The Recipient of 2015 Randall S. Caswell Award for Distinguished Achievements in the Field of Ionizing Radiation Measurements and Standards

Dr. X. George Xu
The Edward E. Hood Endowed Chair of Engineering Professor of Nuclear Engineering Rensselaer Polytechnic Institute

Tuesday, April 28, 2015 @CIRMS 2015
Dr. Randall S. Caswell

- Physicist, Radiation Physics Division, 1952-1957
- Chief, Neutron Physics Section, 1957-1969
- Deputy Director, Center for Radiation Research, 1969-1978
# Past Randall S. Caswell Awardees

<table>
<thead>
<tr>
<th>Year</th>
<th>Name</th>
<th>Organization</th>
</tr>
</thead>
<tbody>
<tr>
<td>2002</td>
<td>H. Thompson Heaton II</td>
<td>FDA</td>
</tr>
<tr>
<td>2004</td>
<td>Anthony J. Berejka</td>
<td>Ionicorp</td>
</tr>
<tr>
<td>2006</td>
<td>Kenneth L. Swinth</td>
<td>Swinth Associates</td>
</tr>
<tr>
<td>2007</td>
<td>Bert M. Coursey</td>
<td>U.S. DHS</td>
</tr>
<tr>
<td>2008</td>
<td>Larry A. DeWerd</td>
<td>University of Wisconsin</td>
</tr>
<tr>
<td>2009</td>
<td>Marshall R. Cleland</td>
<td>IBA Industrial, Incorporated</td>
</tr>
<tr>
<td>2010</td>
<td>Geoffrey Ibbott</td>
<td>MD Anderson Cancer Center</td>
</tr>
<tr>
<td>2011</td>
<td>Dr. Kenneth Inn</td>
<td>NIST</td>
</tr>
<tr>
<td>2012</td>
<td>Joseph C. McDonald</td>
<td>PNNL</td>
</tr>
<tr>
<td>2013</td>
<td>Stephen M. Seltzer</td>
<td>NIST</td>
</tr>
</tbody>
</table>
Research on Radiation Dosimetry and Monte Carlo Simulation at RPI – A Review

X. George Xu
(xug2@rpi.edu)
Tuesday, April 28, 2015 @CIRMS 2015
Acknowledgements
Rensselaer Radiation Measurements and Dosimetry Group (RRMDG):
http://RRMDG.rpi.edu
Outline

1. Computational Human Phantoms

2. ARCHER Monte Carlo Code
**Experimental vs Computational Approaches**

**Measurements**
- Dosimeters
- Physical phantom

**Monte Carlo Simulations**
- Computational phantoms
- Monte Carlo codes

- AP
- PA
- RLAT
- LLAT
Boltzmann Radiation Transport Calculations

\[ \frac{1}{v} \frac{\partial}{\partial t} \psi(\mathbf{r}, \hat{\Omega}, E, t) + \hat{\Omega} \cdot \nabla \psi(\mathbf{r}, \hat{\Omega}, E, t) + \Sigma_t(\mathbf{r}, E) \psi(\mathbf{r}, \hat{\Omega}, E, t) \]
\[ = \int dE' \int d\Omega' \Sigma_s(\mathbf{r}, E' \rightarrow E, \hat{\Omega}', \hat{\Omega}) \psi(\mathbf{r}, \hat{\Omega}', E', t) + S(\mathbf{r}, \hat{\Omega}, E, t) \]
Monte Carlo Simulation Methods

Ptrac tracking
Moritz software
The Cell Cards define the geometry using the shapes provided in the Surface Cards. They also define the material type and its density:
- Cell 1 → Material 4 (Aluminum), \( \rho = 2.698 \text{ g/cm}^3 \)
- Cell 2 → Material 2 (Air), \( \rho = 0.000125 \text{ g/cm}^3 \)
- Cell 3 → Void

The negative signs designate which face of the geometry the program is to consider.

Not include cell #2

MCNP Geometry Example – HPGe Gamma Detector

<table>
<thead>
<tr>
<th>C CELL CARDS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>3</td>
</tr>
</tbody>
</table>

Cell Card 1

Cell Card 2

Cell Card 3

Container with Air Inside and Void Outside
US Patent Serial #6,518,579
50-Year History of Computational Phantoms

- Radiation Protection
- Medical Imaging
- Radiotherapy

1st Generation
MIRD anthropomorphic models in 1980s
STYLIZED

2nd Generation
Image-based rigid, 3D model in 1990-2000s
VOXEL

3rd Generation
Deformable and moving 4D models 2008-2010
BREP

Personalization is Future
2nd-Generation “Voxel” Phantoms
- Example of the VIP-Man (1997-2000)
Xu et al. Health Physics 2000

Identification of organs in each slice of a 2D pixel map
Registration of all slices
Finished 3D voxel phantom
VIP-Man Phantom For Radiation Dosimetry

“VIP-Man: An image-based whole-body adult male model constructed from color photographs of the visible human project for multi-particle Monte Carlo calculations”.

EGS4 Code

0.33 mm x 0.33 mm x 1 mm Resolution
Photons / Electrons

MCNP5 Code

4 mm x 4mm x 4 mm Resolution
Photons/Electrons/Neutrons

MCNPX Code

And

GEANT4 Code

Protons etc

Dr. T.C. (Ephraim) Chao,
Class 2001

Dr. Ahmet Bozkurt,
Class 2000
Earlier Pregnant Female Phantoms

Stylized models

Partial-body CT phantom (7-month)


Shi and Xu (2004)
A New Method of Morphing and Deforming

A Major Advancement in Phantom Geometry  
from Constructed Solid Geometry (CSG) to Boundary Representation (BREP)

Non-Uniform Rational B-Splines (NURBS)

\[ A: \left( \frac{X-8.5}{5} \right)^2 + \left( \frac{Y}{7.5} \right)^2 + \left( \frac{Z-43.5}{24} \right)^2 \leq 1 , Z \geq 43.5 \]

\[ B: \left( \frac{X-2.5}{5} \right)^2 + \left( \frac{Y}{7.5} \right)^2 + \left( \frac{Z-43.5}{24} \right)^2 \geq 1 , \text{if } y < 0 \]

Polygon meshes
RPI Adult Male and Female Phantoms


RPI Adult Male

Height: 176 cm
Weight: 73 Kg

RPI Adult female

Height: 163 cm
Weight: 60 Kg

70 Organs; 45 Bone Components; 4 Muscle Structures
Size and Weight Adjustable Phantoms


• Same height (e.g. 176cm Male), but different weights:

<table>
<thead>
<tr>
<th>Weight</th>
<th>Percentile</th>
</tr>
</thead>
<tbody>
<tr>
<td>58.5kg</td>
<td>5th</td>
</tr>
<tr>
<td>66.3kg</td>
<td>25th</td>
</tr>
<tr>
<td>73.1kg</td>
<td>50th</td>
</tr>
<tr>
<td>86.4kg</td>
<td>75th</td>
</tr>
<tr>
<td>103.8kg</td>
<td>95th</td>
</tr>
</tbody>
</table>

The skin meshes from an open source software, MakeHuman™ version 0.9.1 RC11 (http://www.makehuman.org/)
Radiograph Image Optimization (External Dosimetry)

- Simulator linking image quality with x-ray tube settings (mAs, kVp, filtration, grid etc).
- Optimization involves
  - Maximizing diagnostic information (resolution, contrast, SNR)
  - Minimizing organ doses

The relative contribution of diagnostic procedures to the collective medical dose estimated for the year 1996.
Simulation of Lesions

Locations

1. Right Lung, Behind Rib
2. Left Lung, Clear
3. Behind Heart
4. In Liver
Results
Comparison of chest x-ray from different mAs settings and doses

Low dose and low resolution

High dose and high resolution

Optimized dose and resolution


A platform independent, browser-based software

http://www.virtual-dose.com
3D CRT Beam Selection Using Adjoint MC


OARs
- Bladder
- Rectum

PTV
- Prostate
Secondary Cancer from Non-target Doses in Radiation Therapy: A Price to Pay for Successful RT


- Cancer patients survive and live longer
- Patient younger
- Latent effects expected to increase
- IMRT requires greater MU (x3 3DCRT)
Secondary Cancer from Non-target Doses in Radiation Therapy


- Include both accelerator model and computational phantom
- The Accelerator Details:
  - Varian blueprints of 2100C
  - Model by Kase et al. in HPJ
- Patient Details:
  - RANDO Phantom
  - VIP-Man
  - Pregnant patients
  - RPI adult male and female
PET and The Partial Volume Effect

Arises from the poor spatial resolution:

1) Spreading of counts across physical tumor boundaries due to image blurring
2) Tissue fractionation due to coarse voxel grid

*General tendency is to make small lesions look less metabolically active*
Exp. Methods: Ellipsoid Phantom Designs

<table>
<thead>
<tr>
<th>Axis Ratio</th>
<th>Fill Volume (cm³)</th>
<th>Inner Diameter (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A</td>
<td>B</td>
</tr>
<tr>
<td>1:1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Major</td>
<td>37.0</td>
<td>28.0</td>
</tr>
<tr>
<td>4:3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minor</td>
<td>33.6</td>
<td>25.4</td>
</tr>
<tr>
<td>Major</td>
<td>44.8</td>
<td>33.9</td>
</tr>
<tr>
<td>8:5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minor</td>
<td>31.6</td>
<td>23.9</td>
</tr>
<tr>
<td>Major</td>
<td>50.6</td>
<td>38.3</td>
</tr>
<tr>
<td>2:1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minor</td>
<td>29.4</td>
<td>22.2</td>
</tr>
<tr>
<td>Major</td>
<td>58.7</td>
<td>44.4</td>
</tr>
</tbody>
</table>

Tumor volumes same as that of NEMA image quality phantom
Experimental Methods:
Preparation of Phantoms with Radioactivity
CAD/CAM Phantom Fabrication

1. Rapid Prototyping the lung in a plaster material (i.e., 3D printing)
2. Suspend lung prototype in mold box
3. Pour foaming plastic around to form a mold and wait to cure
4. Cut mold apart after and seal with epoxy

(1) CAD model  (2) Prototype  (3) Molding box  (4) Mold parts
4D Geometry-Based Respiration Modeling

Two Treatment Plans Simulated in Monte Carlo Code

Treatment Planning #1 (gating TP)
- The center of ODM is aligned to the lesion in Phase 1 (early inhalation), i.e., 3D treatment planning

Treatment Planning #2 (4D TP)
- The “image-guided” 4D TP where PTV moves according to 8 phases
4D Monte Carlo Dose Simulations

- The center of ODM is always kept conformal to the center of the lesion in Phase1.
- The data show that dose distributions in phase 3 and phase 4 are under-dosed.
Posture Simulation for Criticality Accident


• 1997 accident at a nuclear testing facility in Sarov, Russia

• Technician exposed to radiation resulting from a criticality excursion

• Death 66 hours later
Simulating the Sarov Accident
Simulating the Sarov Accident
Results: Neutron Kerma

Simulation results normalized to literature results for the chest.

<table>
<thead>
<tr>
<th>Location</th>
<th>Simulation</th>
<th>Literature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Face</td>
<td>40±5</td>
<td>35±2</td>
</tr>
<tr>
<td>Back of Head</td>
<td>10±1</td>
<td>9±1</td>
</tr>
<tr>
<td>Left Armpit</td>
<td>35±3</td>
<td>30±2</td>
</tr>
<tr>
<td>Right Armpit</td>
<td>50±5</td>
<td>45±3</td>
</tr>
<tr>
<td>Pubic Area</td>
<td>25±2</td>
<td>20±1</td>
</tr>
<tr>
<td>Chest</td>
<td>45±4</td>
<td>40±3</td>
</tr>
<tr>
<td>Back</td>
<td>15±1</td>
<td>10±0.5</td>
</tr>
</tbody>
</table>
<<Handbook of Anatomical Models for Radiation Dosimetry>>
– curtsey images from various authors
Published in late 2009

- 50-y history
- 30 chapters
- 64 authors
- 13 countries (regions)
- 100+ phantoms
50-Year History of Computational Phantoms

- Radiation Protection
- Medical Imaging
- Radiotherapy

1st Generation

MIRD anthropomorphic models in 1980s

STYLIZED

2nd Generation

Image-based rigid, 3D model in 1990-2000s

VOXEL

3rd Generation

Deformable and moving 4D models 2008-2010

BREP

Personalization is Future
The Number of New Phantoms Increased Exponentially


*Top-10 most-downloaded paper in PMB during 2014*
Outline

1. Computational Human Phantoms

2. ARCHER Monte Carlo Code
Recent Work on Fast Monte Carlo Methods

• Monte Carlo method is the gold standard in radiation transport analysis and dose calculations

• Advantages
  ➢ Accurate physics model
  ➢ Particle tracking in heterogeneous systems
  ➢ 3-D geometry

• Disadvantage
  ➢ Long computation time to achieve acceptable statistical uncertainty (a few hours to days)

• Traditional parallel paradigms are CPU-based
  ➢ Message Passing Interface (MPI): MPICH, OpenMPI
  ➢ Multithreading: OpenMP, Pthreads
High-Performance Computing Depends on Hardware Accelerators

- Hardware accelerators
  - High computing efficiency

![Hardware Accelerators Images]

ARChER – A Monte Carlo Testbed

Accelerated Radiation-transport Computations in Heterogeneous Environments

Application
- CT imaging
- Radiotherapy
- Shielding design
- Reactor analysis

Hardware
- Intel/AMD multi-core CPU
- NVIDIA Fermi/Kepler GPU
- AMD GCN GPU
- Intel MIC coprocessor

Software
- MPI
- OpenMP
- Pthreads
- CUDA
- OpenACC
- OpenCL
- Cilk

www.archer-MC.com
Two Recent Examples:

1. CT imaging

2. Radiotherapy
Materials and Methods: Hardware @ $10k

- Tyan FT77B7015 server
- Intel Xeon X5650 CPU
  - 6 cores
  - 12 hyperthreads in total
- Nvidia Tesla M2090 GPU
- Intel Xeon Phi 5110p coprocessor

[1] CPU figure resource: SuperBiiz
Method: Nvidia Tesla M2090 GPU

- **Fermi architecture**
  - 16 Streaming Multiprocessors (SM)/GPU
  - 32 Streaming Processors (SP)/SM → CUDA core
  - 6 GB RAM

- **Parallelism achieved by:**
  - GPU: thread blocks are distributed among the SMs for **simultaneous** execution
  - SM: threads are pushed into the instruction pipelines for **concurrent** execution

- **Number of active resident threads on a GPU**
  - Problem-dependent
  - ~8000 in our case
Introduction: Intel Xeon Phi “coprocessor”

- Many Integrated Core (MIC) architecture
  - 60 Pentium cores
  - 8 GB RAM
- Parallelism achieved by:
  - coprocessor: threads are distributed among the cores for **simultaneous** execution
  - core: 4 hyper-threads for **concurrent** execution
- Number of threads on a coprocessor
  - 240 (fixed)
Materials and Methods: CT scanner model (w Dr. Bob Liu and Mannu Kalra, MGH)

• **GE LightSpeed third-generation 16-multi-detector CT scanner**
  - Validated with experimental CTDI data

• **Scan protocol**
  - Tube voltage: 80, 100, 120, 140 kVp
  - Beam collimation: 1.25, 5, 10, 20 mm
  - Scan type: head, body bowtie filters
  - Scan mode: helical, axial
Results and Discussion: Performance benchmark

| Code             | Runtime configs                      | Computation time [min] | Speedup to ARCHER-CP  
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Parallel MCNPX</td>
<td>12 MPI procs</td>
<td>476.35</td>
<td>--</td>
</tr>
<tr>
<td>ARCHER-CT_CPU</td>
<td>12 HTs</td>
<td>11.40</td>
<td>1.00×</td>
</tr>
<tr>
<td>ARCHER-CT_GPU</td>
<td>100 photons/thread</td>
<td>2.38</td>
<td>4.80×</td>
</tr>
<tr>
<td></td>
<td>256 threads/block</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ARCHER-CT_COP</td>
<td>60 MPI procs, 4 HTs/proc</td>
<td>3.48</td>
<td>3.28×</td>
</tr>
<tr>
<td></td>
<td>Native execution mode</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

• Theoretical peak performance
  - GPU: 1.3 TFLOPS
  - Coprocessor: 2 TFLOPS
• But ARCHER-CT_GPU is 46% faster than ARCHER-CT_COP
Results and Discussion: Clinical CT case

- CT images converted to voxelized phantom

- 3D CT imaging dose distribution by ARCHER-CT\textsubscript{GPU}
  
  - 1 GPU: 3.7 seconds
  - 6 GPUs: 0.6 seconds – *real-time speed*
Simulation of Tomotherapy (w/ Dr Bryan Bednarz of UW-Madison)

MC for helical tomotherapy dose calculation

- Megavoltage X-ray source
  - 6MV electron linac
  - secondary electrons transported
- Phase space file (PSF) used for input
  - Patient-specific
- Electron + photon transport in ARCHER

Introduction: TomoTherapy PSF

6 MeV photon hit on target, generate X-ray

Mean energy: 1.45 MeV

With the rotation of gantry and translation of bench, the PS particles form a cylinder

~10^8 photons PSF size ~GBs
Reading time nontrivial ~30 sec

Adopted from TomoTherapy website
Materials and Methods: cases tested

- 6 MV SIEMENS PRIMS accelerator PSF dose distribution in water
- Three clinical TomoTherapy cases
- Prostate PSF, 200M particles, 2x recycle (600M particles in total)
- Lung PSF, 53M particles, 9x recycle (530M particles in total)
- Head & Neck PSF, 160 M particles, 4x recycle (800M particles in total)
- $E_{\text{cutoff}} = 200$ keV ; $P_{\text{h cutoff}} = 10$ keV
Results: Lung case

Statistical error in PTV \(\sim1\%\)

2%/2mm Gamma test pass rate: 98.5%
### Results: MC Transport Time Comparison

<table>
<thead>
<tr>
<th>Clinical cases</th>
<th>Intel X5650 (12 threads) time [s]</th>
<th>K40 GPU time [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prostate</td>
<td>729 (1x)</td>
<td>37.9 (19.2x)</td>
</tr>
<tr>
<td>Lung</td>
<td>507 (1x)</td>
<td>29.7 (17.1x)</td>
</tr>
<tr>
<td>Head &amp; neck</td>
<td>876 (1x)</td>
<td>44.2 (19.8x)</td>
</tr>
</tbody>
</table>

In contrast, GEANT4 needs ~ 500 CPU hours for the similar simulation.
Summary

1. Phantom research advanced exponentially in the past 60 years

2. GPU and MIC hardware will drive high-performance computing in this decade, leading to “real-time” Monte Carlo simulations

More info at http://RRMDG.rpi.edu