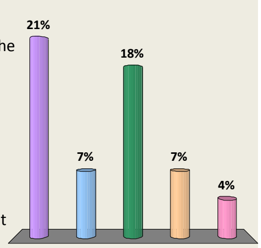
Why is the method called “Monte Carlo”?

1. For the Monte Carlo Casino, due to the random nature of the method
2. For James Bond, due to his ability to solve any problem!
3. For the Monte Carlo Opera, where the inventor of the method, Stanislaw Ulam, used to sing when he was younger
4. For the Chevy Monte Carlo, the favorite car of the inventor of the method, Stanislaw Ulam
5. For the Monte Carlo Beach Hotel, where we would all prefer to be right now…



Why is the method called "Monte Carlo"?

Metropolis, N. (1987). "The beginning of the Monte Carlo method". Los Alamos Science (1987 Special Issue dedicated to Stanislaw Ulam): 125–130

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Thank you!

Questions?

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