Application of computational human phantoms and Monte Carlo methods in normal tissue dose reconstructions

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WE-AB-FS1 - The Role of Physics in Long Term Epidemiological Studies of Pediatric Radiotherapy Patients

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Disclosure

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  - Varian medical system, Inc

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Contents / Learning Objectives

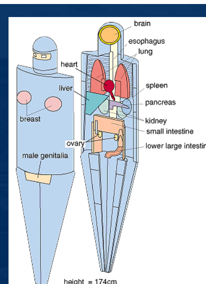
- Evolution of anthropomorphic computational phantoms
- Choice of dose calculation engines
  - Commercial TPS vs. general purpose Monte Carlo code
- Computational phantoms for therapy studies
  - When do we need phantoms?
  - DICOM RT ready computational phantoms
  - Patient-phantom merge (APE phantoms)
- Example application

Background

- Physical phantoms
  - Simple material composition
  - Coupled with detectors (TLDs, ion-chamber, etc)
    - Point dose (not average dose)
  - Subject to various measurement uncertainties
    - Repeat measurement required for each irradiation scenarios

Background

- Computational phantoms
  - Digital equations / images
  - Coupled with Monte Carlo transport code
  - Requires accurate radiation source modeling
  - Free-from setup/measurement uncertainties
  - Batch calculation can be performed



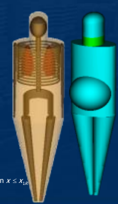
Cristy and Eckerman (1983)

Computational Human Phantoms

- 1st generation human phantoms

Stylized phantoms

Base	Equations (sphere, cylinder, ellipsoid, etc.)
Advantages	Less memory, fast computing Able to handle thin layers Reference individual
Disadvantages	Simplified anatomy Difficult to modify the shapes
Availability	0,1,5,10, 15, and Adult male (ORNL) ADAM and EVA (GSF) Pregnant women (3, 6, and 9 month)



$$\left(\frac{x+x_0}{a}\right)^2+\left(\frac{y}{b}\right)^2+\left(\frac{z+z_0}{c}\right)^2\le 1$$

and $z \ge z_0$

if $z_{1R} \le z \le z_{2R}$ and $y < y_{2R}$, then $x \le x_{1R}$

Computational Human Phantoms

- 2nd generation human phantoms

Voxel phantoms

Base	Tomographic images (CT, MRI, etc.)
Advantages	Realistic anatomy Can represent arbitrary organ shapes Scalable
Disadvantages	More memory, slower computing Stair-stepped surface (finite voxel resolution) Individual specific model
Availability	Various male, female, and pediatric

GSF BABY and CHILD voxel phantoms

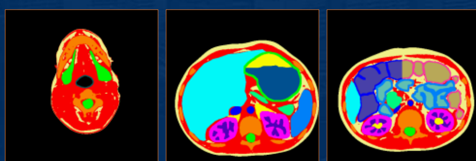
Computational Human Phantoms

- 2nd generation human phantoms

Model	Age and sex	Height (cm) / weight (kg)	Covered area	Images	Subject
Zubal Phantom	Adult	NA / 70.3	Head and torso	CT	Patient
NORMAN	Adult	176 / 73	Whole	MRI	NA
Golem	38-yr	176 / 68.93	Whole	CT	Patient
VIP-man	38-yr	186 / 104.277	Whole	Color photo	Cadaver (VHP)
Otoko	Adult	170 / 65	Whole	CT	NA
Visible-human	38-yr	125 / 87.8 (180 / 103.2)	Knees and up	CT	Cadaver (VHP)
Frank	48-yr	96.5 / 65.4	Head and torso	CT	Patient
MAX	Adult	175.3 / 74.65	Whole	CT	Patient
KRMAN	28-yr	172 / 65	Whole	MRI	Volunteer
Nagaoka man	22-yr	172.8 / 65.0	Whole	MRI	Volunteer
KRMAN-2	33-yr	175 / 70	Whole	PET-CT	Volunteer

Computational Human Phantoms

- 2nd generation human phantoms



Lee et al. MP 2006

Computational Human Phantoms

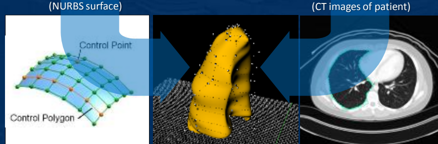
- 3rd generation human phantoms (Hybrid)

Stylized phantom

Mathematical Flexibility
(NURBS surface)

Voxel phantom

Anatomical Realism
(CT images of patient)



Computational Human Phantoms

Reference organ volume
(ICRP Publication 89)

Reference organ composition
(ICRU Report 46 & ICRP Publication 89)

Reference gastro-intestine
(ICRP Publication 100)

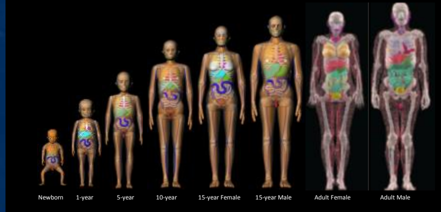
Reference anthropometry
(CDC NHANES* data)

Lee et al. PMB 2010

*National Health and Nutrition Examination Survey

ICRP Reference Phantoms Series

Lee et al. (2007, 2008, 2010)
Zankl M and Petoussi-Henss N (2005)

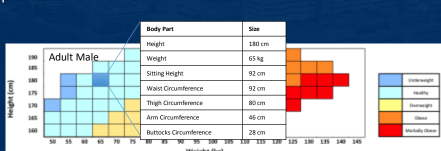


Body size-specific phantoms

- Body size significantly varies among patients at the same age
- Radiation dose depends on age and body size

Extended Phantom Library

- BMI distribution grid developed from US CDC survey data
- Body size-dependent phantoms developed by deforming the reference phantoms

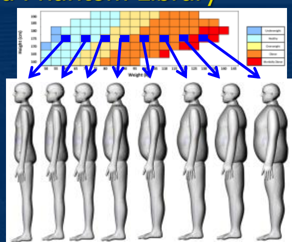


Body Part	Size
Height	180 cm
Weight	65 kg
Sitting Height	92 cm
Waist Circumference	92 cm
Thigh Circumference	80 cm
Arm Circumference	46 cm
Buttocks Circumference	28 cm

Geyer et al. PMB 2014

Extended Phantom Library

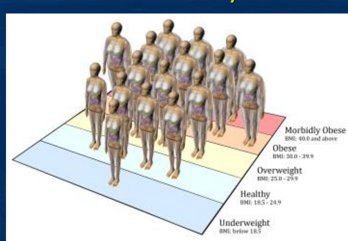
Adult Male



Geyer et al. PMB 2014

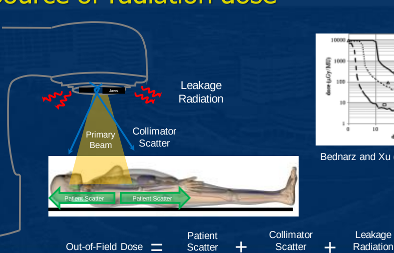
A series of the adult male phantoms at 175 cm high and different weights, 60 – 130 kg

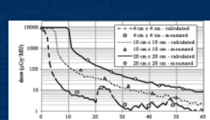
Extended Phantom Library



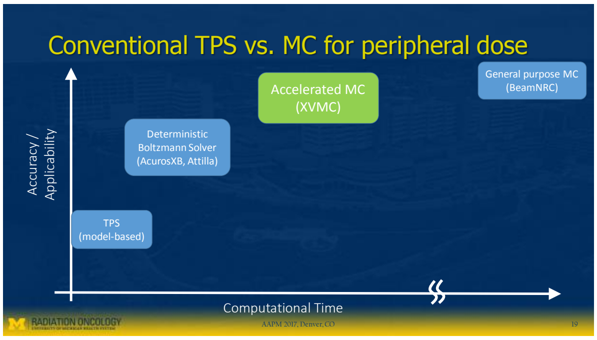
Geyer et al. PMB 2014

Source of radiation dose





Bednarz and Xu (2009)



Conventional TPS vs. MC for peripheral dose
Accuracy / Applicability
Accelerated MC (XVMC)
General purpose MC (BeamNRC)
Deterministic Boltzmann Solver (AcurosXB, Attilla)
TPS (model-based)
Computational Time
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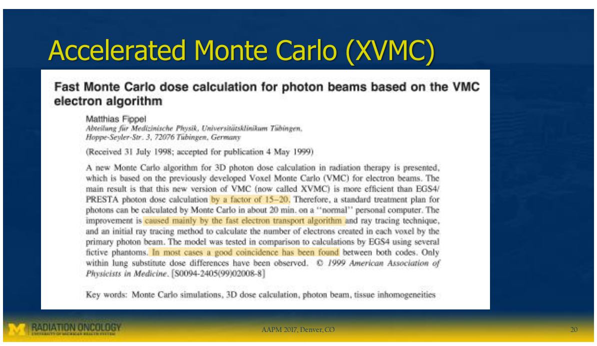

Accelerated Monte Carlo (XVMC)
Fast Monte Carlo dose calculation for photon beams based on the VMC electron algorithm
Matthias Fippel
Abteilung für Medizinische Physik, Universitätsklinikum Tübingen, Hoppe-Seyler-Str. 3, 72076 Tübingen, Germany
(Received 31 July 1998; accepted for publication 4 May 1999)
A new Monte Carlo algorithm for 3D photon dose calculation in radiation therapy is presented, which is based on the previously developed Voxel Monte Carlo (VMC) for electron beams. The main result is that this new version of VMC (now called XVMC) is more efficient than EGS4/PRESTA photon dose calculation by a factor of 15–20. Therefore, a standard treatment plan for photons can be calculated by Monte Carlo in about 20 min. on a ''normal'' personal computer. The improvement is caused mainly by the fast electron transport algorithm and ray tracing technique, and an initial ray tracing method to calculate the number of electrons created in each voxel by the primary photon beam. The model was tested in comparison to calculations by EGS4 using several fictive phantoms. In most cases a good coincidence has been found between both codes. Only within lung substitute dose differences have been observed. © 1999 American Association of Physicists in Medicine. [S0094-2405(99)02008-8]
Key words: Monte Carlo simulations, 3D dose calculation, photon beam, tissue inhomogeneities
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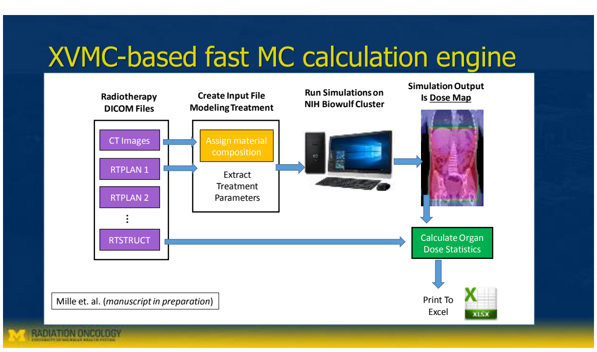

XVMC-based fast MC calculation engine
Radiotherapy DICOM Files
Create Input File Modeling Treatment
Run Simulations on NIH Biowulf Cluster
Simulation Output Is Dose Map
CT Images
RTPLAN 1
RTPLAN 2
RTSTRUCT
Assign material composition
Extract Treatment Parameters
Calculate Organ Dose Statistics
Print To Excel
XLSX
Mille et. al. (manuscript in preparation)
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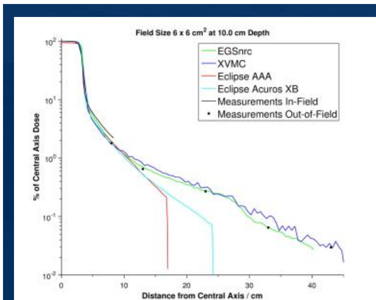
Comparison of peripheral dose calculation

- Simple water box phantom
  - Homogenous water phantom
  - Simple square fields – Varian 6MV LINAC
  - Calculated with commercial TPS (AAA, AcurosXB v13.6)
  - Monte Carlo codes - XVMC and EGSnrc

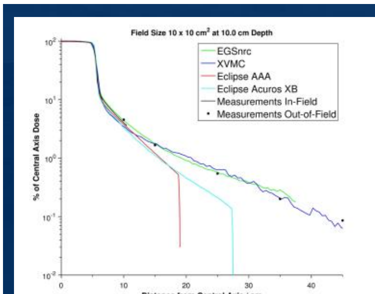
  - Verification measurement - Ion chamber + water (in-field) + solid water (out of field) phantoms*

*Owrangi et al (2016) JACMP



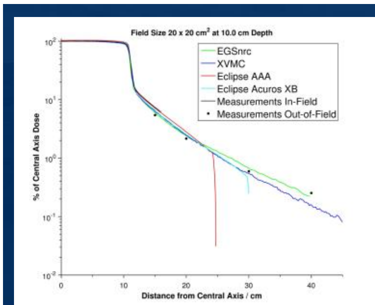
- 6x6 cm Jaw field
- 6MV
- 100cm SSD

Jung et al (HPS 2017)



- 10x10 cm Jaw field
- 6MV
- 100cm SSD

Jung et al (HPS 2017)

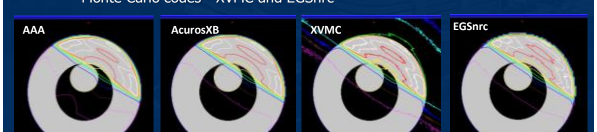


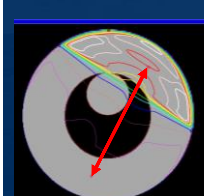
- 20x20 cm Jaw field
- 6MV
- 100cm SSD

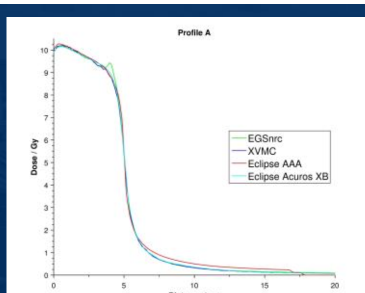
Jung et al (HPS 2017)

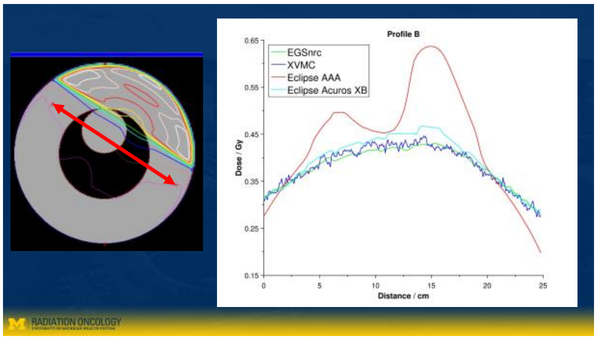
Comparison of peripheral dose calculation

- Simple chest phantom
  - Heterogeneous phantom with body, lung, and heart
  - Simple tangent fields with 6MV segments (to simulate left breast Tx)
  - Calculated with commercial TPS (AAA, AcurosXB v13.6)
  - Monte Carlo codes - XVMC and EGSnrc








Profile B
EGSnrc
XVMC
Eclipse AAA
Eclipse Acuros XB
Dose / Gy
Distance / cm
0.65
0.55
0.45
0.35
0.25
0.15
0
5
10
15
20
25
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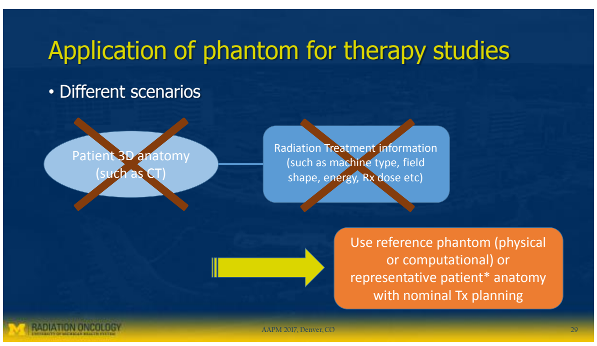
Application of phantom for therapy studies
• Different scenarios
Patient 3D anatomy (such as CT)
Radiation Treatment information (such as machine type, field shape, energy, Rx dose etc)
Use reference phantom (physical or computational) or representative patient* anatomy with nominal Tx planning
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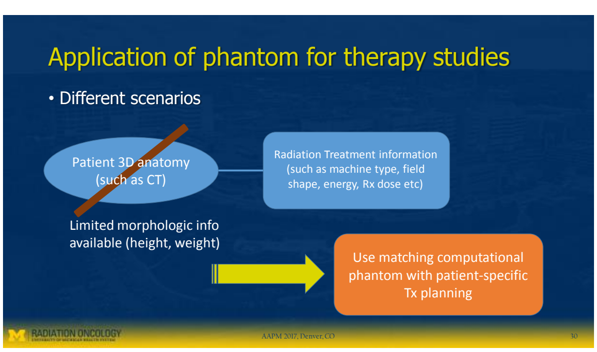
Application of phantom for therapy studies
• Different scenarios
Patient 3D anatomy (such as CT)
Limited morphologic info available (height, weight)
Radiation Treatment information (such as machine type, field shape, energy, Rx dose etc)
Use matching computational phantom with patient-specific Tx planning
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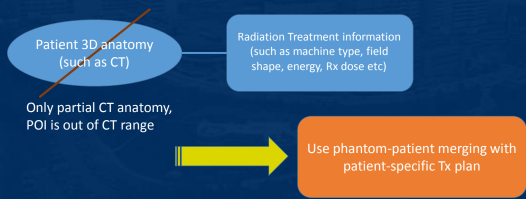
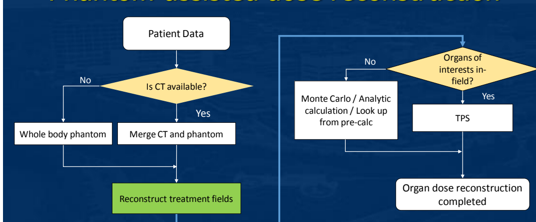
Application of phantom for therapy studies

- Different scenarios



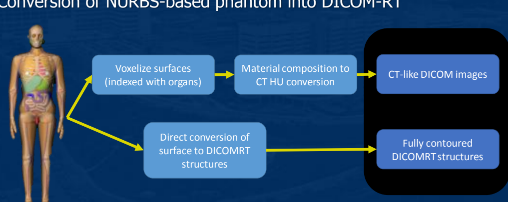
Phantom-assisted dose reconstruction



Lee et al. Phys Med Biol (2015)

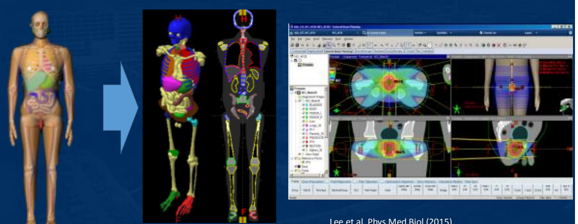
Phantom to DICOMRT conversion

- Conversion of NURBS-based phantom into DICOM-RT



Lee et al. Phys Med Biol (2015)

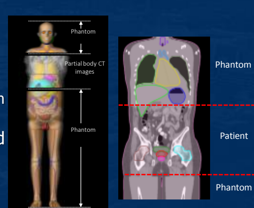
Phantom to DICOMRT conversion



Lee et al. Phys Med Biol (2015)
Lee et al. ICCR (2016)

Phantom-patient merging

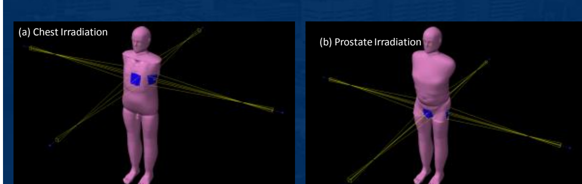
- Fully automated merging process
  - BMI-matched phantom augments partial patient CT based on skeleton map
  - Phantom dimension adjusted to match with patient
- Advantage of using accurate in-field anatomy + alternate anatomy for peripheral dose estimation
- Anatomically Predictive Extension (APE) phantom



Kuzmin et. al. AAPM (2016)

Phantom-patient merging

- Dosimetric comparison of full patient / full reference phantom / APE



Phantom-patient merging: dose comparison

A. Chest Irradiation

Organ	Patient 169-68 BMI=24			Patient 180-86 BMI=27			Patient 193-104 BMI=28			Patient 176-90 BMI=28			Patient 162-78 BMI=30		
	Ref.	APE	Patient	Ref.	APE	Patient	Ref.	APE	Patient	Ref.	APE	Patient	Ref.	APE	Patient
Heart	59.120	66.844	66.751	59.120	61.730	61.770	59.120	62.005	62.009	59.120	61.376	61.499	59.120	65.404	65.299
Lung Left	15.249	19.207	19.167	15.249	18.506	18.493	15.249	15.245	15.245	15.249	17.223	17.232	15.249	19.443	19.762
Lung Right	14.868	13.167	13.157	14.868	13.021	13.027	14.868	12.857	12.858	14.868	12.801	12.803	14.868	13.189	13.415
Liver	2.849	7.779	8.347	2.849	2.622	2.005	2.849	2.806	2.184	2.849	5.848	4.067	2.849	10.372	8.629
Stomach	2.620	6.143	6.121	2.620	2.890	2.890	2.620	2.746	2.552	2.620	2.882	3.689	2.620	6.354	7.117
Bladder	0.021	0.021	0.030	0.021	0.036	0.018	0.021	0.019	0.020	0.021	0.027	0.020	0.021	0.029	0.027
Prostate	0.010	0.011	0.019	0.010	0.018	0.010	0.010	0.010	0.015	0.010	0.014	0.013	0.010	0.015	0.018

Absolute Percent Difference
< 10%
10 - 25 %
> 25 %

Kuzmin et al. *(manuscript in preparation)*

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Phantom-patient merging: dose comparison

B. Prostate Irradiation

Organ	Patient 169-68 BMI=24			Patient 180-86 BMI=27			Patient 193-104 BMI=28			Patient 176-90 BMI=28			Patient 162-78 BMI=30		
	Ref.	APE	Patient	Ref.	APE	Patient	Ref.	APE	Patient	Ref.	APE	Patient	Ref.	APE	Patient
Prostate	69.289	69.690	69.634	69.289	69.251	69.251	69.289	69.972	69.944	69.289	69.779	69.758	69.289	69.370	69.614
Bladder	31.946	61.215	61.207	31.946	45.380	45.371	31.946	66.740	66.753	31.946	56.410	56.409	31.946	60.649	60.681
Stomach	0.044	0.050	0.062	0.044	0.046	0.038	0.044	0.095	0.089	0.044	0.046	0.043	0.044	0.066	0.057
Liver	0.038	0.051	0.060	0.038	0.049	0.048	0.038	0.086	0.082	0.038	0.074	0.069	0.038	0.063	0.053
Heart	0.011	0.013	0.024	0.011	0.016	0.012	0.011	0.022	0.019	0.011	0.018	0.016	0.011	0.019	0.022
Lung Left	0.008	0.012	0.024	0.008	0.011	0.013	0.008	0.015	0.019	0.008	0.014	0.015	0.008	0.017	0.019
Lung Right	0.008	0.012	0.018	0.008	0.011	0.012	0.008	0.015	0.018	0.008	0.013	0.014	0.008	0.017	0.018

Absolute Percent Difference
< 10%
10 - 25 %
> 25 %

Kuzmin et al. *(manuscript in preparation)*

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Example application to epidemiological study

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Retrospective Study Using NWTS Cohort

- **Wilms Tumor** – Cancer of the kidney that occurs most often in children
  - Approximately 500 cases diagnosed in U.S. annually.
  - 75% cases occur in otherwise normal children
  - Highly responsive to treatment (5 yr. survival > 90%) → ideal for late-effects research
- **National Wilms Tumor Study (NWTS)**
  - Started in 1969 to improve survival and study long-term outcomes
  - 5002 patients have contributed information to Late Effects Study (2606 patients with >20 years past diagnosis)

http://www.webpathology.com

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Retrospective Study Using NWTS Cohort

- NCI-funded dose reconstruction study to conduct late-effects study with *organ dose reconstruction*
- Pilot study
- 20 Simulated treatment plans (10 male, 10 female pediatric patients)
  - Surrogate CT (not actual patient)provided from Quality Assurance Review Center (QARC)
  - OAR contoured and treatment plan created on paired set of 20 surrogate patient CTs and 20 matching phantoms - following treatment record based on the anatomical landmarks
  - TPS dose and MC dose compared.

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Mean Organ Dose: patient CT vs Phantom

Organ	Mean Difference	Standard Deviation Difference	Max Absolute Value Difference
Heart	1.4%	10.9%	32.3%
Thyroid	5.9%	19.7%	46.6%
Kidneys (L&R)	1.8%	14.7%	53.4%
Testes	-6.4%	26.7%	46.2%
Lungs (Avg)	-17.2%	22.78%	57.8%
Ovaries (L&R)	-5.5%	9.8%	40.0%
Uterus	13.6%	68.6%	192.7%

- Surrogate CTs and phantoms agreed quite well for most organs
- Heart substructure contouring pending

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Gopalakrishnan et al. ASTRO 2016

Mean Organ Dose: patient CT vs Phantom

Organ	Mean Difference	Standard Deviation Difference	Max Absolute Value Difference
Heart	-1.8%	3.1%	11.9%
Thyroid	-18.8%	25.4%	70.1%
Kidneys (L&R)	-0.4%	2.8%	11.1%
Testes	-30.0%	13.1%	48.3%
Lungs (Avg)	-3.0%	4.3%	17.3%
Ovaries (L&R)	3.4%	8.3%	32.7%
Uterus	-0.6%	8.6%	27.9%

- Difference: (TPS – MC)/MC x 100
- Overall TPS underestimates MC
- For organs located far away from field edge TPS underestimates MC up to 30%

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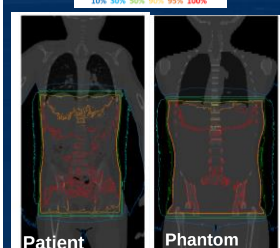
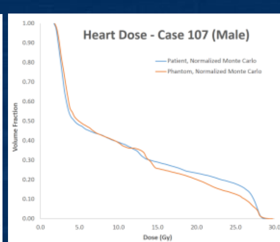
Example MC dose

Male Case 107, Abdomen = 30 Gy
Fraction of Prescribed Dose
10% 30% 50% 90% 95% 100%





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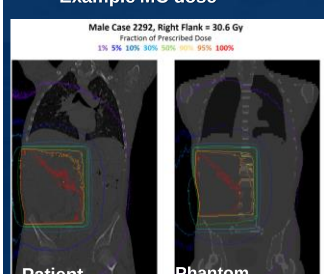
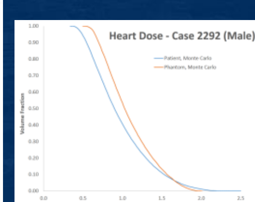
Example MC dose





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Summary

- Computational human phantoms have evolved from simple form to realistic and flexible form
- Workflow for organ dose in therapy patients developed based on accelerated MC method and phantoms
- The new method applied to epidemiological investigations
- Improved dosimetry is hypothesized to provide more accurate risk analysis in epidemiological studies

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Thank you for your attention!

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