PIMAL: Phantom wIth Moving Arms and Legs

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2017 RAMP Users' Group Meeting
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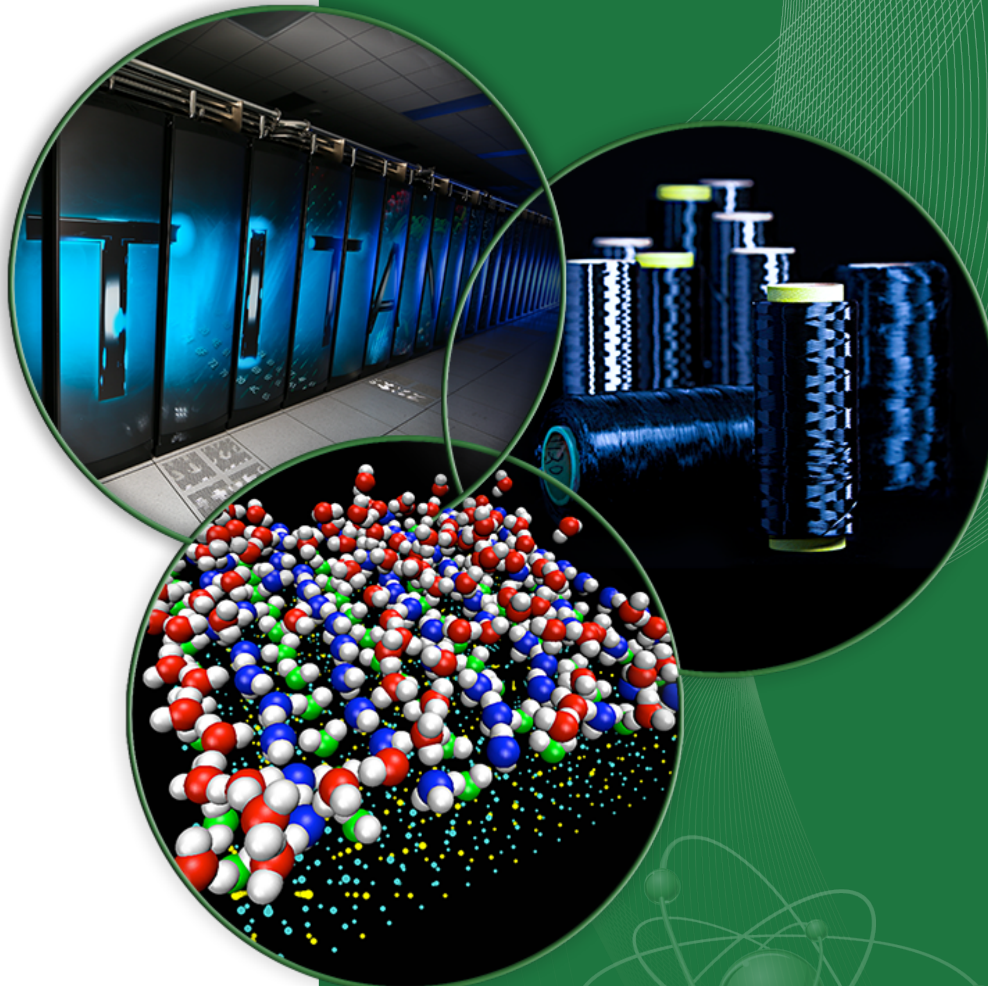
Slide contribution credit: Mauritius Hiller



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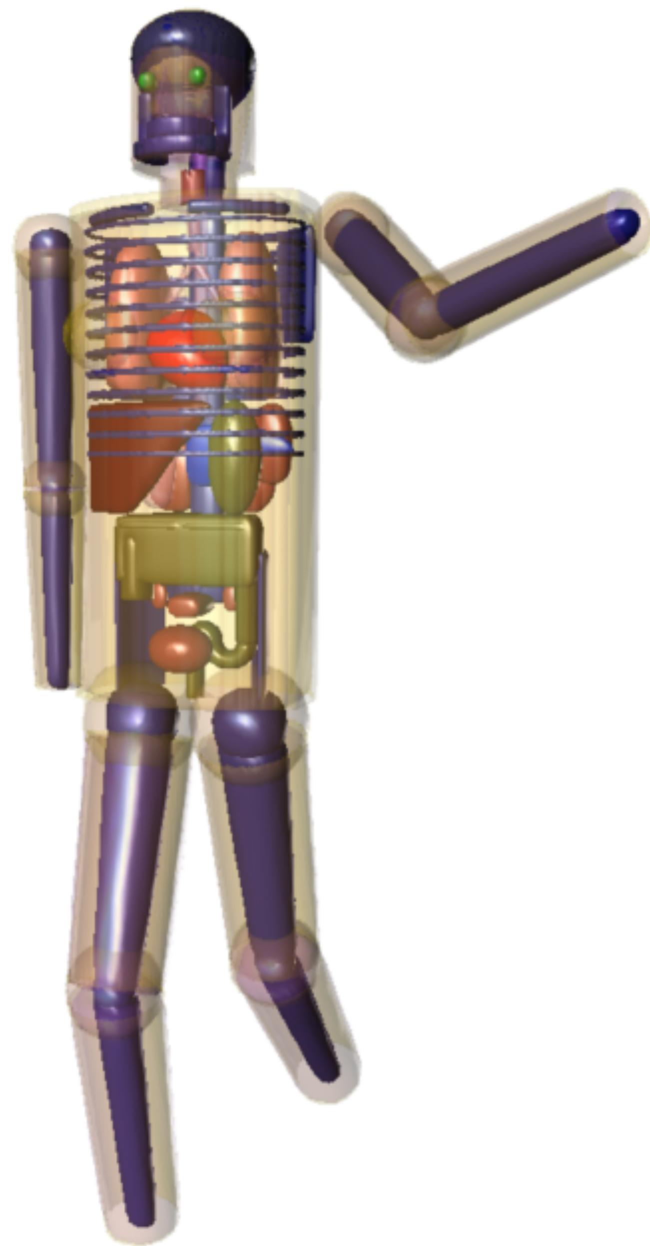
Welcome

2017 RAMP Users Group Meeting



Course Objectives

The objectives of this course are to:

1. Provide participants with a review of fundamental dosimetric quantities as they pertain to operational and radiation protection quantities.
2. Elaborate the history and capabilities of computational phantoms and the requirement for position-specific phantoms.
3. Highlight the development and capabilities of the PIMAL software application in the estimation of radiation organ and effective doses using Monte Carlo (MCNP®) simulation.
4. Demonstrate how to navigate PIMAL's capabilities with simple and intermediate-level real-life problems and applications.
5. Provide in-person resources for RAMP users to navigate needs using PIMAL.

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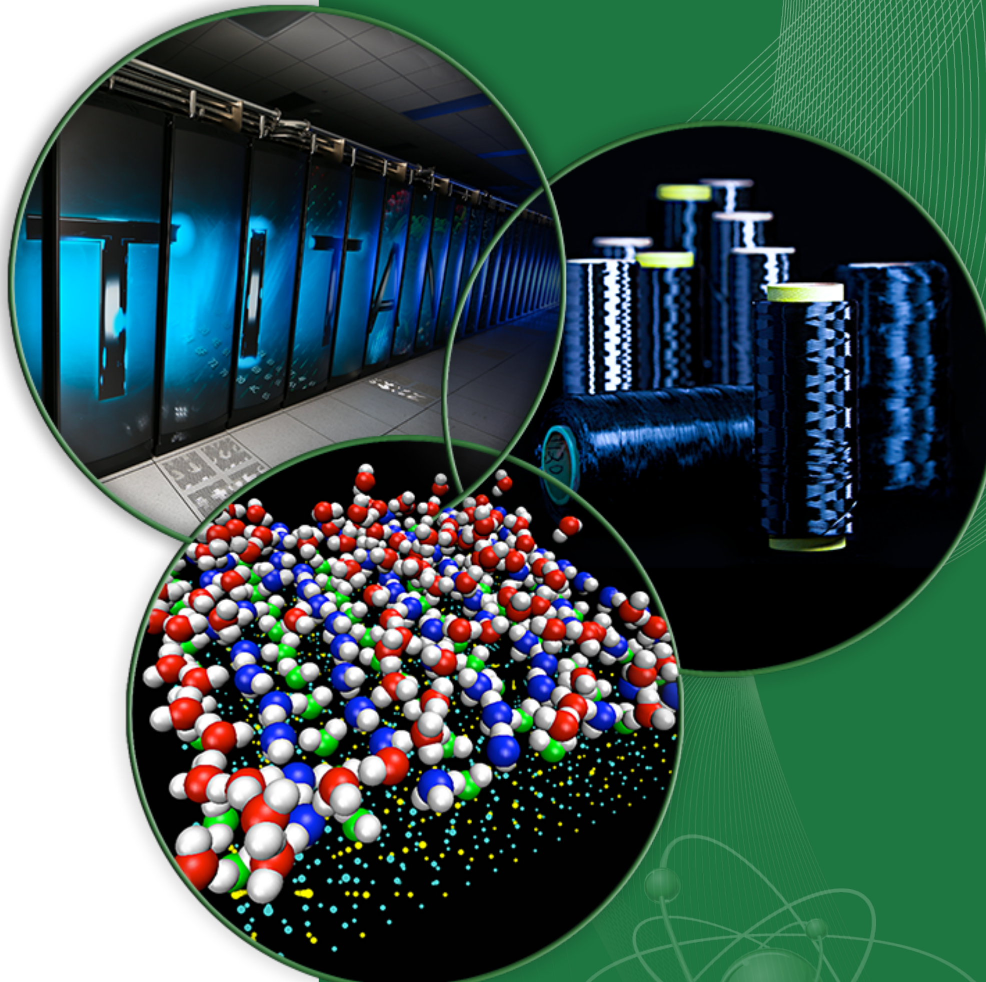

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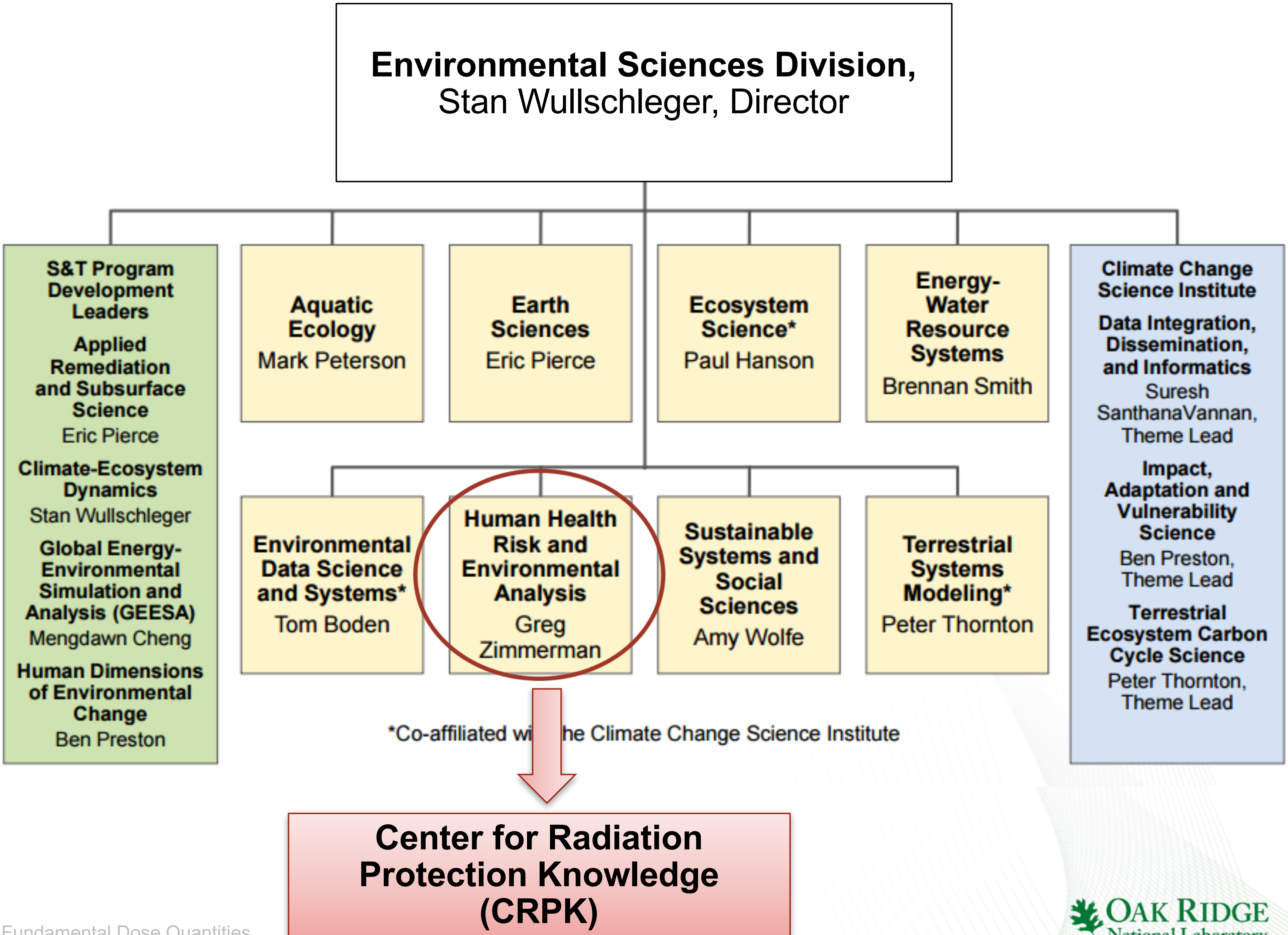
Environmental Sciences Division,
Stan Wullschleger, Director
S&T Program Development Leaders
Applied Remediation and Subsurface Science
Eric Pierce
Climate-Ecosystem Dynamics
Stan Wullschleger
Global Energy-Environmental Simulation and Analysis (GEESA)
Mengdawn Cheng
Human Dimensions of Environmental Change
Ben Preston
Aquatic Ecology
Mark Peterson
Earth Sciences
Eric Pierce
Ecosystem Science*
Paul Hanson
Energy-Water Resource Systems
Brennan Smith
Climate Change Science Institute
Data Integration, Dissemination, and Informatics
Suresh SanthanaVannan, Theme Lead
Impact, Adaptation and Vulnerability Science
Ben Preston, Theme Lead
Terrestrial Ecosystem Carbon Cycle Science
Peter Thornton, Theme Lead
Environmental Data Science and Systems*
Tom Boden
Human Health Risk and Environmental Analysis
Greg Zimmerman
Sustainable Systems and Social Sciences
Amy Wolfe
Terrestrial Systems Modeling*
Peter Thornton
*Co-affiliated wi he Climate Change Science Institute
Center for Radiation Protection Knowledge (CRPK)

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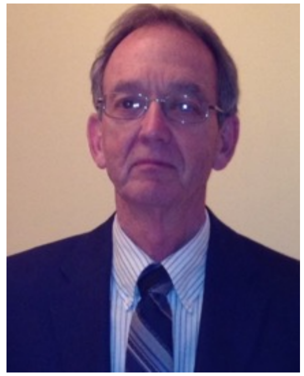
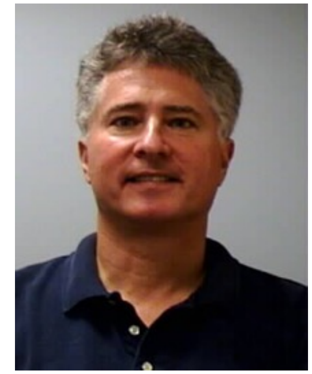








Top:
Nolan Hertel - Director (JFA, GaTech)
Keith Eckerman (Emeritus)
Rich Leggett (Senior R&D Scientist)
Michael Bellamy (ORNL, R&D Engineer)
Shaheen Dewji (ORNL, R&D Engineer)
Greg Zimmerman (ORNL, Group Leader)

Middle:
Derek Jokisch (JFA, Francis Marion U)
Nicole Martinez (JFA, Clemson U)
Rob Hayes (JFA, NCSU)
Kathryn Bales (Post-BSc Intern)

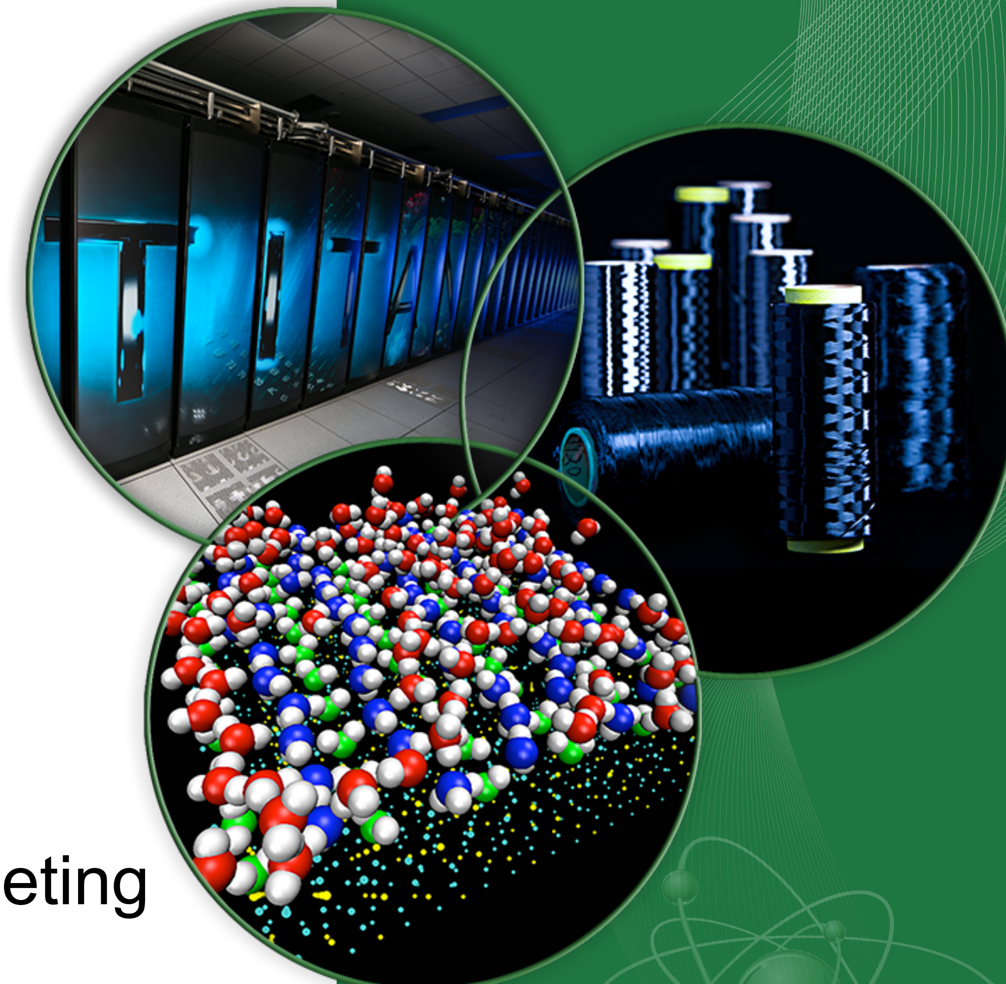
Bottom:
Clay Easterly (Consultant)
Ken Veinot (Consultant)
Pat Scofield (ORNL)
Scott Schwahn (ORNL)

Alumni Post-Doc/Students: Mauritius Hiller, Cailin O'Connell, Mullin Green, Eli Sanchez, Isaac D'Agostino, Keresten Goodman, K. Lisa Reed, Eric Maez, Miriam Rathbun, Keith Griffin, Lauren Finklea

Center for Radiation Protection Knowledge: Value to Radiation Protection Stakeholders

1. Provide infrastructure and resources to continue to provide services in radiation protection and dosimetry
   – Retain expertise to conduct fundamental R&D domestically
2. Collaborate and communicate across organizational boundaries
3. Capture critical knowledge before it is lost to create organizational memory
4. Facilitate the decision making process
5. Create sustainable KM system in radiation protection

PIMAL Installation



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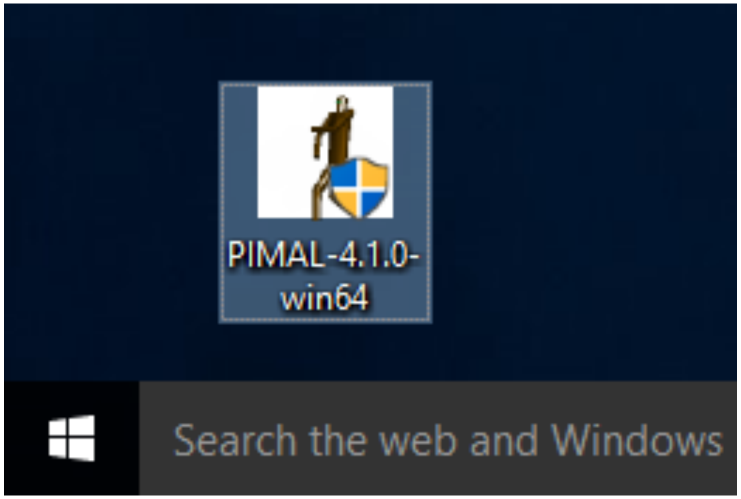
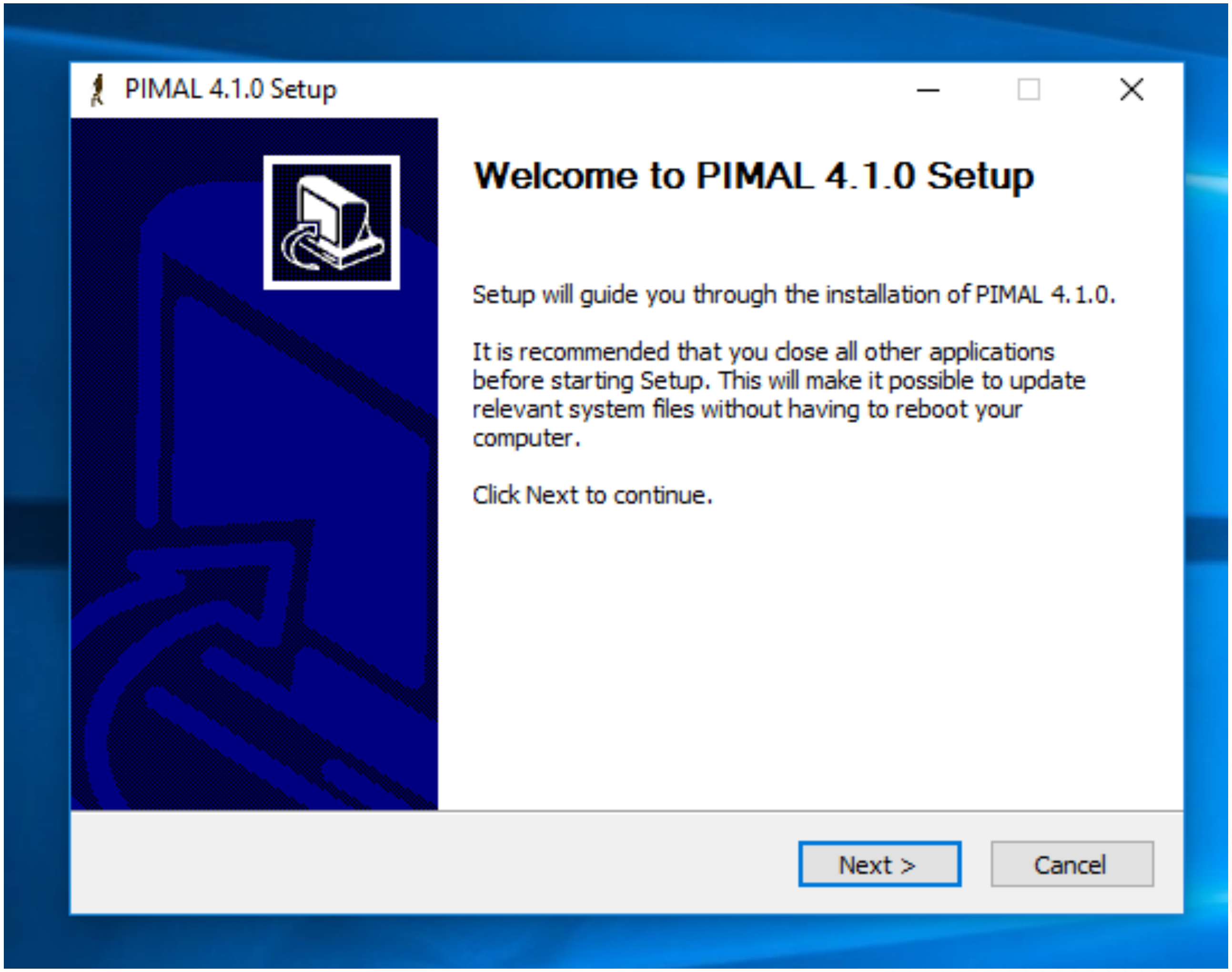
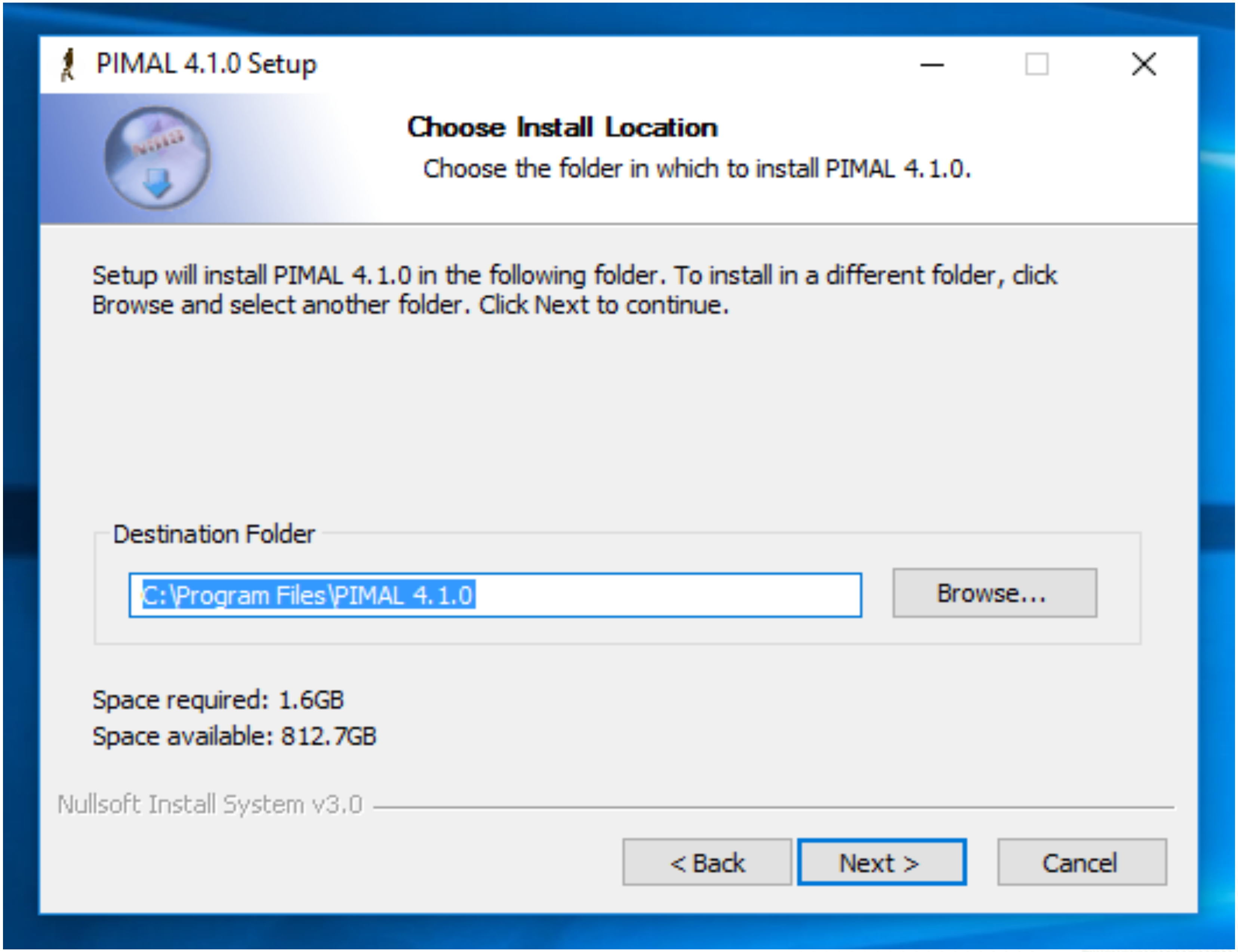
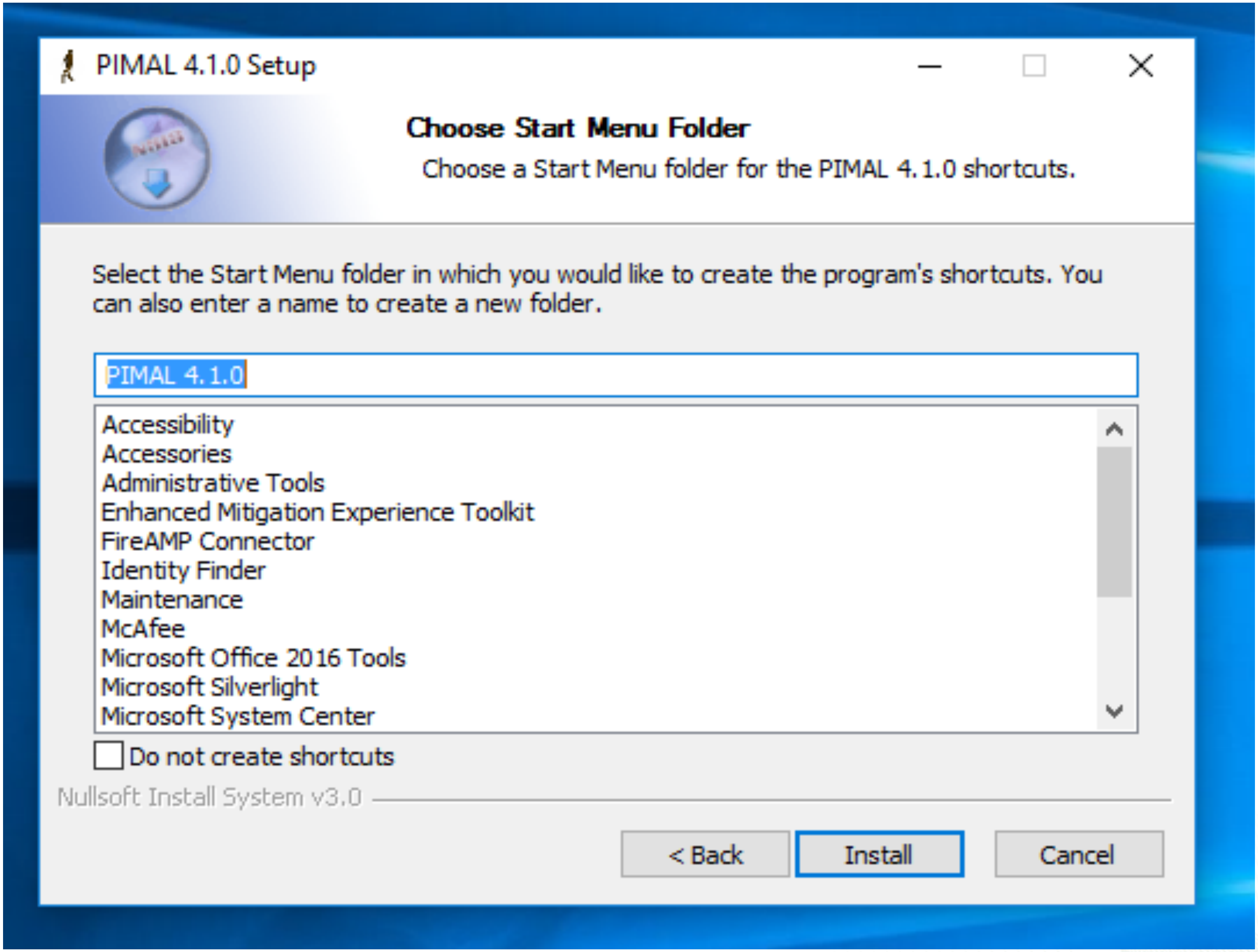
PIMAL Installer

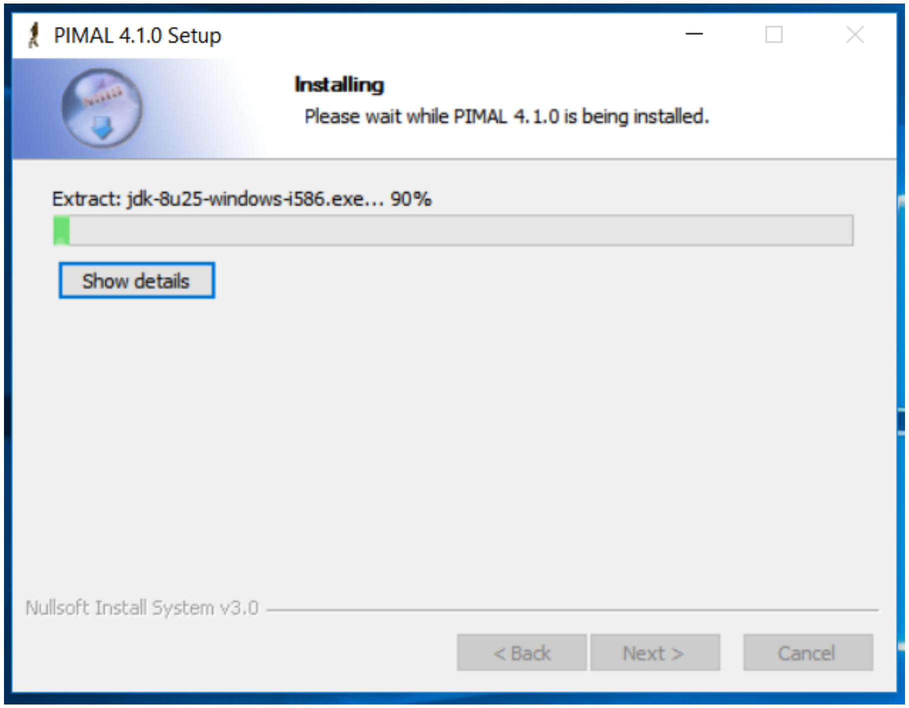


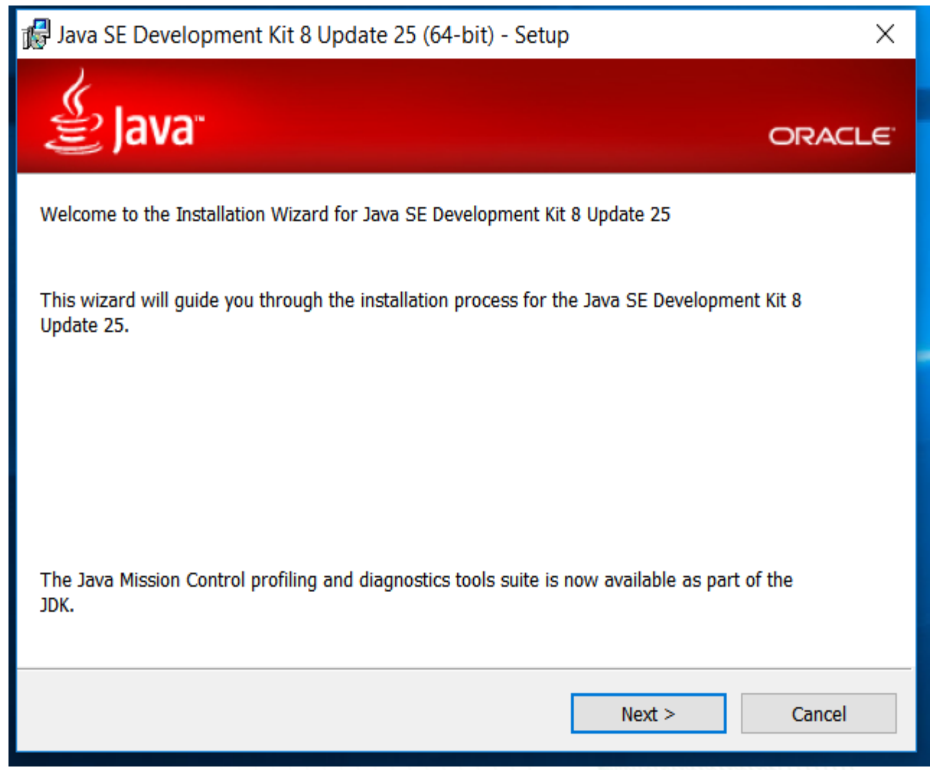

PIMAL 4.1.0 Setup
Welcome to PIMAL 4.1.0 Setup
Setup will guide you through the installation of PIMAL 4.1.0.
It is recommended that you close all other applications before starting Setup. This will make it possible to update relevant system files without having to reboot your computer.
Click Next to continue.
Next >
Cancel

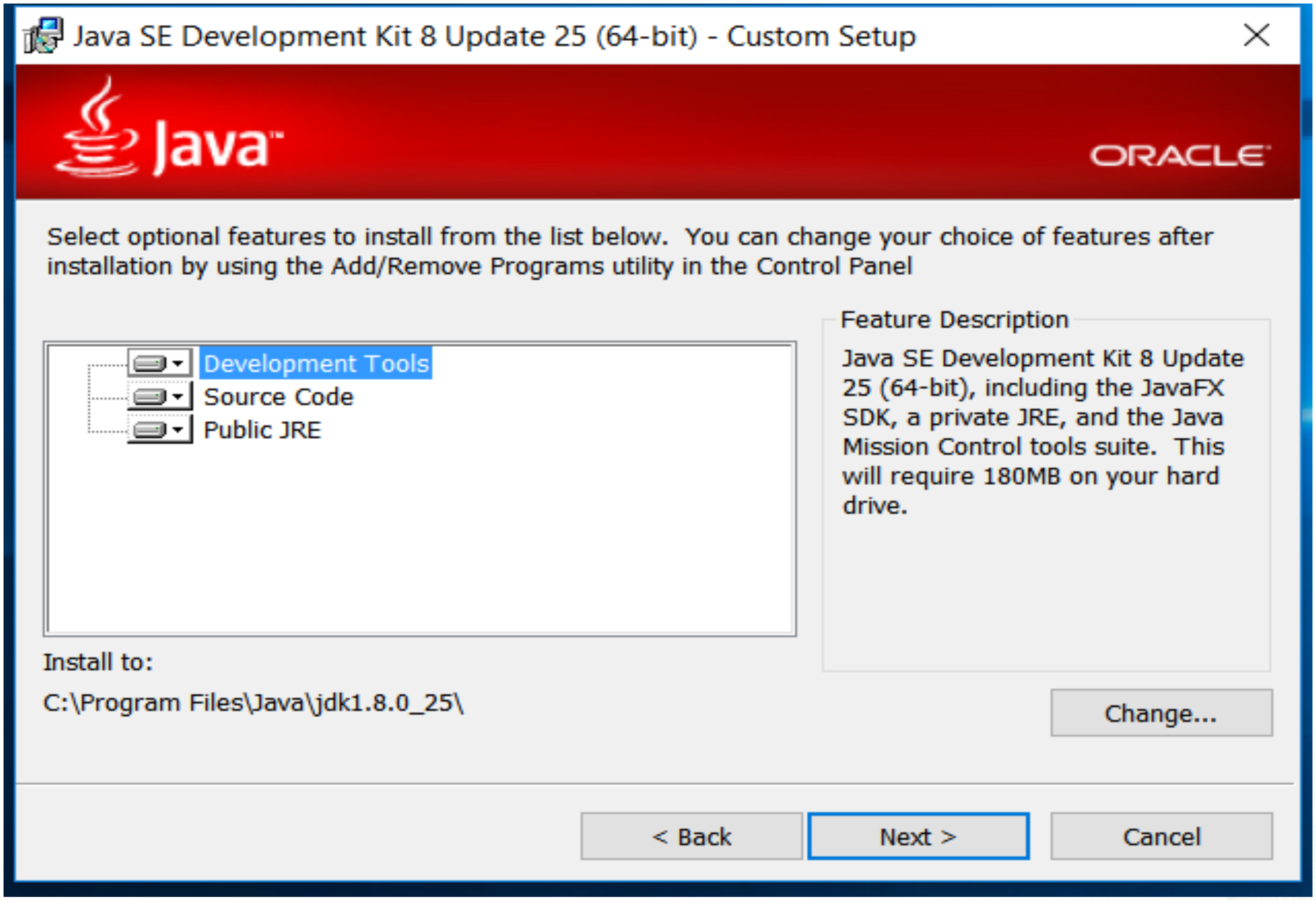

PIMAL 4.1.0 Setup
Choose Install Location
Choose the folder in which to install PIMAL 4.1.0.
Setup will install PIMAL 4.1.0 in the following folder. To install in a different folder, click Browse and select another folder. Click Next to continue.
Destination Folder
C:\Program Files\PIMAL 4.1.0
Browse...
Space required: 1.6GB
Space available: 812.7GB
Nullsoft Install System v3.0
< Back
Next >
Cancel

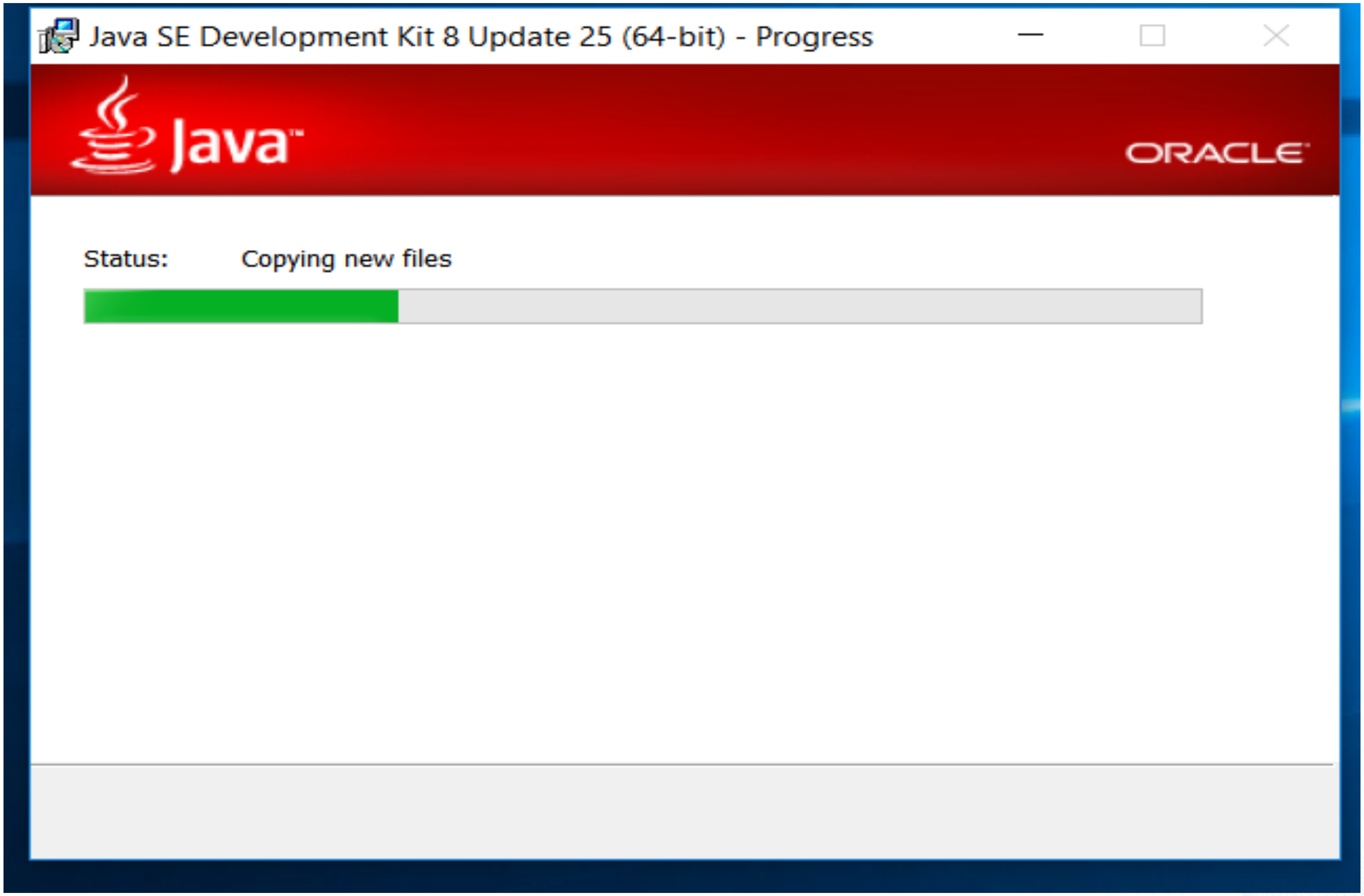

PIMAL 4.1.0 Setup
Choose Start Menu Folder
Choose a Start Menu folder for the PIMAL 4.1.0 shortcuts.
Select the Start Menu folder in which you would like to create the program's shortcuts. You can also enter a name to create a new folder.
PIMAL 4.1.0
Accessibility
Accessories
Administrative Tools
Enhanced Mitigation Experience Toolkit
FireAMP Connector
Identity Finder
Maintenance
McAfee
Microsoft Office 2016 Tools
Microsoft Silverlight
Microsoft System Center
Do not create shortcuts
Nullsoft Install System v3.0
< Back
Install
Cancel

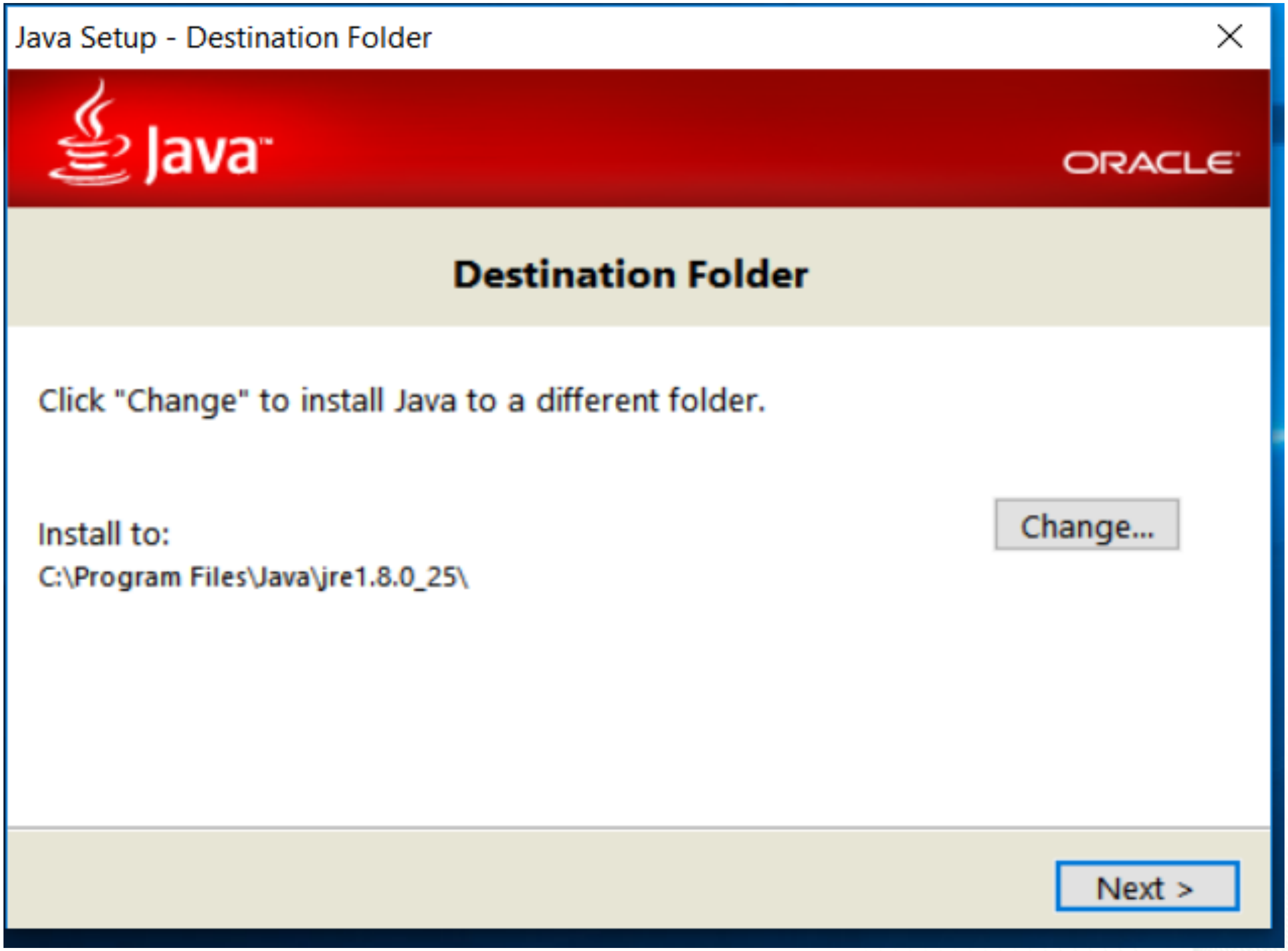
Java installation






Java SE Development Kit 8 Update 25 (64-bit) - Custom Setup
Java
ORACLE
Select optional features to install from the list below. You can change your choice of features after installation by using the Add/Remove Programs utility in the Control Panel
Development Tools
Source Code
Public JRE
Feature Description
Java SE Development Kit 8 Update 25 (64-bit), including the JavaFX SDK, a private JRE, and the Java Mission Control tools suite. This will require 180MB on your hard drive.
Install to:
C:\Program Files\Java\jdk1.8.0_25\
Change...
< Back
Next >
Cancel

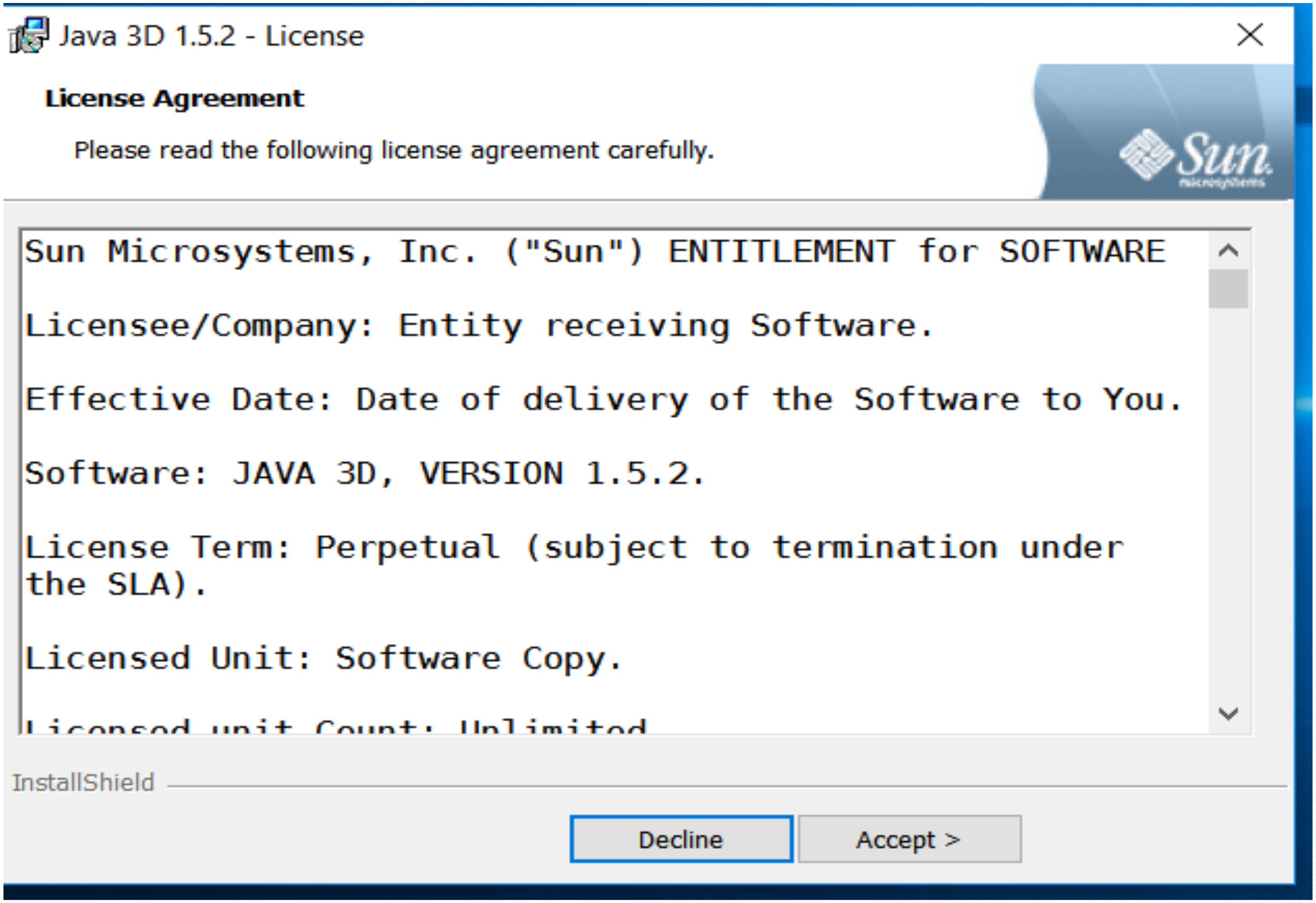

Java SE Development Kit 8 Update 25 (64-bit) - Progress
Java
ORACLE
Status: Copying new files

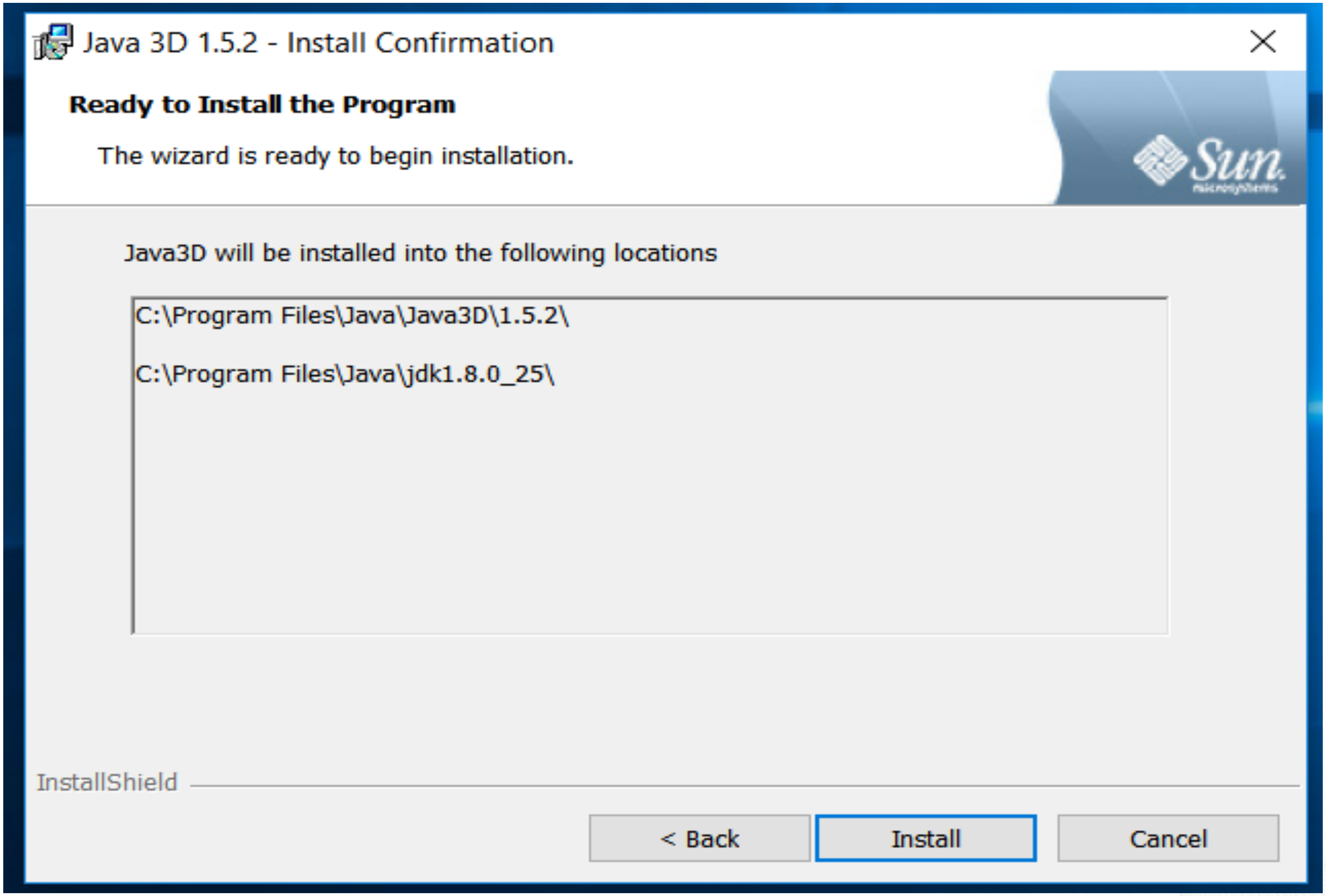

Java Setup - Destination Folder
Java
ORACLE
Destination Folder
Click "Change" to install Java to a different folder.
Install to:
C:\Program Files\Java\jre1.8.0_25\
Change...
Next >


Java Setup - Progress
Java
ORACLE
Status: Installing Java
3 Billion Devices Run Java
Computers, Printers, Routers, Cell Phones, BlackBerry, Kindle, Parking Meters, Public Transportation Passes, ATMs, Credit Cards, Home Security Systems, Cable Boxes, TVs...
ORACLE

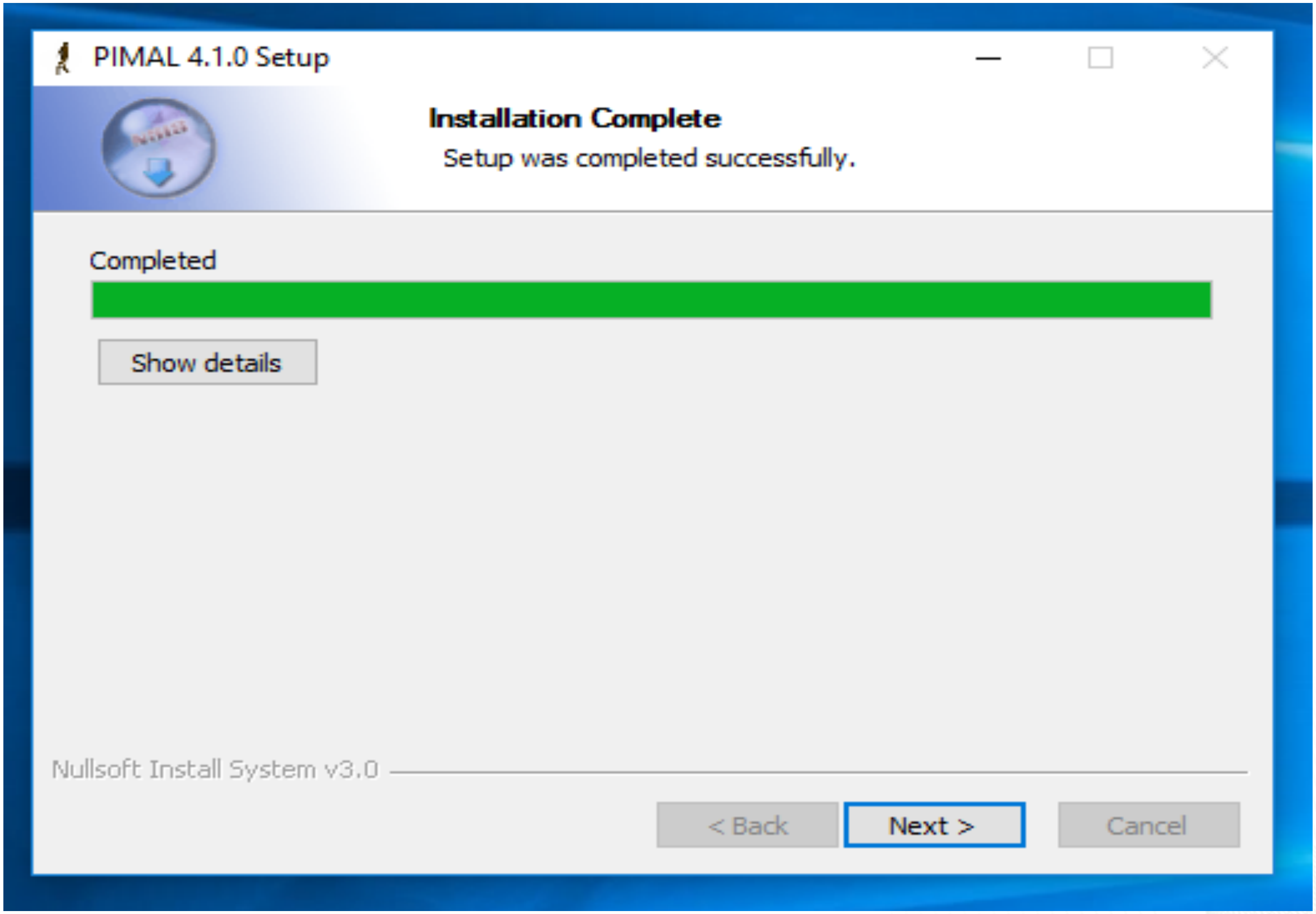

PIMAL 4.1.0 Setup
Installing
Please wait while PIMAL 4.1.0 is being installed.
Execute: "C:\Program Files\PIMAL 4.1.0\64Bit\jdk-8u25-windows-x64.exe"
Show details
Nullsoft Install System v3.0
< Back
Next >
Cancel
Java SE Development Kit 8 Update 25 (64-bit) - Complete
Java
ORACLE
Java SE Development Kit 8 Update 25 (64-bit) Successfully Installed
Click Next Steps to access tutorials, API documentation, developer guides, release notes and more to help you get started with the JDK.
Next Steps
Close

Java 3D installation

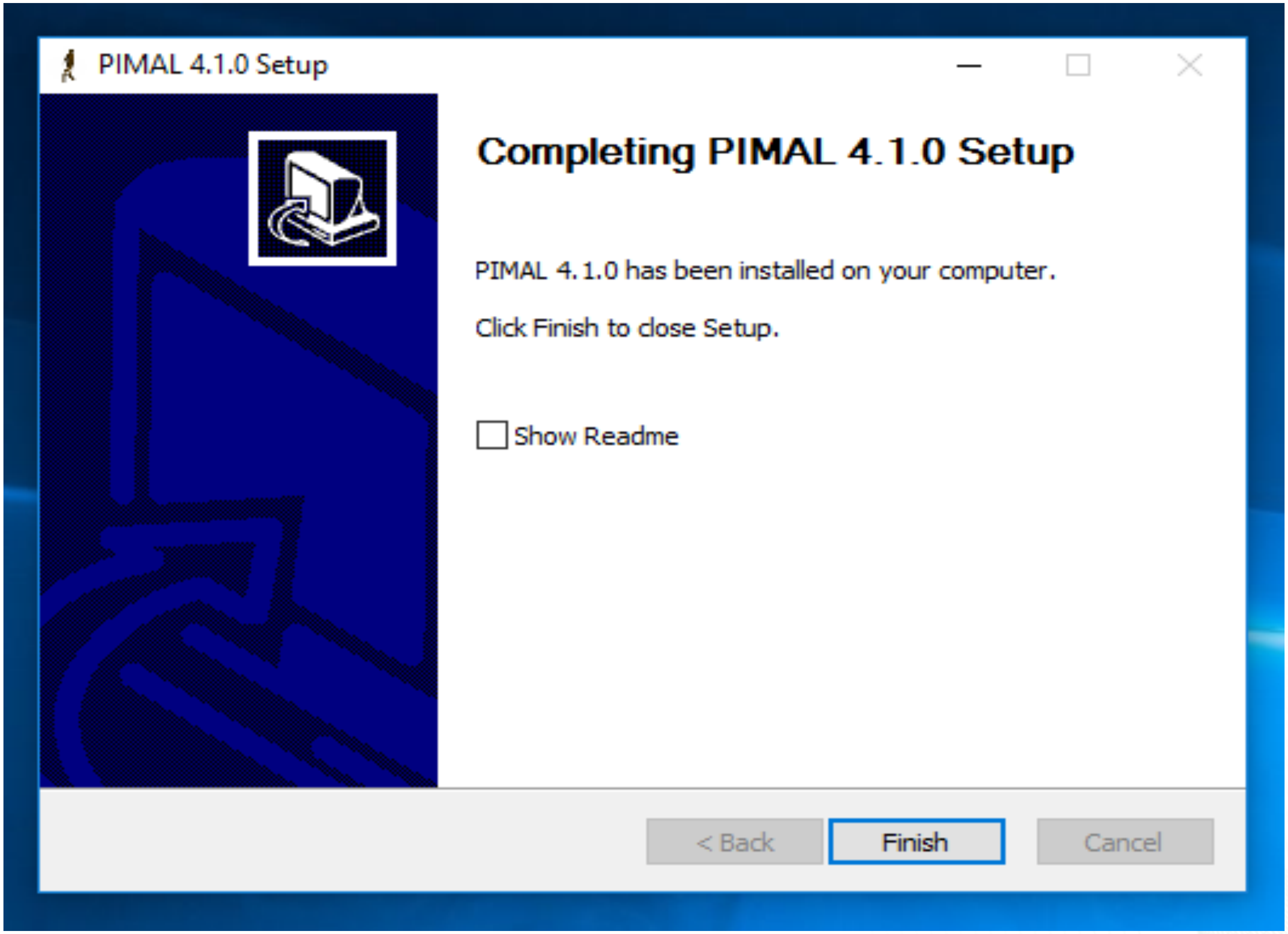



Java 3D 1.5.2 - Install Confirmation
Ready to Install the Program
The wizard is ready to begin installation.
Sun
Java3D will be installed into the following locations
C:\Program Files\Java\Java3D\1.5.2\
C:\Program Files\Java\jdk1.8.0_25\
InstallShield
< Back
Install
Cancel


PIMAL 4.1.0 Setup
Installing
Please wait while PIMAL 4.1.0 is being installed.
Execute: "C:\Program Files\PIMAL 4.1.0\64Bit\j3d-1_5_2-windows-amd64.exe"
Show details
Nullsoft Install System v3.0
< Back
Next >
Cancel
Java 3D 1.5.2 - Complete
Java
Complete
Java 3D 1.5.2 has been successfully installed. Click Finish to exit.
Sun
Open Readme File
Finish


PIMAL 4.1.0 Setup
Installation Complete
Setup was completed successfully.
Completed
Show details
Nullsoft Install System v3.0
< Back
Next >
Cancel

Done!



PIMAL 4.1.0 Setup
Completing PIMAL 4.1.0 Setup
PIMAL 4.1.0 has been installed on your computer.
Click Finish to close Setup.
Show Readme
< Back
Finish
Cancel

PIMAL in Action - Examples

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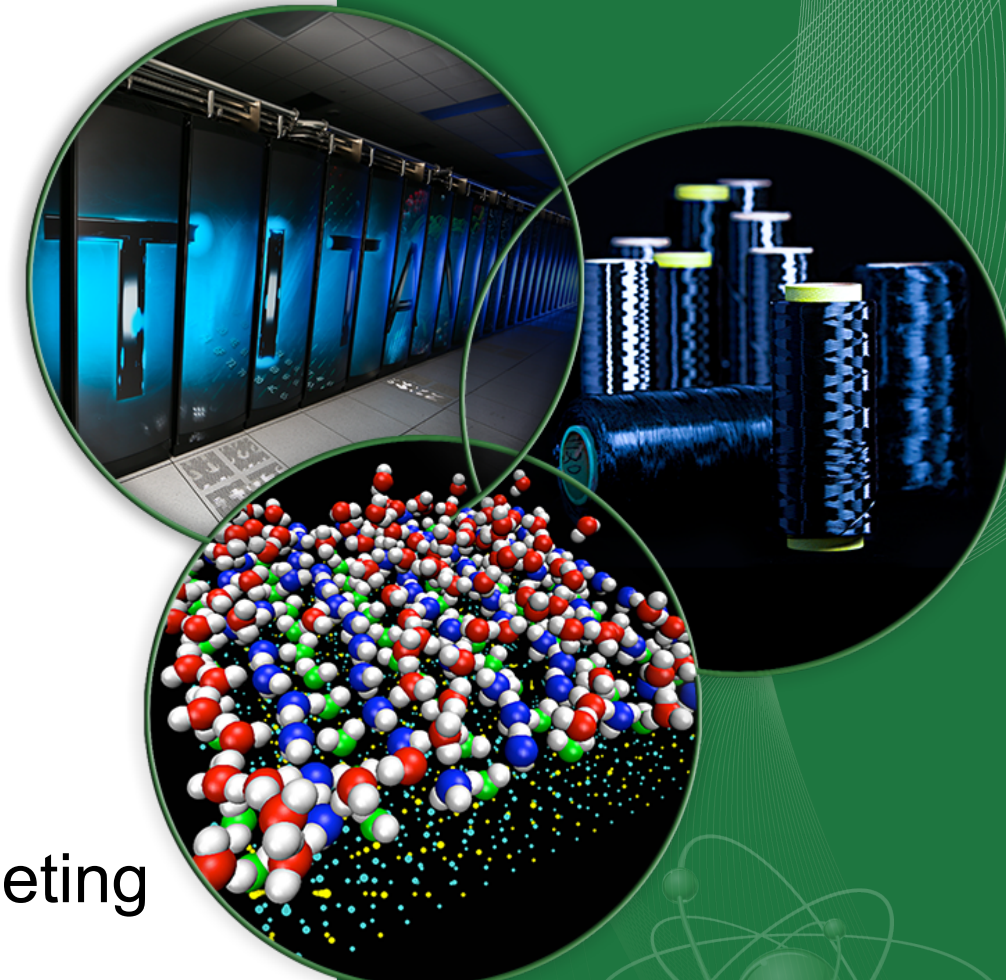

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Why PIMAL?

- Radiation dose calculations require computational modeling because complex geometries such as the human body are involved.
- Both old and recent human body models have almost always been rigidly created in the vertical, upright position.
- ORNL addressed this issue in 2007 by developing a piece of software named **P**hantom w**I**th **M**oving **A**rms and **L**egs (PIMAL) which creates a flexible phantom model for Monte Carlo N-Particle (MCNP) code simulations.
- ICRP 89 tissue compositions and densities.

PIMAL

- **Available** (registration required) on **U.S. Nuclear Regulatory Commission Radiation Protection and Computer Code Maintenance Program (RAMP)**

NRC RAMP Website | RAMP Website

- https://www.usnrc-ramp.com

- ORNL inquiry:
  crpk@ornl.gov
  pimal@ornl.gov

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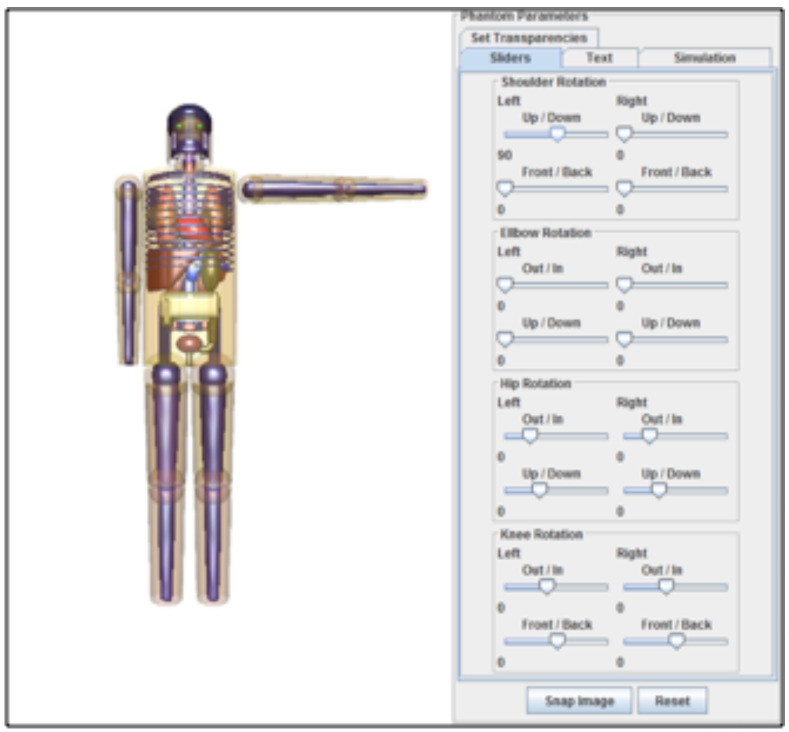
PIMAL Methods

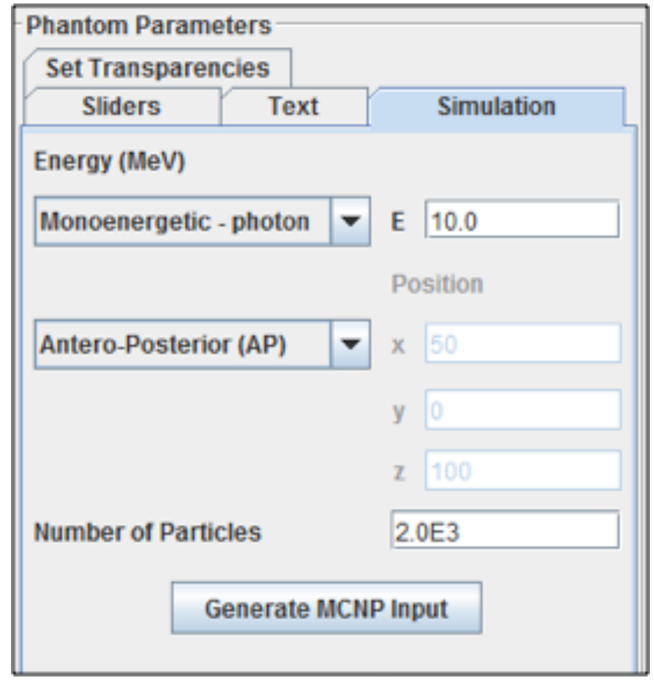
- Geometry Customization
  - Phantom geometry can be articulated using slider bars or textbox input of joint angle.
  - Customizable joints: shoulders, elbows, hips, knees



Screenshot of PIMAL 4.1.0 GUI Interface with sliders to define joint articulation of limbs.

PIMAL Methods

- Source Configuration
  - **Source Energies and Spectra**
    - Radionuclide sources (^{60}Co, ^{131}I, ^{134}Cs)
    - X-ray sources (80-120 kVp)
    - Neutron spectra (AmBe or PuBe)
  - **External Source Configuration**
    - Point source (user specified X, Y, Z coordinates)
    - Standard irradiation geometries (AP, PA, RLAT, LLAT, ISO)
  - **Organ Volume Sources**
    - Brain, Thyroid, Heart Wall/Content, Stomach Wall/Content, Liver, Left/Right/Both Lungs, Left/Right Kidney, Pancreas



PIMAL source configuration simulation tab.

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Examples

1. **Glovebox Worker**
2. I-131 Patient Release Study
3. Upright vs. PIMAL Bent for ICRP 116 Geometries
   - Photon
   - Neutron
   - TLD

Assessment of Organ Doses for a Glovebox Worker Using Realistic Postures with PIMAL and VOXMAT (Akkurt et al., 2009)

- PIMAL used in a more realistic posture, compared to the standard vertical upright position, to represent a glovebox worker.

PIMAL – Glovebox (2)

- The source spectrum, based on clean weapons-grade plutonium.
- Absorbed organ dose values for both postures for all phantom models were computed using MCNPX.
- Total dose, neutron and photon doses were calculated separately.

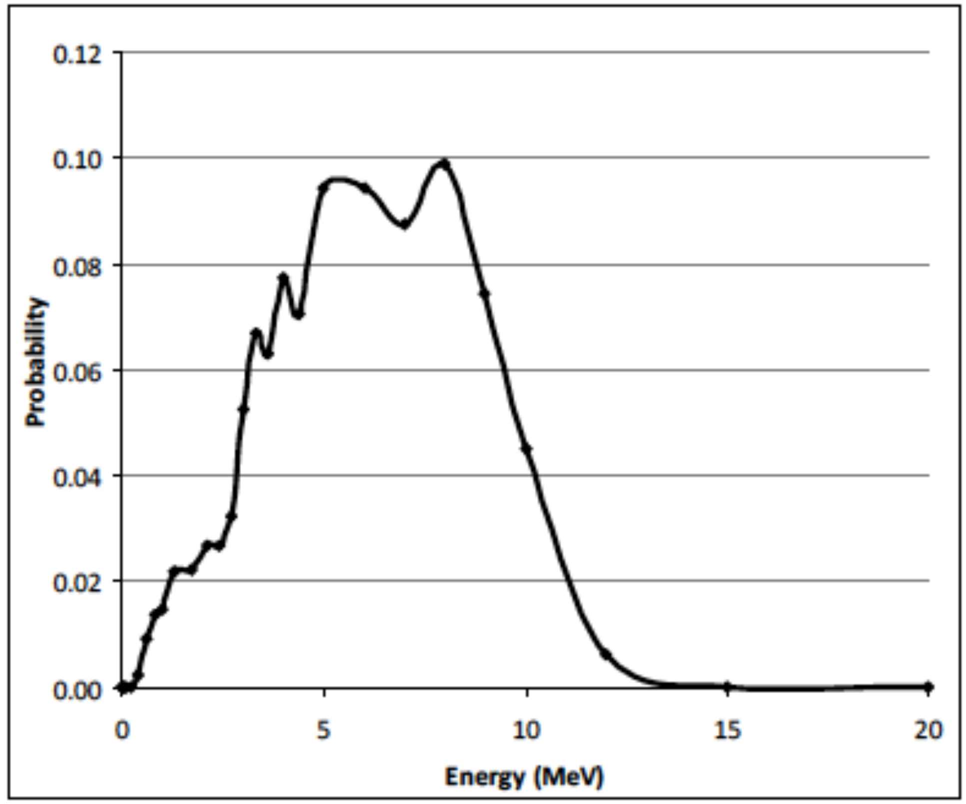

Fig. 2. Neutron source spectrum

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Akkurt et. al (2009)

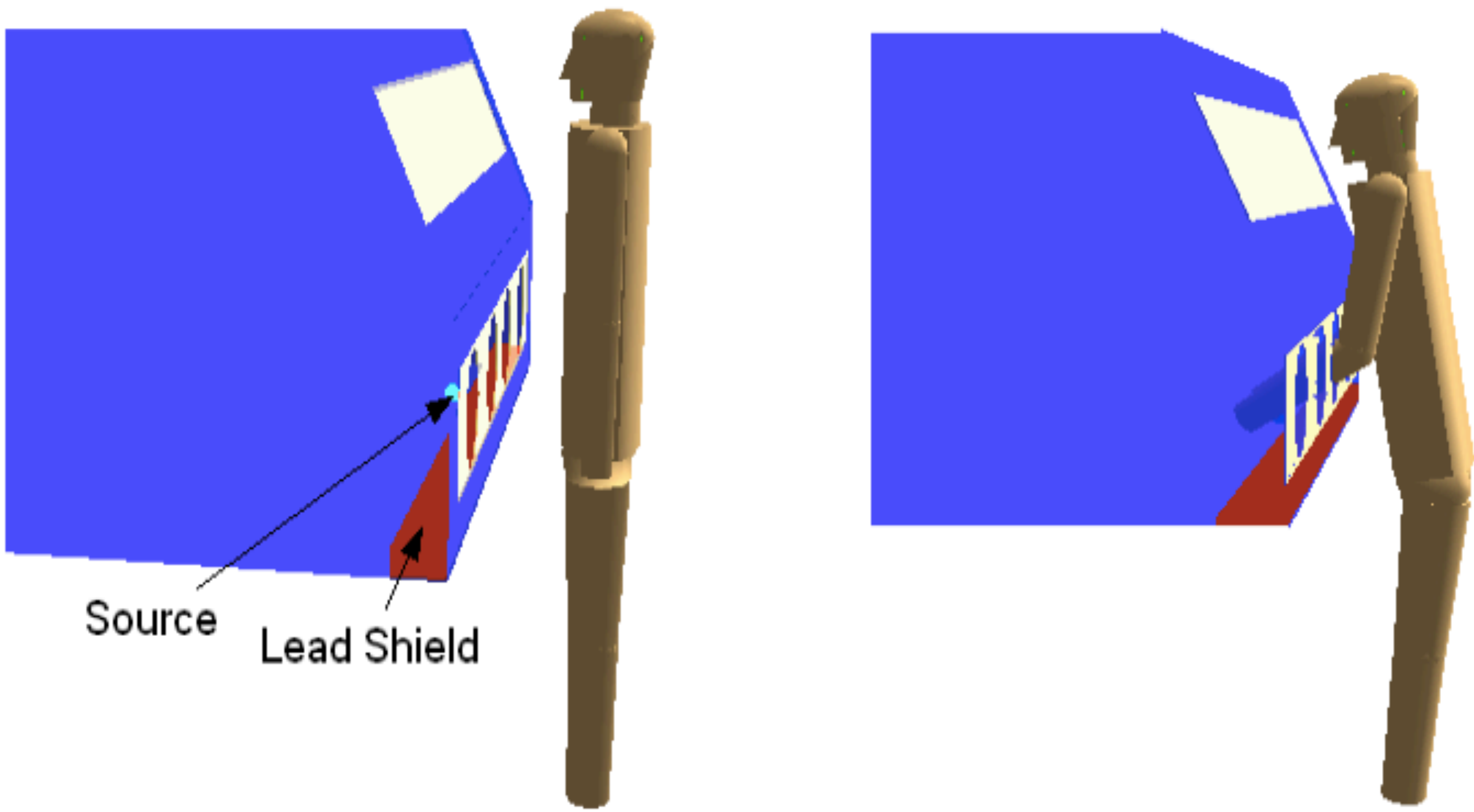


Fig. 1. PIMAL as a glovebox worker in traditional vertical upright position (left) and in realistic posture for better representation of the worker's posture (right).

Akkurt et. al (2009)

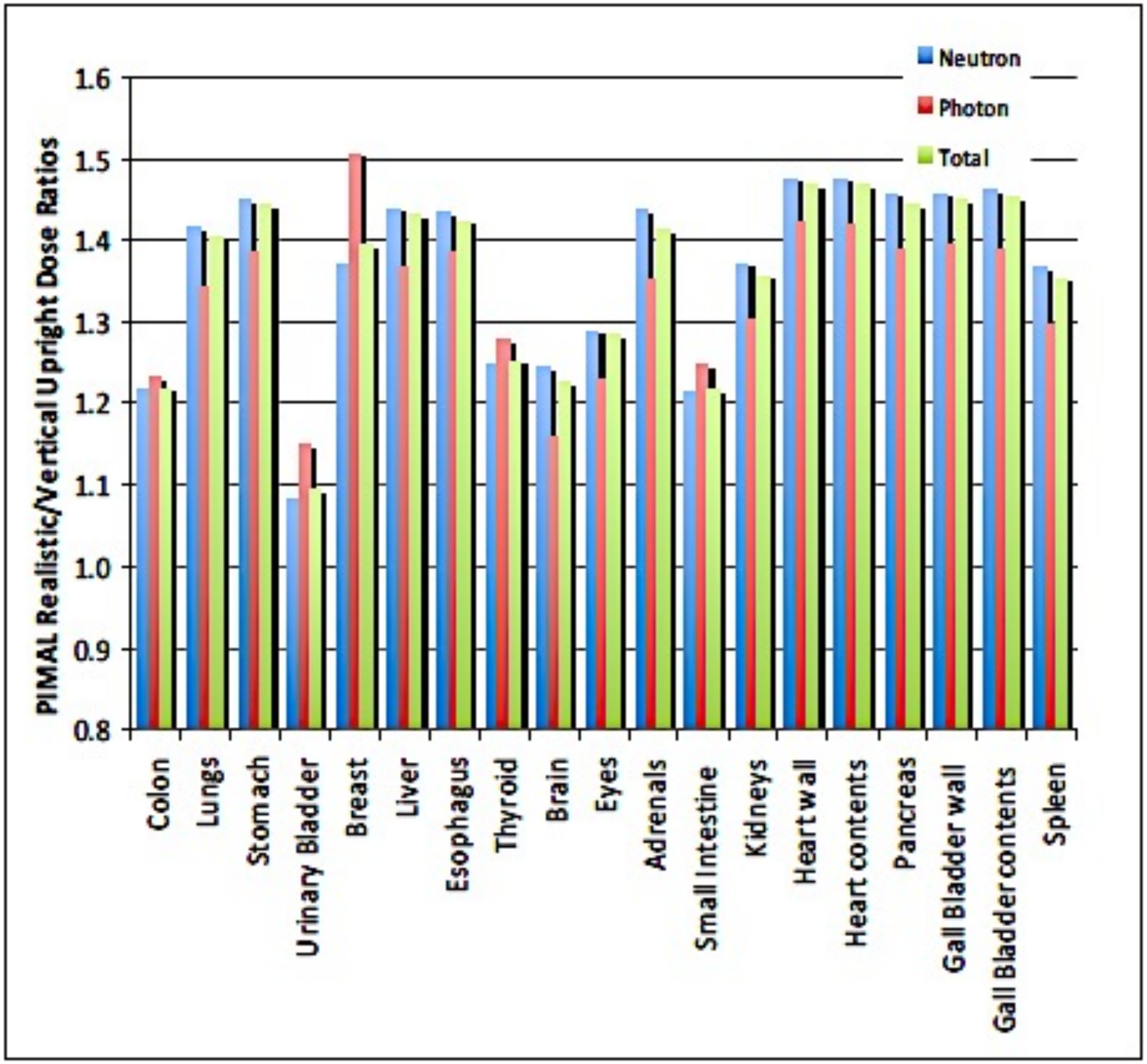


Fig. 3. The ratio of the organ dose values for realistic posture to vertical upright posture for PIMAL

Examples

1. Glovebox Worker
2. **I-131 Patient Release Study**
3. Upright vs. PIMAL Bent for ICRP 116 Geometries
   - Photon
   - Neutron
   - TLD

Estimated External Doses to Members of the Public from Patients with ^{131}I Treatment (Dewji et al., 2015)

- 10 CFR Part 35: Guidance on calculation of dose to a member of public in §35.75 contained in Regulatory Guide 8.39 “Release of Patients Administered Radioactive Materials”
- Criteria: Release patients administered licensed material if TEDE not likely to exceed 5 mSv

S. Dewji, M. Bellamy, N. Hertel, R. Leggett, S. Sherbini, M. Saba, K. Eckerman**.** Assessment of Point Source Method for Estimating Doses to Members of the Public from Exposure to Patients with ^{131}I Thyroid Treatment. Health Physics Journal (DOI 10.1097/HP.0000000000000327).
S. Dewji, M. Bellamy, N. Hertel, R. Leggett, S. Sherbini, M. Saba, K. Eckerman**.** Estimated Doses to Members of the Public from External Exposure to Patients with ^{131}I Treatment. Medical Physics (DOI: 10.1118/1.4915084).

Objective

- Extensive data on measured doses to medical staff and to family members but, for obvious reasons, none on dose to fellow passengers and workers at hotels and nursing homes, which are places that may be frequented by recently released patients.
- Calculate external dose resulting from released patients to members of the public in various exposure scenarios:

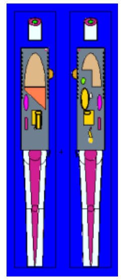
1. Public Transportation
2. Nursing Home
3. Hotel

Patient Cases Considered

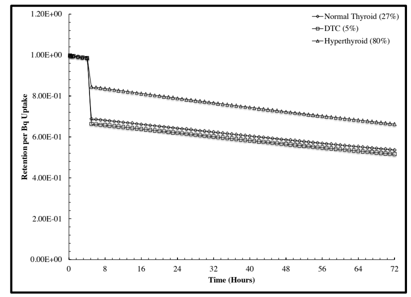
Thyroid Cancer	• DTC - 5% uptake
Normal	• 30% peak content with no decay, ~27% for I-131
Hyperthyroid	• 80% peak content

Methodology

Model the patient and member of the public



Model movement of ^{131}I in the patient's body as a function of time



Calculate the dose rate to the member of the public as a function of time

Integrate dose rates to calculate total dose for the exposure scenarios

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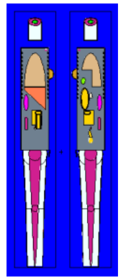
Exposure Cases Considered

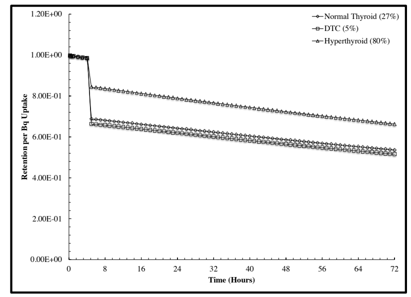
- **I) Public Transportation**
  1. Face-to-Face Standing (10cm Separation)
  2. Patient Seated in Front of Person
  3. Patient Seated Behind Person
  4. Patient Seated Side-by-Side
  5. Person Standing beside Seated Person
  6. Patient Seated beside Standing Person
- **II) Nursing Home**
  1. Caregiver Seated 30cm from Patient Bed
  2. Patient 250cm from Nursing Home Roommate
- **III) Hotel Room**
  1. Back-to-Back Seated in Bed in Adjacent Rooms
  2. Back-to-Back Lying in Bed in Adjacent Rooms

Methodology

Model the patient and member of the public



Model movement of ^{131}I in the patient's body as a function of time

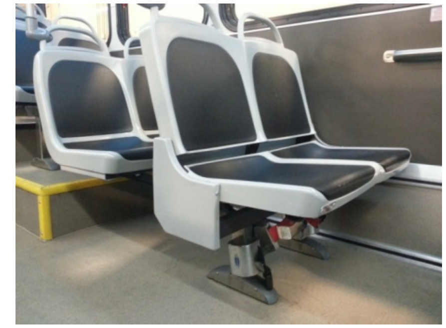


Calculate the dose rate to the member of the public as a function of time

Integrate dose rates to calculate total dose for the exposure scenarios

Case 1: Public Transportation

- **Public Transportation**
  1. Face-to-Face Standing (10cm Separation)
  2. Patient Seated in Front of Person
  3. Patient Seated Behind Person
  4. Patient Seated Side-by-Side
  5. Person Standing beside Seated Person
  6. Patient Seated beside Standing Person



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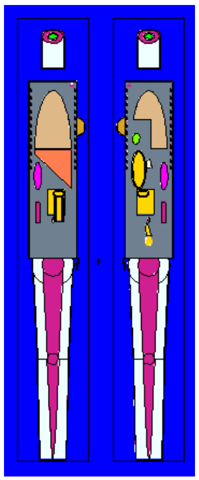
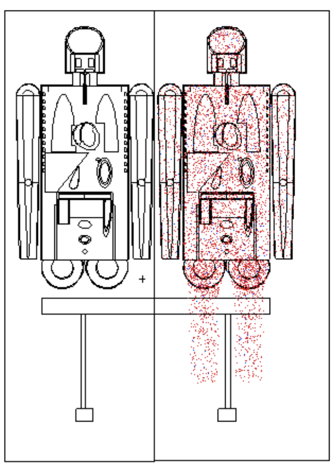
Case 1: Public Transportation

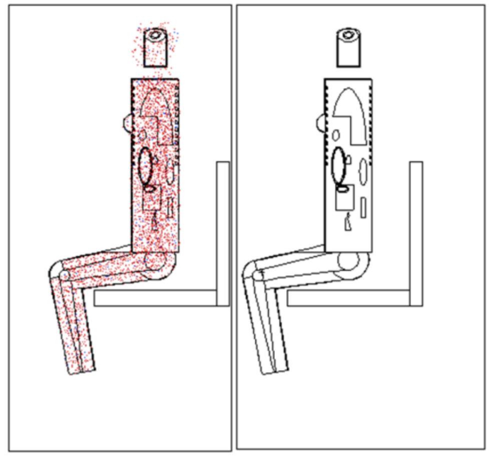
1. Bus: Standing Face-to-Face Chest-to-Chest (10cm Separation)



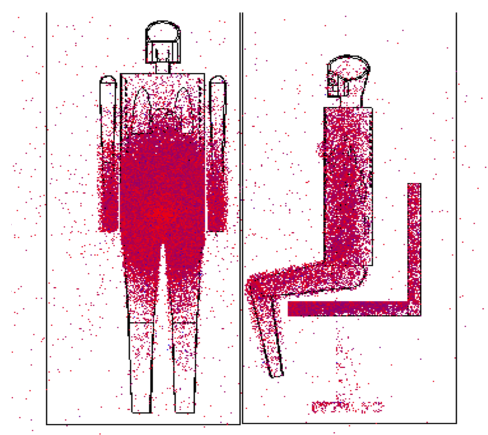
4. Bus: Patient Seated Side-by-Side (Whole Body Source)



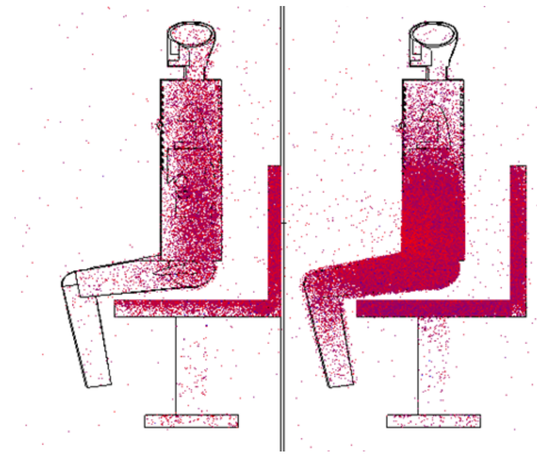
2. Bus: Patient Seated in Front. (Whole Body Source)



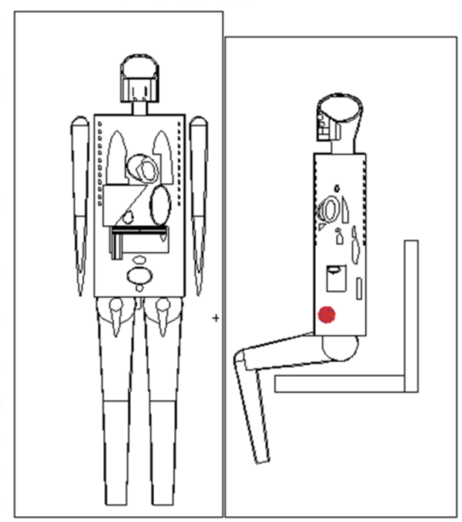
5. Bus: Patient Standing, Public Seated (Bladder Source)



3. Bus: Patient Seated Behind (Bladder Source)

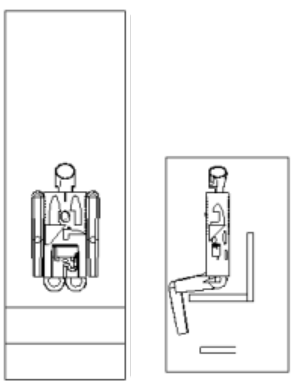


6. Bus: Patient Seated, Public Standing (Bladder Source)



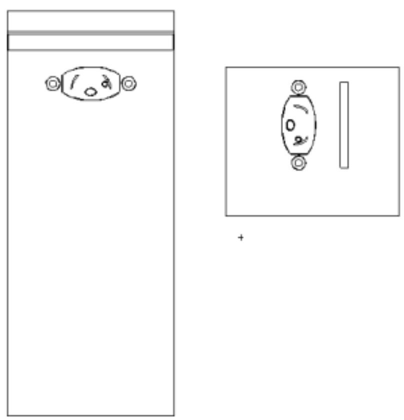
Case 2 - Nursing Home

- **Nursing Home:** Caregiver was seated 30 cm from the edge of the ^{131}I patient's bed (~125 cm from the patient's chest to the caregiver's chest).



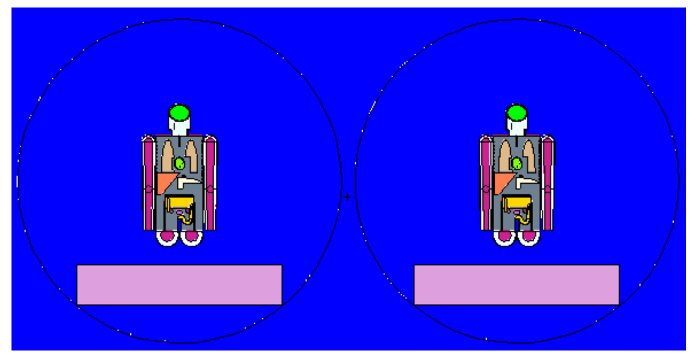
Patient reclining in bed *Caregiver 30cm from bed*

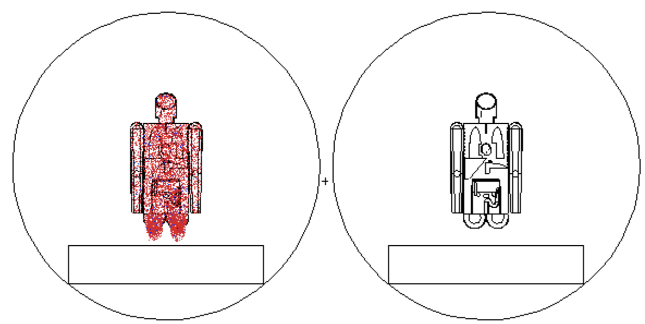
Profile view



Aerial view

- **Nursing Home:** ^{131}I patient and another nursing home resident were seated in adjacent beds 250 cm apart.





Patient reclining in bed *Roommate reclining in bed*

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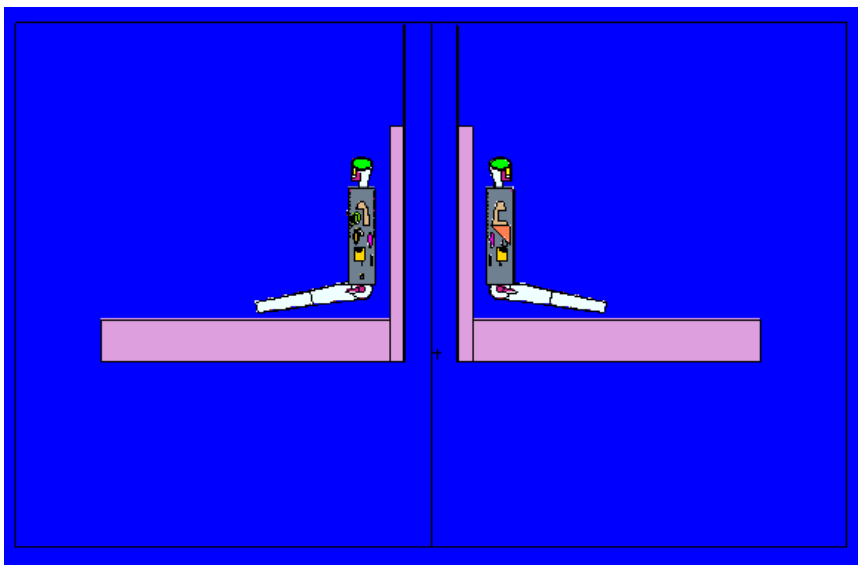
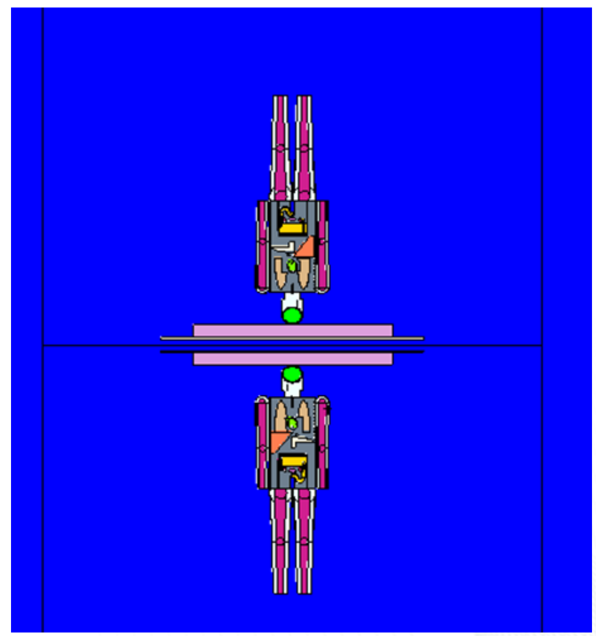
Case 3: Hotel Room

- **Hotel:** ^{131}I patient and another hotel guest in an adjacent room were investigated for **back-to-back seated in bed** position.

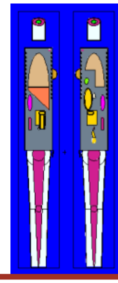


- **Hotel:** ^{131}I patient and another hotel guest in an adjacent room were investigated for **back-to-back lying flat** positions in beds on opposite sides of the common wall.

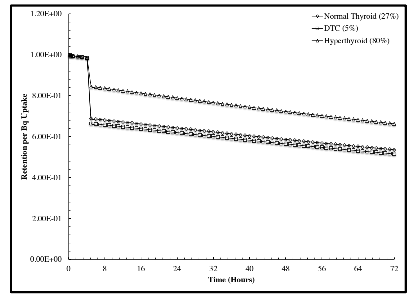


Methodology

Model the patient and member of the public



Model movement of ^{131}I in the patient's body as a function of time

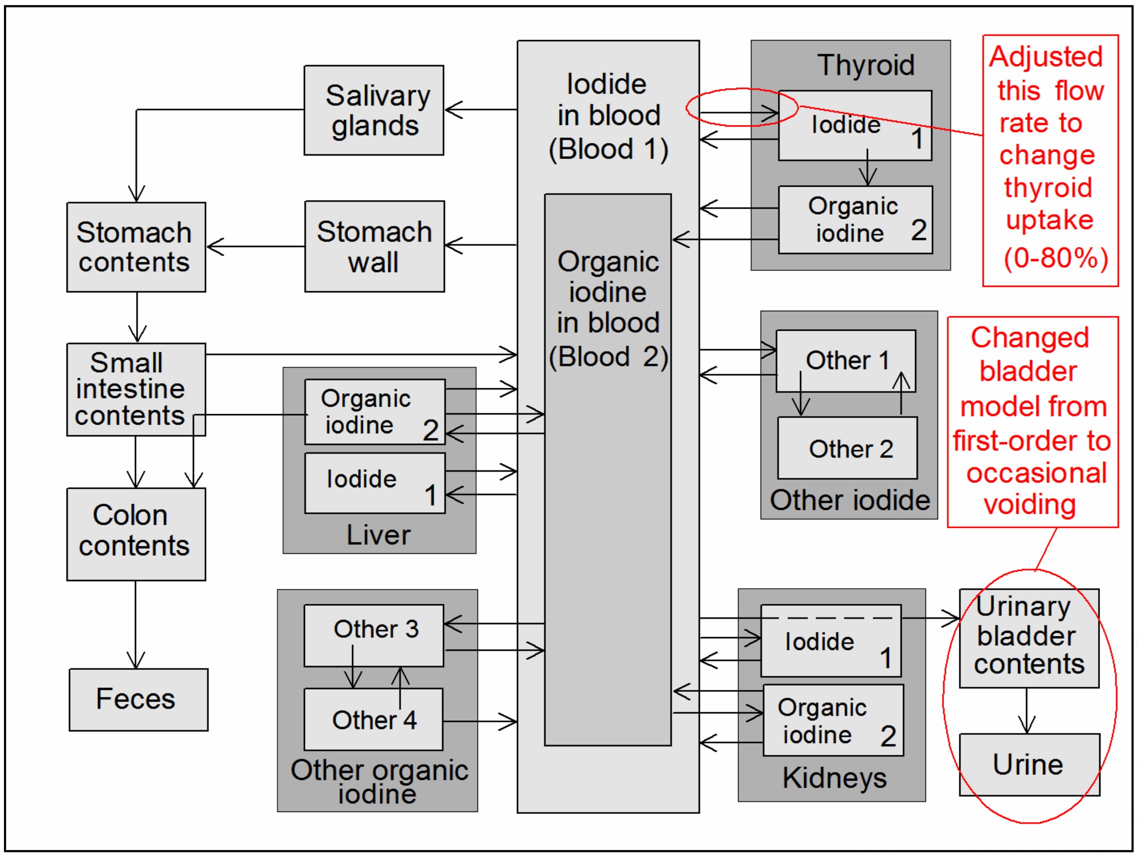


Calculate the dose rate to the member of the public as a function of time

Integrate dose rates to calculate total dose for the exposure scenarios

Biokinetic Modeling

- Biokinetic models predict the movement of ^{131}I in the body as a function of time

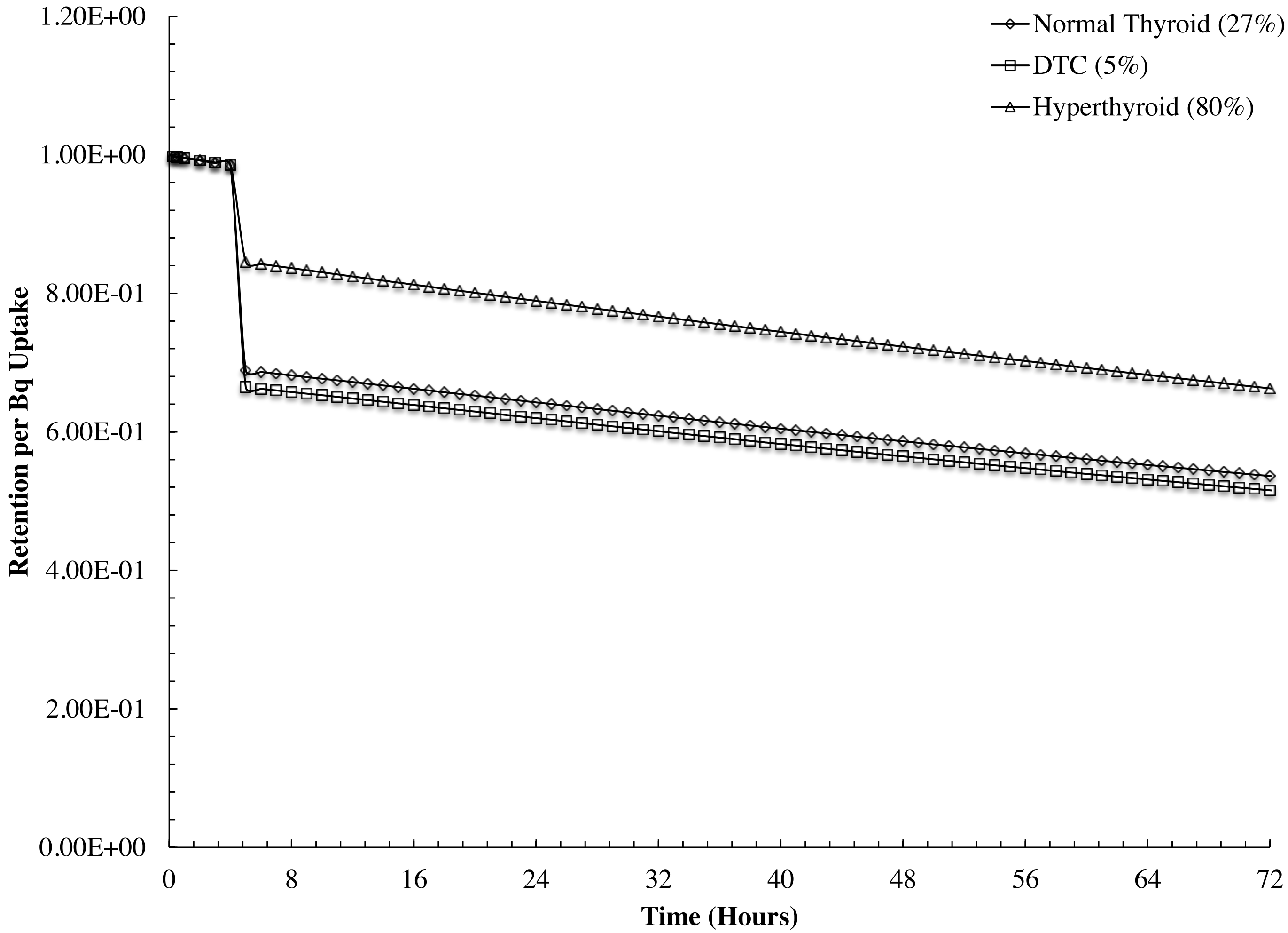


Revised ^{131}I model *(Leggett, Radiation Research 174, 2010)*

Biokinetic Modes: Voiding Public Transit

- Bladder voiding addressed with each thyroid uptake case
- ***Single Voiding:***
  - Assume a single void occurs at a specified time post administration (2, 4, or 8 hours)
  - No further voiding occurs thereafter
  - Voiding is considered to have occurred immediately after the 2-, 4-, or 8-hour time period after administration.
  - Represents upper bound to the bladder content, following a single void
  - Conservative estimate based on patient release guidelines that recommend the patient voids at least once prior to release
- Patient assumed to board bus immediately after void

Biokinetic Model – Single Void



Model predictions of retained fraction of ^{131}I in the body assuming single void at 4 hours after administration.

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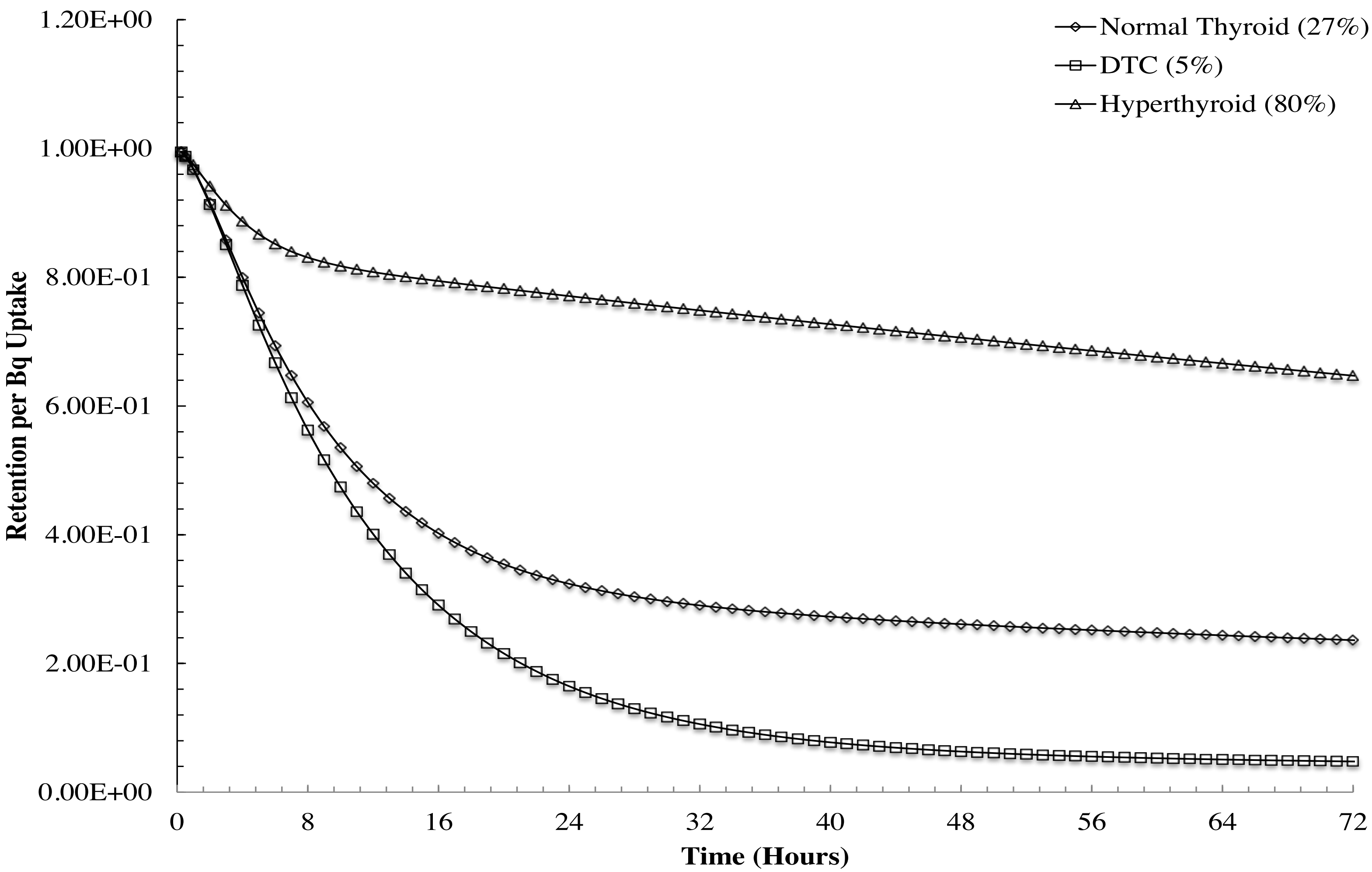
Biokinetic Modes – Voiding Nursing Home

- ***First-Order Continuous Voiding:***
  - Urinary bladder content removal in urine depicted as **continuous voiding at a constant rate**
  - First-order process occurring at rate recommended for adults by ICRP

Biokinetic Model – Continuous Void

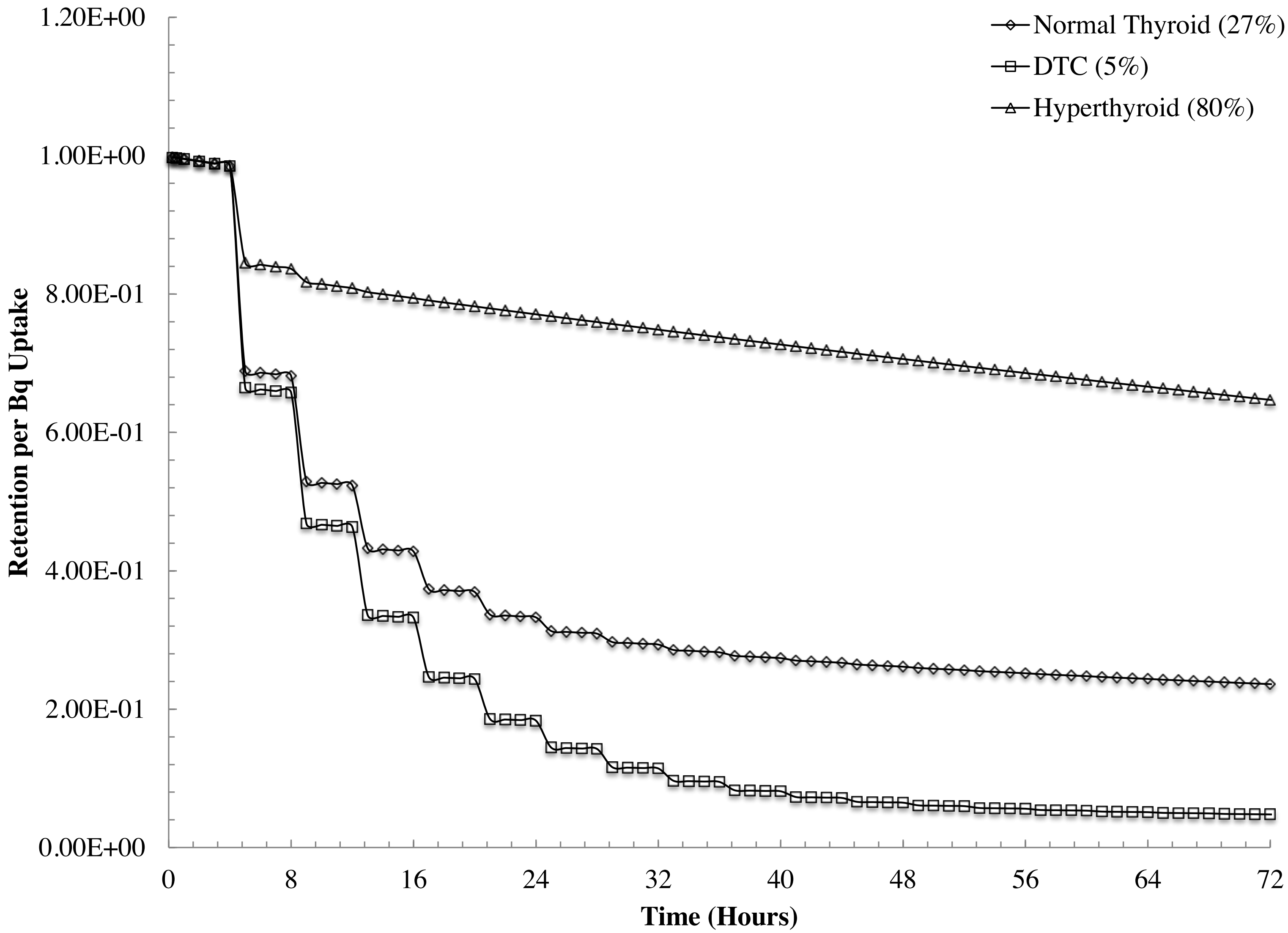


Model predictions of retained fraction of ^{131}I in the body as a function of time assuming a continuous voiding pattern.

Biokinetic Modes – Voiding Hotel

- ***Intermittent (Periodic) Voiding:***
  - Voiding of urinary bladder contents occurs only at specified time intervals, i.e. every 4, 8 or 12 hours following administration of ^{131}I.
  - Instantaneous and complete voiding of the urinary bladder contents was assumed.
  - Voiding is considered to have occurred immediately after every recurrent 4-, 8-, or 12-hour time period after administration.
  - Step-wise function of periodic bladder voiding.

Biokinetic Model – Periodic Void



Model predictions of retained fraction of ^{131}I in the body as a function of time assuming a 4-hour periodic voiding pattern.

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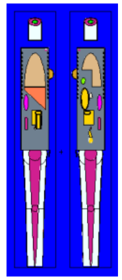
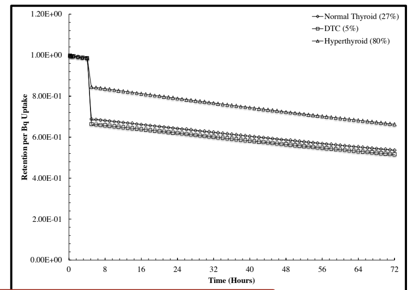
Methodology

Model the patient and member of the public



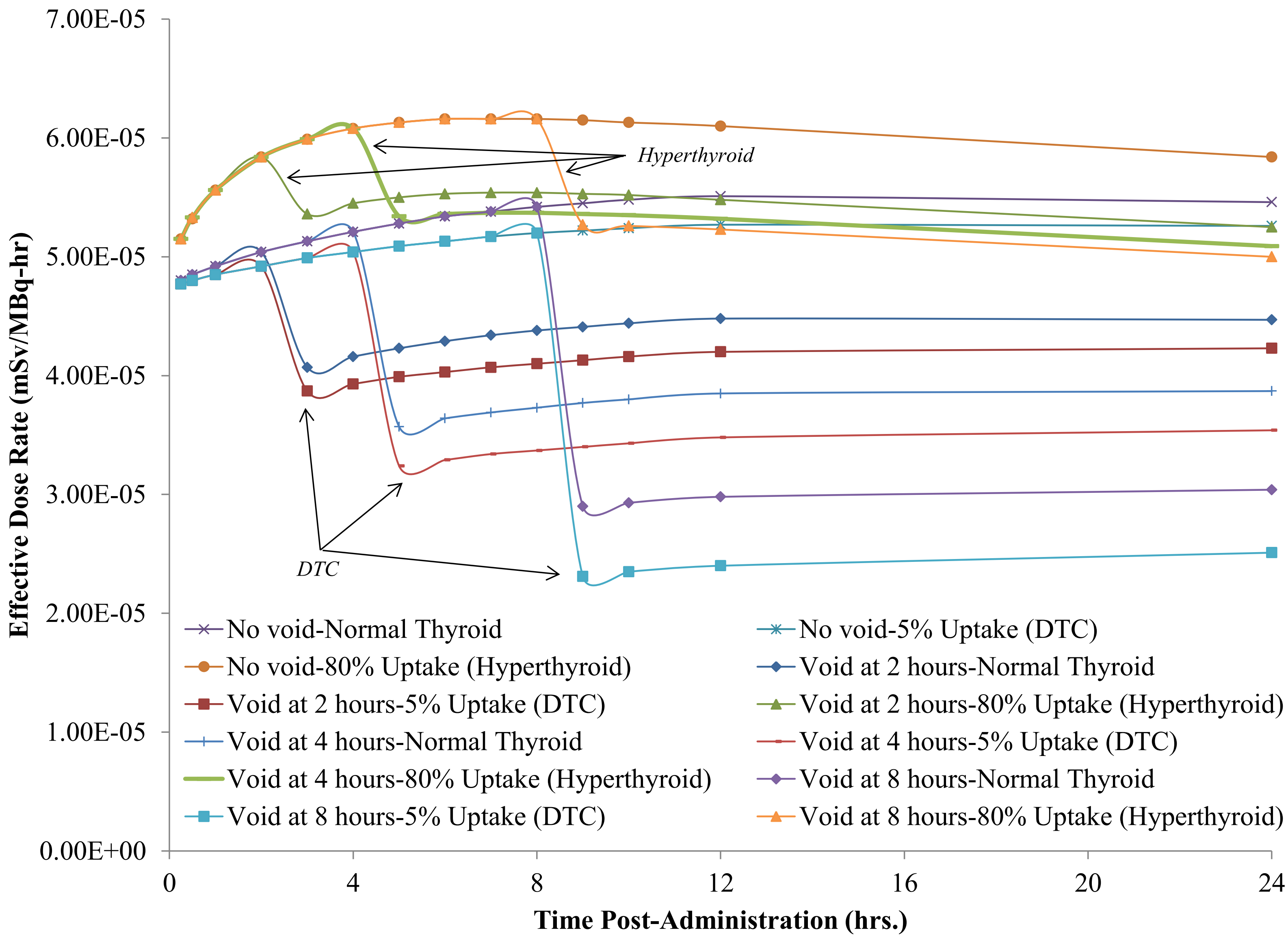
Model movement of ^{131}I in the patient's body as a function of time



Calculate the dose rate to the member of the public as a function of time

Integrate dose rates to calculate total dose for the exposure scenarios

Results: Effective Dose Rate on Public Transportation



Effective Dose Rate (mSv/MBq-hr) on Public Transportation: Facing 10cm Separation.

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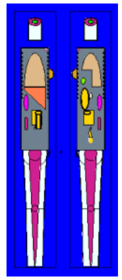
Results: Effective Dose Rate on Public Transportation

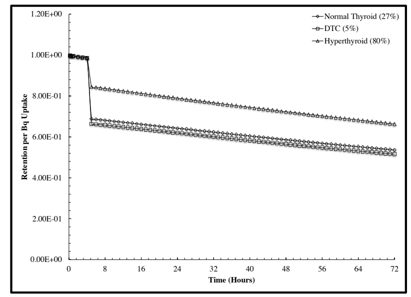
- Overall, ***Standing Face-to-Face 10 cm Separation***, provides the most conservative dose rate of the six cases simulated for public exposure on public transportation.
- From the seated cases alone, ***Patient Seated Behind Member of Public*** provides the most conservative dose rate for public exposure for the seated cases.
- Assumed that occupancy factors are not necessary in public transit since the scenario is a single exposure in a finite single timeframe where the placement of the patient and member of the public are unchanged relative to each other.

Methodology

Model the patient and member of the public



Model movement of ^{131}I in the patient's body as a function of time



Calculate the dose rate to the member of the public as a function of time

Integrate dose rates to calculate total dose for the exposure scenarios

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(Dewji et al. 2015)

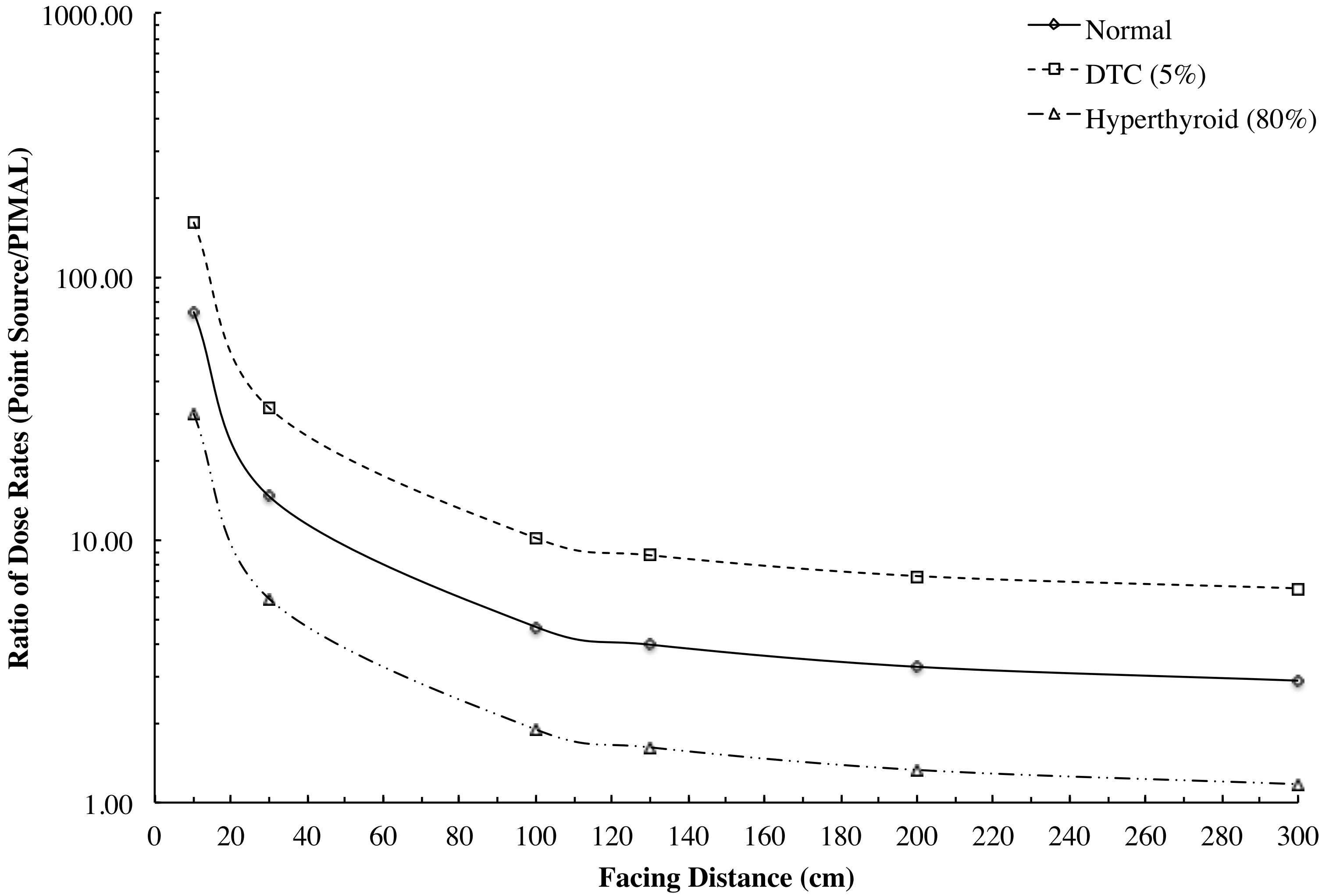

Figure 10. Ratio of Effective dose rates calculated using point source method to biokinetic PIMAL phantom results at various separation distances for normal, DTC, and hyperthyroid uptake modes (24 h following ^{131}I administration).

Conclusions

- Using PIMAL phantoms in permutations of seated, standing, and lying down positions
  - permitted realistic geometry models to determine more plausible dose rate coefficients for exposure to members of the public.

References

- Dewji, S., et al. "Estimated dose rates to members of the public from external exposure to patients with 131I thyroid treatment." Medical physics 42.4 (2015): 1851-1857.
- Dewji, Shaheen Azim, et al. "Assessment of the point-source method for estimating dose rates to members of the public from exposure to patients with 131I thyroid treatment." *Health physics* 109.3 (2015): 233-241.
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Examples

1. Glovebox Worker
2. I-131 Patient Release Study
3. **Upright vs. PIMAL Bent for ICRP 116 Geometries**
   - **Photon**
   - Neutron
   - TLD

Introduction

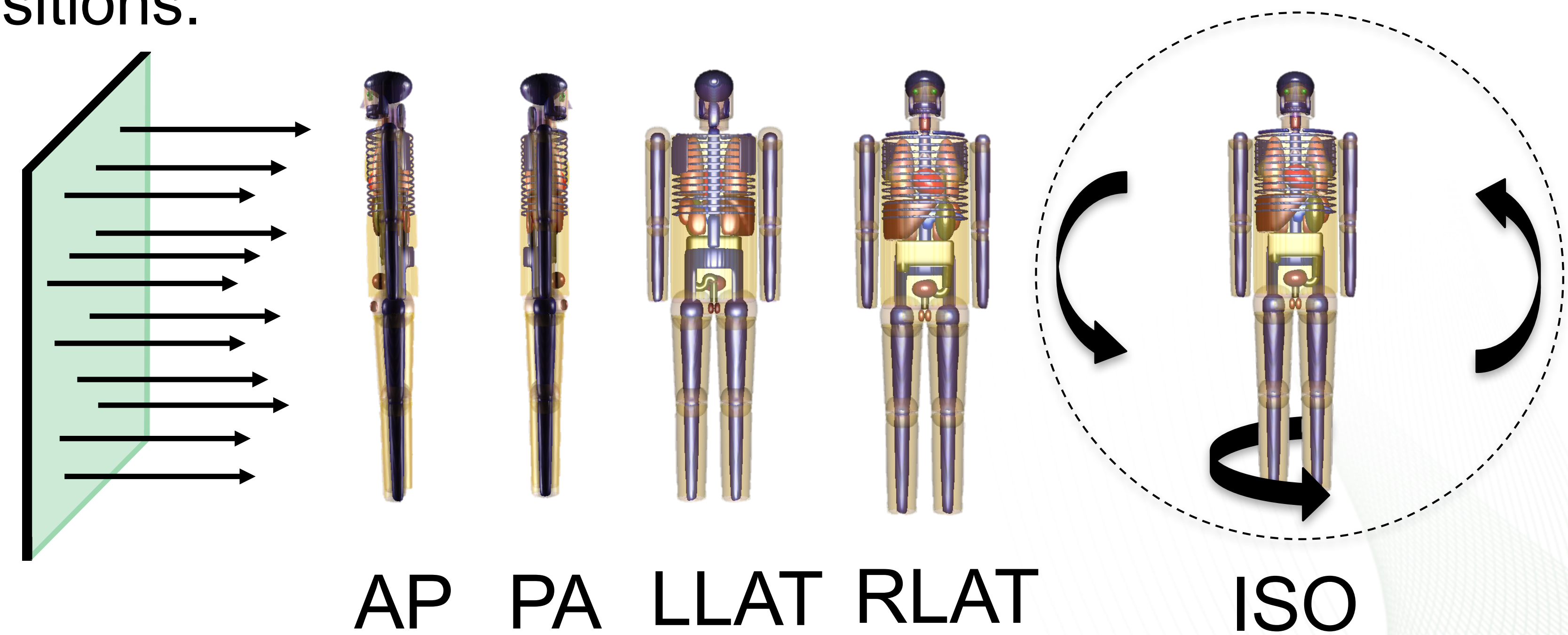
- Radiation dose calculations require computational modeling because complex geometries with the human body are involved, conducted using phantoms.
- Both old and recent human body models have almost always been rigidly created in the vertical, upright position.
- The **PIMAL** (**P**hantom w**I**th **M**oving **A**rms and **L**egs) software creates **MCNP** (**M**onte **C**arlo **N**-**P**article transport code) input files of computational stylized phantoms with repositioned arms and legs.

Upright vs. PIMAL Bent Phantom in ICRP 116 Geometries for Photons (Dewji et al. 2017)

- MCNP simulations were run for:
  - male and female phantom;
  - upright, half bend (45^{o}), and full bend (90^{o}) positions.
- ICRP 116 source irradiation geometries:
  - Irradiation planes (AP, PA, LLAT, RLAT): 200 cm x 200 cm @ 1 m from phantom centroid;
  - Isotropic sphere (ISO): r = 400 cm.
- Over range of five monoenergetic photon energies:
  - 0.05, 0.1, 0.5, 1, and 5 MeV.
- ICRP 89 tissue compositions and densities.
- Organ absorbed doses estimated using the kerma (fluence-to-dose) approximation (MCNP F6 tally).
- Dose rates for active marrow and the bone surface were estimated using skeletal response functions published by Cristy and Eckerman (1987).

Methodology – Monte Carlo Simulation

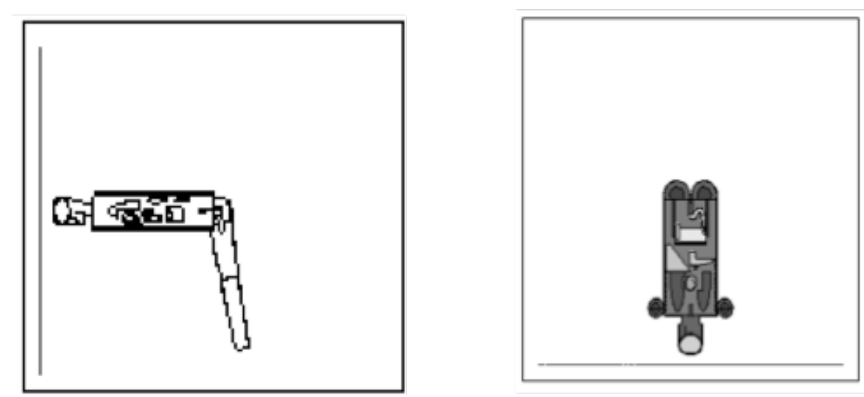
- PIMAL used to generate the MCNP input files for the repositioned phantom
  - International Commission on Radiation Protection Publication 116 irradiation geometries
- Determine the impact on the absorbed organ dose and effective dose between the upright and bent phantom positions.



Methodology – Monte Carlo Simulation

- MCNP simulations were run for the male and female phantoms at the upright, half bend (45^{o}), and full bend (90^{o}) positions

The upright, half bend, and full bend side views taken from the PIMAL 4.1.0 GUI for the stylized phantom.

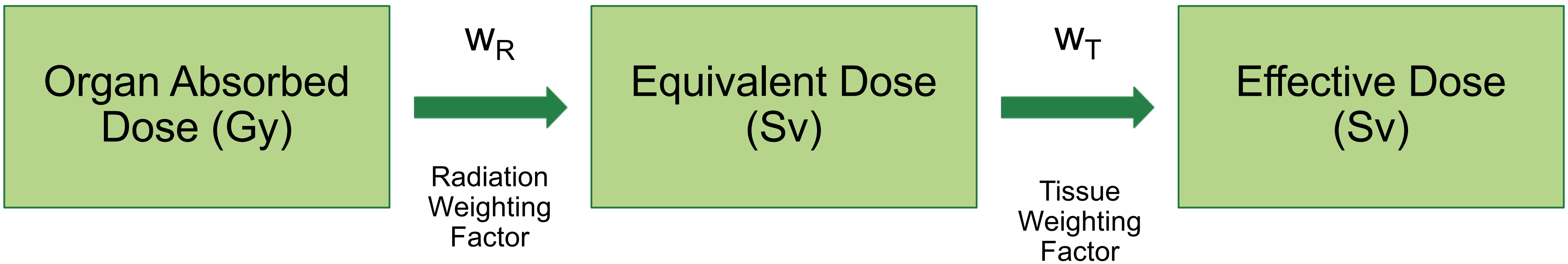


The adult male PIMAL stylized phantom bent in fully bent articulated (90 degree) position.

Left: PIMAL shown in VisEd with AP source (side view);

Right: PIMAL shown in VisEd with AP source (aerial view).

Organ Dose Computation
ICRP Publication 103 Methodology



$$H_T = \sum_R w_R \cdot D_{T,R}$$

$$E = \sum_T w_T \cdot H_T$$

(w_R) = Radiation weighting factors
($D_{T,R}$)= Organ absorbed dose (J/kg)
(H_T)= Equivalent dose (Sv)
(w_T)= Radiation weighting factors

Results

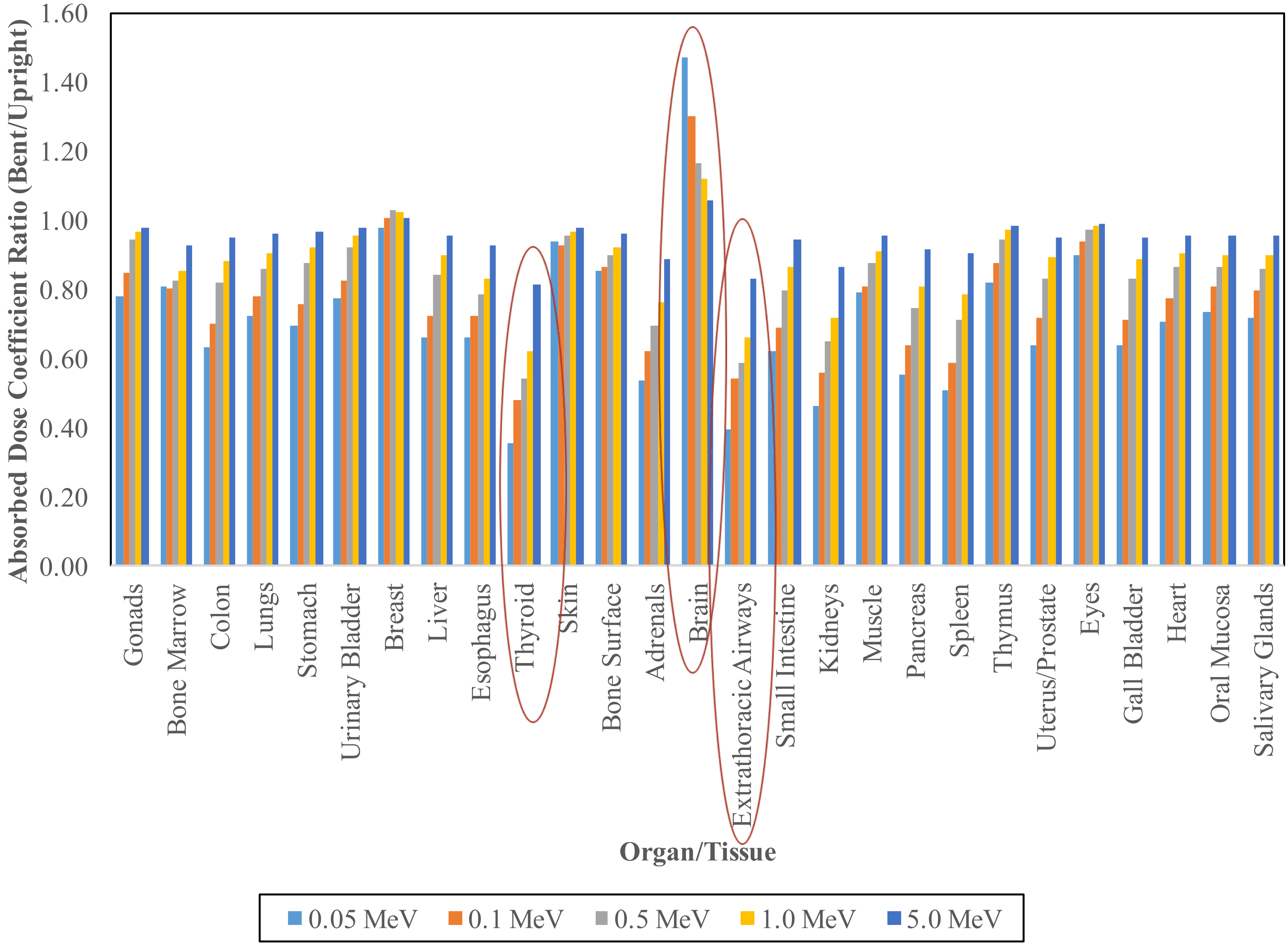
- Organ doses that showed strong positional variation compared to the upright phantom are summarized.
- All simulations were run for 10^9 particles, with statistical errors converging within < 1% for small or deep organs/tissues (e.g. adrenals), for all organs, energies, and irradiation geometries.
- Sex-averaged organ dose coefficients
- Ratio organ absorbed dose (bent/upright)
  - **(Ratio < 1)** Upright phantom overestimates the dose
  - **(Ratio > 1)** Upright phantom underestimates the dose

Results - AP Source Geometry

- AP source geometry showed significant differences between the bent and upright phantom geometries, which became much more pronounced with increasing bending angle.
- Brain received more dose when bent than upright
  - 47% more in 45° bent position
  - 72% more in 90° bent position
- Greatest degree of overestimation by upright organ
  - 50 keV for thyroid (65% for 45°) and (90% for 90°)
  - 50 keV ET airways (60% for 45°) and (79% for 90°)
- All other organs and tissues were overestimated in absorbed organ dose by the upright phantom in the AP irradiation geometry.

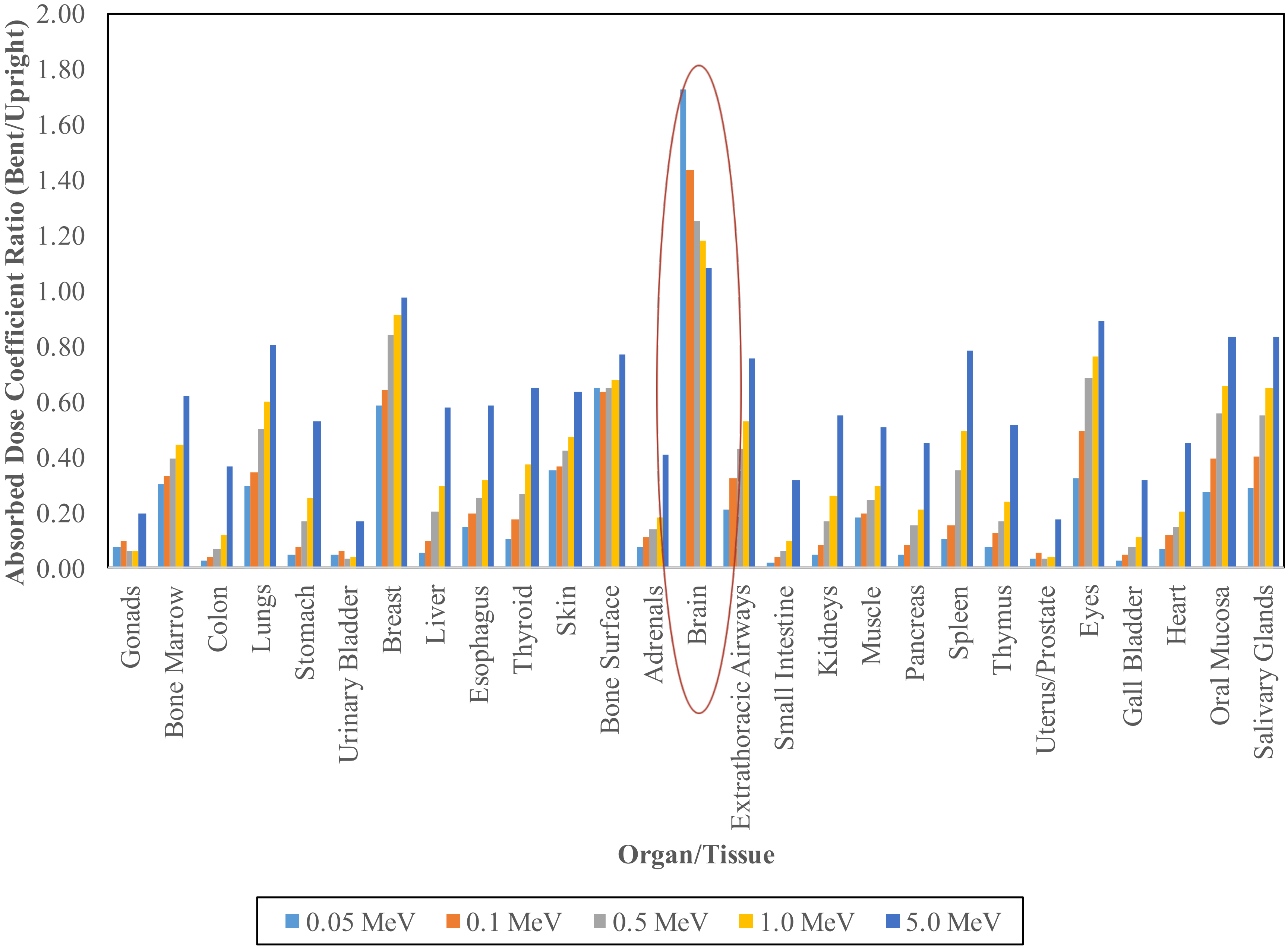
AP Source Geometry

Sex-Averaged Organ Dose Ratio in 45-degree Bent/Upright



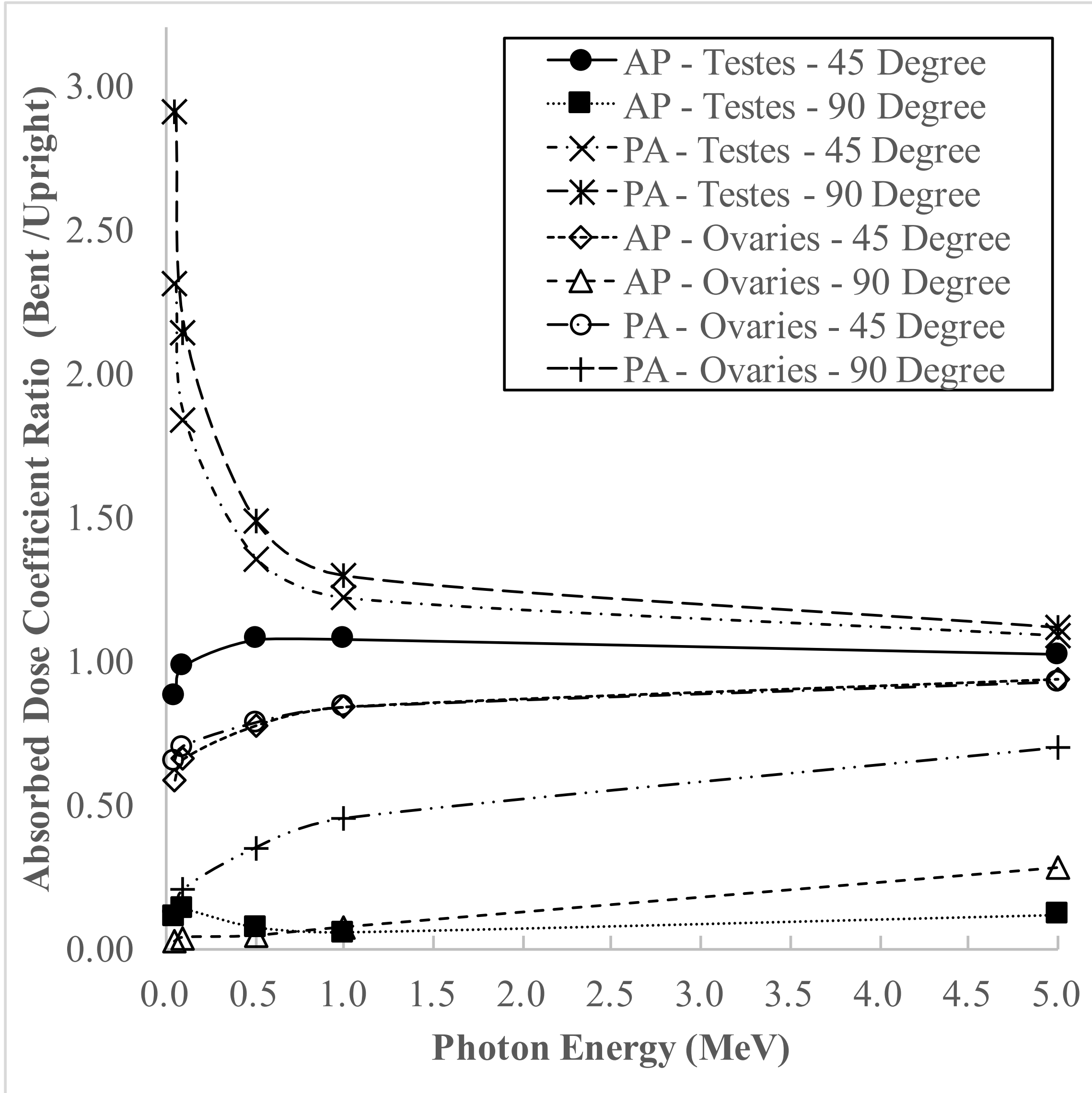
AP Source Geometry

Sex-Averaged Organ Dose Ratio in 90-degree Bent/Upright



Results – PA Source Geometry

- Urinary bladder dose
  - slightly underestimated by the upright phantom by 3% to 15% as a function of decreasing energy from 5 MeV to 50 keV in the 45° bent position
  - overestimated the dose by as much as 21% in the 90° bent position
- Testes underestimated by the upright phantom:
  - factor of 2.31 bent at 45 degrees at 0.05 MeV
  - factor of 2.91 bent at 90 degrees at 0.05 MeV
- Prostate underestimated by the upright phantom:
  - factor of 2.11 bent at 45 degrees at low energies
  - factor of 1.62 bent at 90 degrees at low energies
- All other organs were otherwise overestimated by doses computed for the upright phantom.

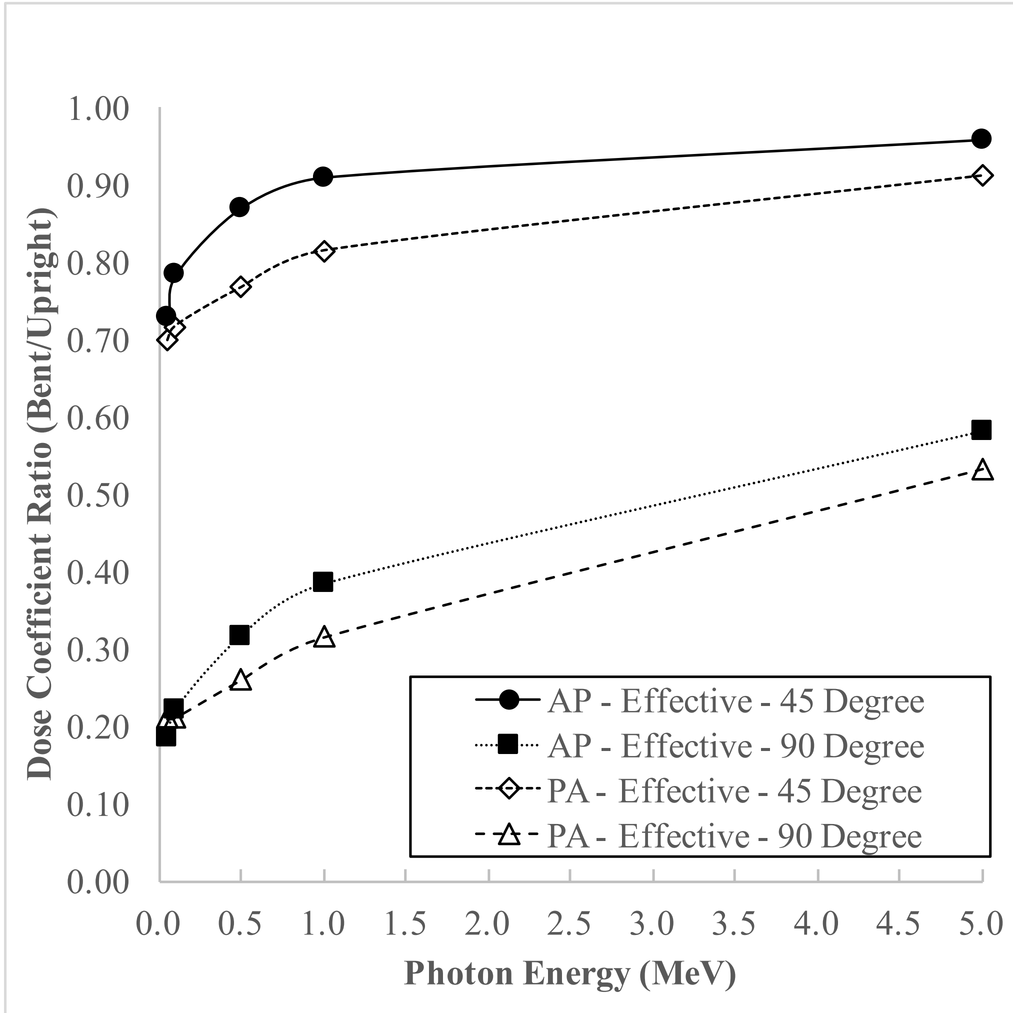


Absorbed dose coefficient ratio for gonads (male: testes; female: ovaries) in AP and PA irradiation geometries with PIMAL bent at 45- and 90-degree positions.

Results – Effective Dose (AP/PA)

- Most notable difference between upright and bent postures found in the AP and PA source geometries
  - Full bend received close to half the effective dose of the upright and half-bent positions
- AP effective dose at 45-degree bend comparable to upright > 1 MeV
  - Dose overestimated by the upright phantom below 1 MeV by as much as 26%
- AP effective dose at 90-degree bend
  - Upright phantom overestimates effective dose by 79% down to 41% as energies increase from 50 keV to 5 MeV
- Effective dose ratio for PA irradiation geometry is only slightly more overestimated by the upright phantom compared to the AP geometry

Effective Dose Ratio (AP and PA)



Sex-averaged effective dose coefficient ratio in AP and PA irradiation geometries with PIMAL bent at 45- and 90-degree positions.

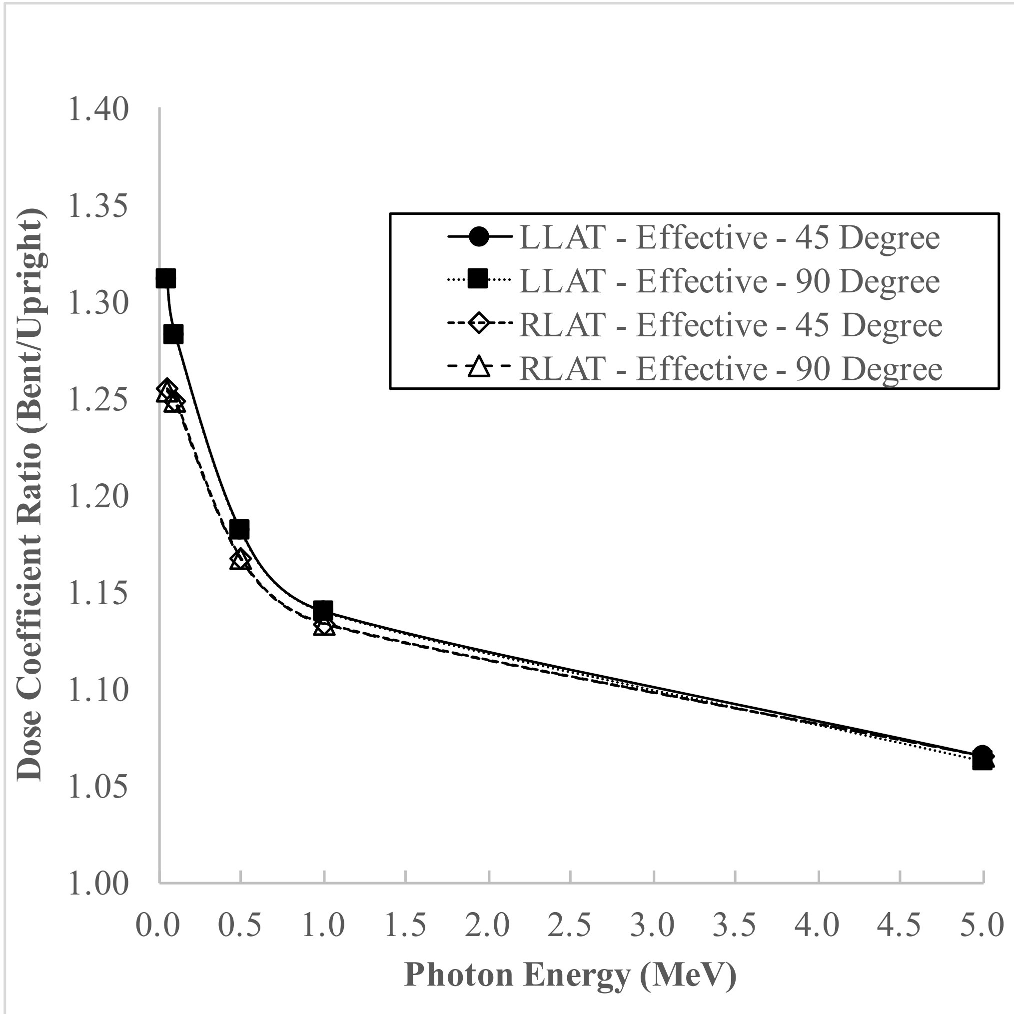
Results – LLAT and RLAT Source Geometry

- LLAT and RLAT bent position have arms angled out
  - organs in torso received more dose than they would have otherwise in the upright position
  - arms serve as shields pinned to the sides of the body for upright
- Not much positional variation from 45° to 90° bend (organs see the same solid angle from source)
- In both the 45° and 90° bent scenarios:
  - breast and thymus receive a lower dose when bent
  - all other organs receive the same or more dose than the upright phantom

Results – Effective Dose (LLAT/RLAT/ISO)

- Effective dose was nearly identical across the postures for LLAT and RLAT irradiation geometries
- LLAT and RLAT 45-degree bent position comparable to 90-degree bent position
  - Unlike AP and PA irradiation geometries, upright phantom underestimates dose to PIMAL by as much as 29% at 50 keV to 6% at 5 MeV for both the 45-degree and 90-degree bending angles
- Ratio for ISO was ~ 1.0 for all positions due to uniform irradiation source, as expected

Effective Dose Ratio (LLAT and RLAT)



Sex-averaged effective dose coefficient ratio in LLAT and RLAT irradiation geometries with PIMAL bent at 45- and 90-degree positions.

Conclusions

- Upright phantom largely underestimates:
  - absorbed dose in the brain for the AP source geometry
  - absorbed dose in testes for PA source geometry
  - both the half and full bend phantom positions
- Upright phantom underestimates:
  - Thoracic organs' absorbed dose due to angled arm position in LLAT/RLAT
- Effective dose to the bent position indicate
  - AP and PA 45° - that the dose is less than or equal to the effective dose of the upright phantom, much more pronounced at 90° (upright overestimates - conservative)
  - LLAT and RLAT 45° and 90° - dose is higher than upright (upright underestimates)

References

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- Dewji, S., et al. "Estimated dose rates to members of the public from external exposure to patients with ^{131}I thyroid treatment." Medical physics 42.4 (2015): 1851-1857.
- Dewji, S., Reed, K.L. & Hiller, M. Radiat Environ Biophys (2017). doi:10.1007/s00411-017-0698-1.
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- ICRP, 2010. Conversion Coefficients for Radiological Protection Quantities for External Radiation Exposures. ICRP Publication 116, Ann. ICRP 40(2-5).
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Radiat Environ Biophys
DOI 10.1007/s00411-017-0698-1

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ORIGINAL ARTICLE

Comparison of photon organ and effective dose coefficients for PIMAL stylized phantom in bent positions in standard irradiation geometries

Shaheen Dewji[1] · K. Lisa Reed[2] · Mauritius Hiller[1]

Received: 17 December 2016 / Accepted: 20 May 2017

Abstract Computational phantoms with articulated arms and legs have been constructed to enable the estimation of radiation dose in different postures. Through a graphical user interface, the Phantom wIth Moving Arms and Legs (PIMAL) version 4.1.0 software can be employed to articulate the posture of a phantom and generate a corresponding input deck for the Monte Carlo N-Particle (MCNP) radiation transport code. In this work, photon fluence-to-dose coefficients were computed using PIMAL to compare organ and effective doses for a stylized phantom in the standard upright position with those for phantoms in realistic work postures. The articulated phantoms represent working positions including fully and half bent torsos with extended arms for both the male and female reference adults. Dose coefficients are compared for both the upright and bent positions across monoenergetic photon energies: 0.05, 0.1, 0.5, 1.0, and 5.0 MeV. Additionally, the organ doses are compared across the International Commission on Radiological Protection's standard external radiation exposure geometries: antero-posterior, postero-anterior, left and right lateral, and isotropic (AP, PA, LLAT, RLAT, and ISO). For the AP and PA irradiation geometries, differences in organ doses compared to the upright phantom become more profound with increasing bending angles and have doses largely overestimated for all organs except the brain in AP and bladder in PA. In LLAT and RLAT irradiation geometries, energy deposition for organs is more likely to be underestimated compared to the upright phantom, with no overall change despite increased bending angle. The ISO source geometry did not cause a significant difference in absorbed organ dose between the different phantoms, regardless of position. Organ and effective fluence-to-dose coefficients are tabulated. In the AP geometry, the effective dose at the 45° bent position is overestimated compared to the upright phantom below 1 MeV by as much as 27% and 82% in the 90° position. The effective dose in the 45° bent position was comparable

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Examples

1. Glovebox Worker
2. I-131 Patient Release Study
3. **Upright vs. PIMAL Bent for ICRP 116 Geometries**
   - Photon
   - **Neutron**
   - TLD

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Upright vs. PIMAL Bent Phantom in ICRP 116 Geometries for Neutrons (Bales et al. 2017)

- Male and Female Stylized Phantoms
  - ICRP 89 tissue compositions and densities.
- Organ dose rates computed using MCNP +F6 Collision Heating tally (MeV/g)
- Dose rates for active marrow and the bone surface were estimated using skeletal response functions from ICRP Publication 116 and MCNP F4 tally (particles/cm^2)
- Source Specifications
  - **Neutron energies:** 0.01-20.0 MeV
  - **Plane:** AP, PA, LLAT, RLAT - 200 X 200 cm
  - **Sphere:** ISO – r=400cm
  - **Particles:** n p e | ! h / * z k ? d t s a #

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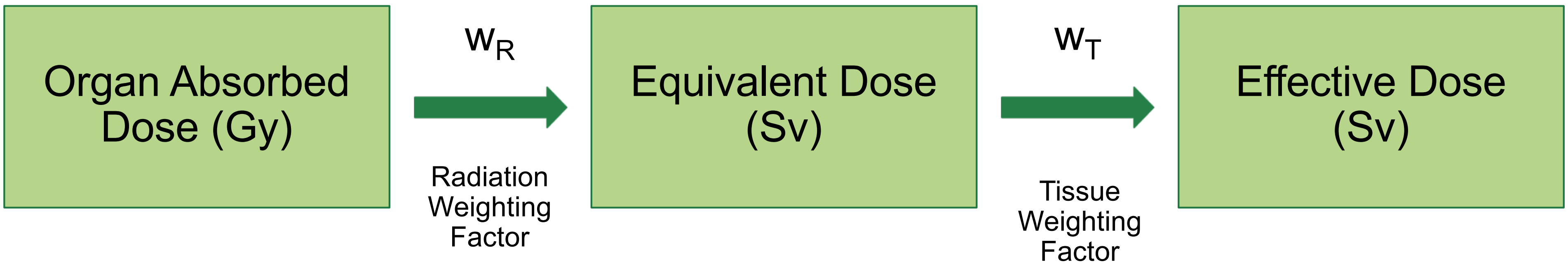
Organ Dose Computation
ICRP Publication 103 Methodology



$$H_T = \sum_R w_R \cdot D_{T,R}$$

$$E = \sum_T w_T \cdot H_T$$

(w_R) = Radiation weighting factors
($D_{T,R}$)= Organ absorbed dose (J/kg)
(H_T)= Equivalent dose (Sv)
(w_T)= Radiation weighting factors

ENDF Libraries

- ICRP 116 Skeletal Response Functions

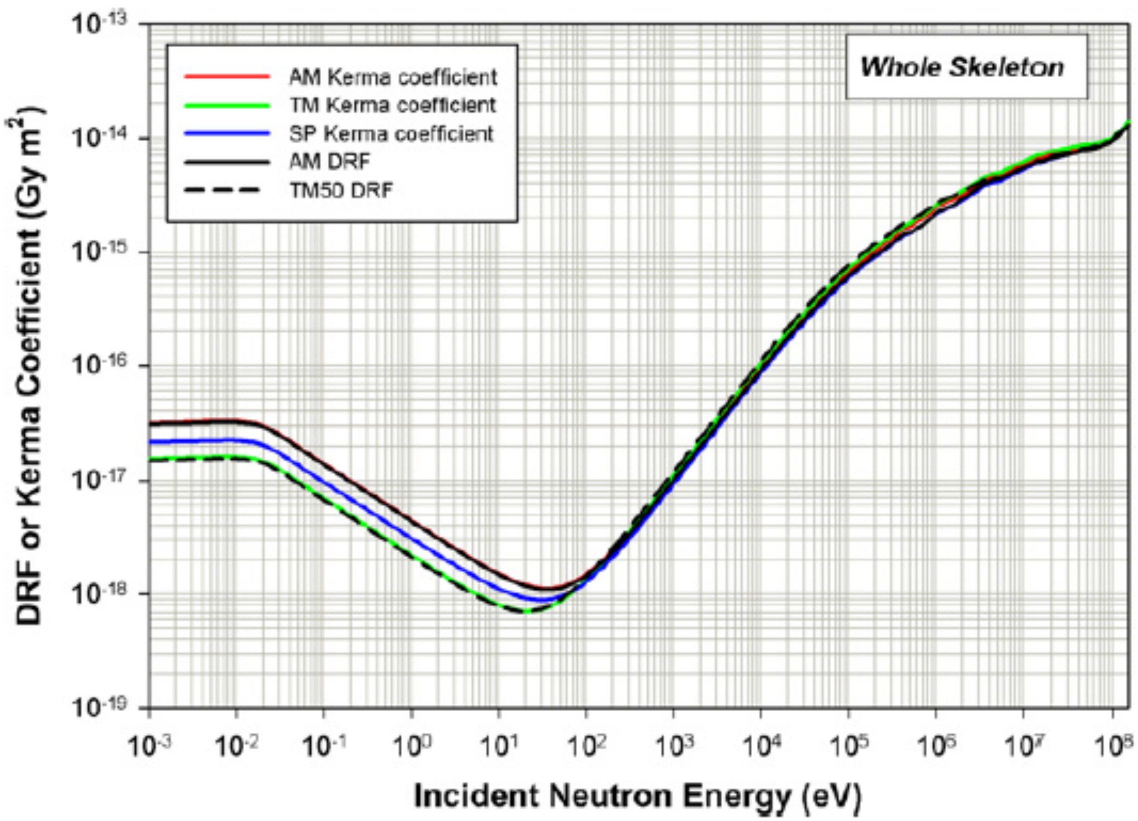


Image courtesy of ICRP Publication 116

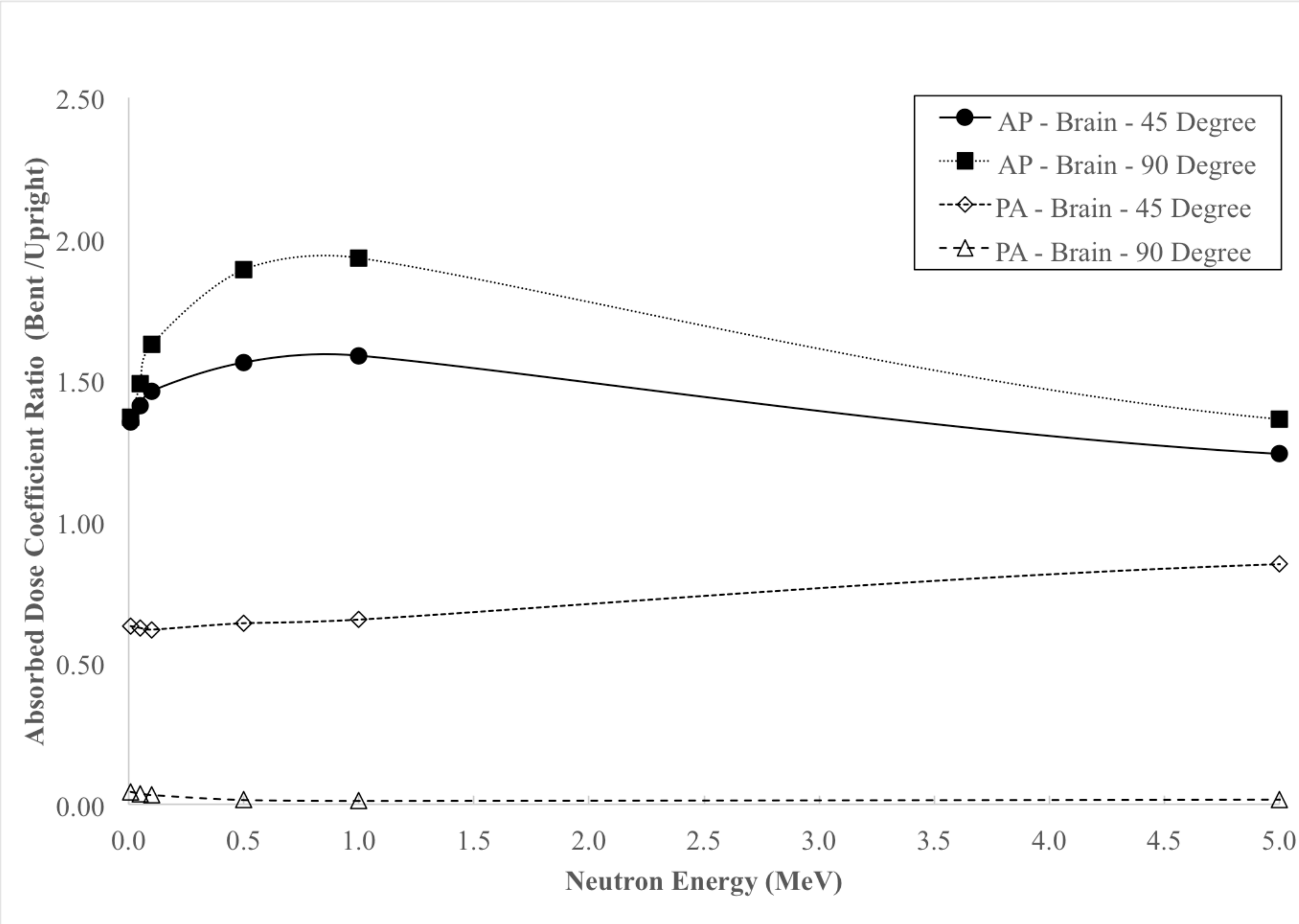
Results

- Organ doses that showed strong positional variation compared to the upright phantom are summarized.
- All simulations were run for 10^9 particles, with statistical errors converging within < 1% for small or deep organs/tissues (e.g. adrenals), for all organs, energies, and irradiation geometries.
- **(Ratio < 1)** Upright phantom overestimates the dose
- **(Ratio > 1)** Upright phantom underestimates the dose

Results - AP Source Geometry

- AP source geometry showed significant differences between the bent and upright phantom geometries, which became much more pronounced with increasing bending angle.
- Brain received more dose when bent than upright
  - As much as 59% more in 45-degree bent position @ 1 MeV
  - As much as 93% more in 90-degree bent position @ 1 MeV
- Greatest degree of overestimation by upright organ
  - Thyroid: 76% for 45-degree @ 1 MeV
  - Thyroid: 94% for 90-degree @ 1 MeV
- All other organs and tissues were overestimated in absorbed organ dose by the upright phantom in the AP irradiation geometry.

AP Source Geometry
Organ Dose Ratio for Male Brain



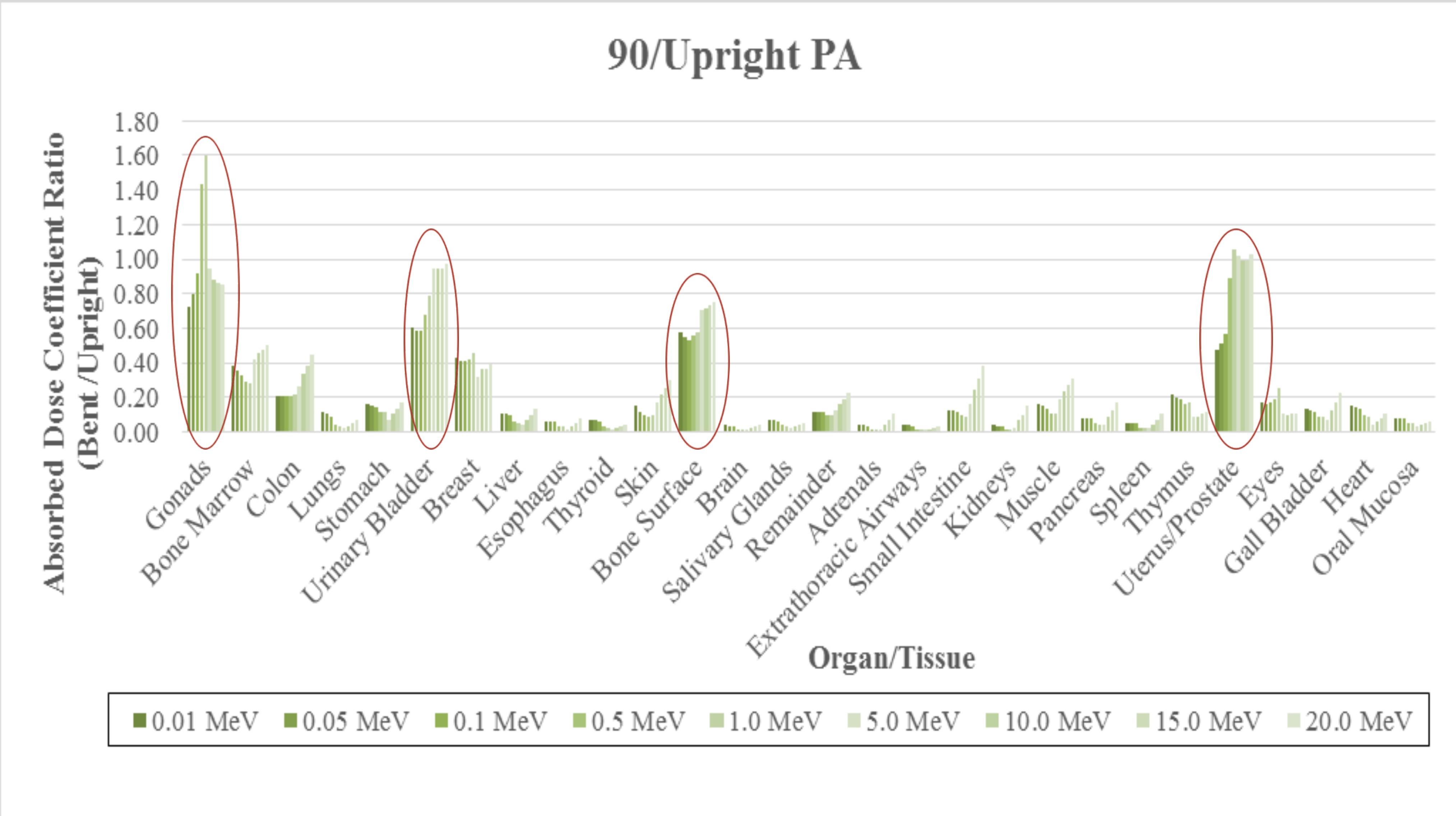
Results – PA Source Geometry

- Urinary bladder, testes and prostate become more vulnerable in the bent positions.
- Absorbed doses of all other organs and tissues were otherwise overestimated by the doses computed for the upright phantom.

Results – PA Source Geometry

- Urinary bladder dose
  - slightly overestimated by the upright phantom by 8% at 50-100 keV range an underestimated by 12% at 1 MeV in the 45-degree bent position
  - overestimated the dose by as much as 46% in the 90 degree bent position (100 keV)
- Testes underestimated by the upright phantom:
  - factor of 2.92 bent at 45 degrees at 1 MeV
  - factor of 4.01 bent at 90 degrees at 1 MeV
- Prostate underestimated by the upright phantom:
  - factor of 3.07 bent at 45 degrees at 1 MeV
  - factor of 1.99 bent at 90 degrees at 1 MeV

PA Source Geometry
Organ Dose Ratio in 90-degree Bent/Upright



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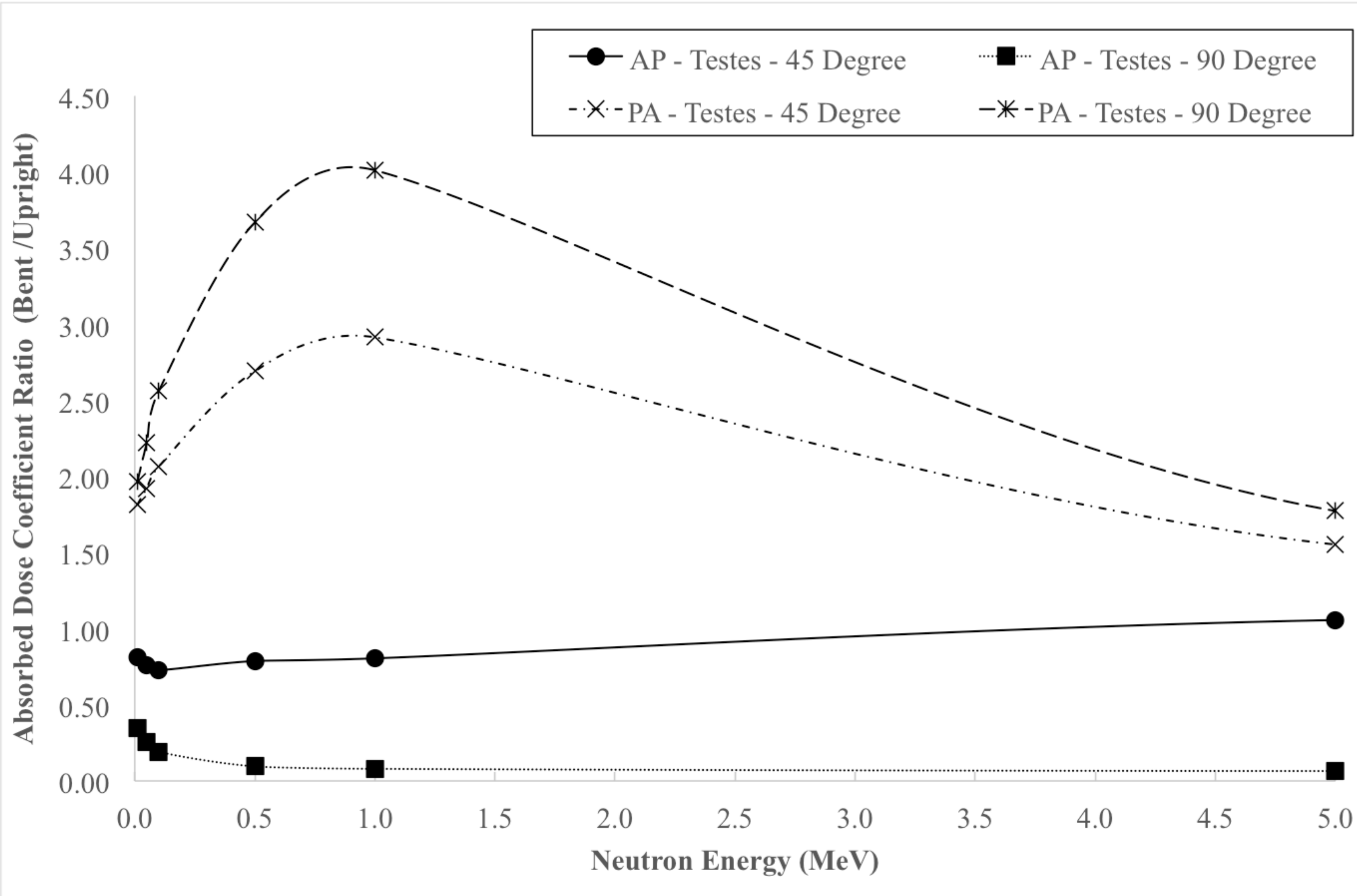
PA Source Geometry
Organ Dose Ratio for Male Testes



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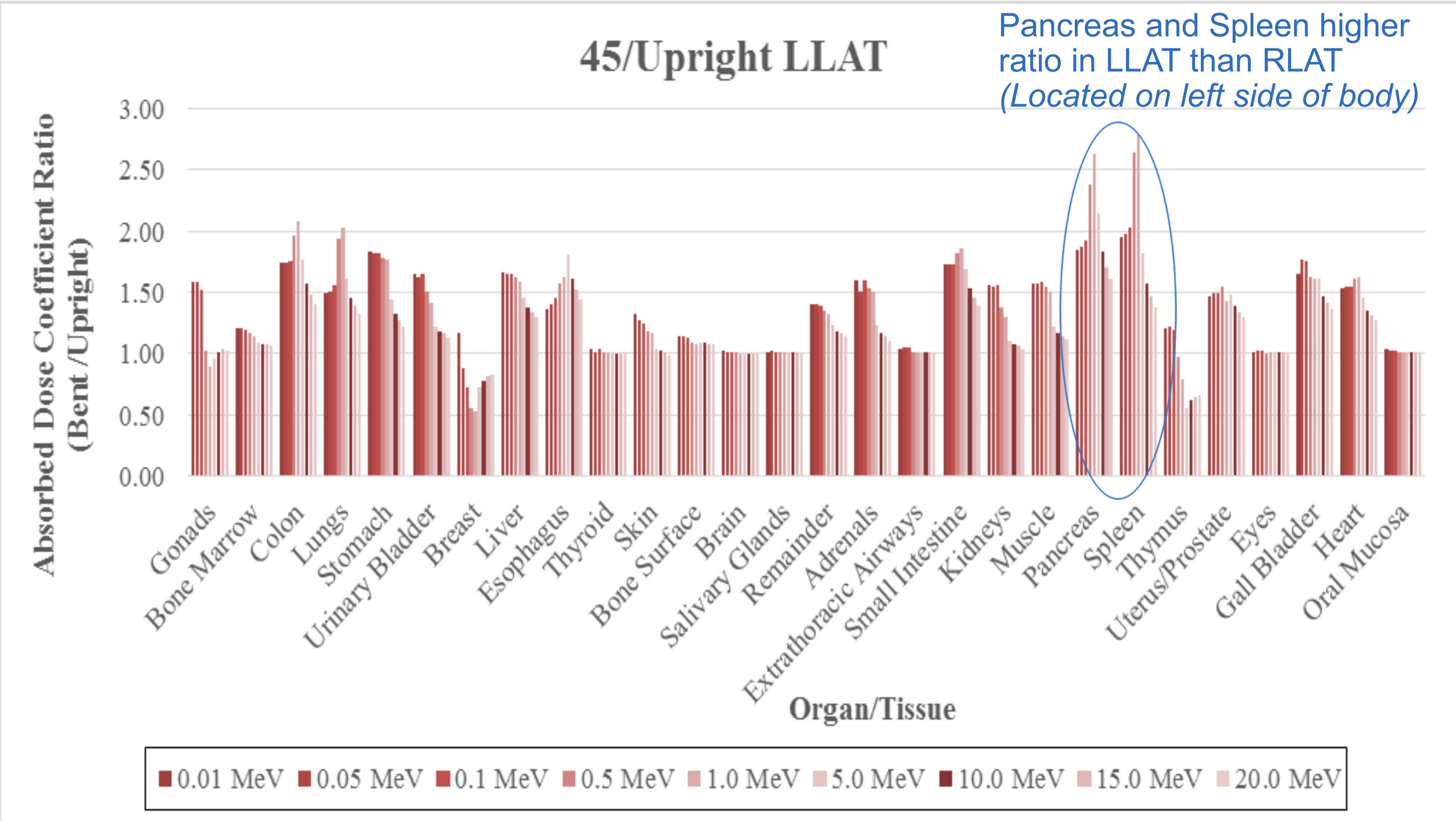
Results – LLAT and RLAT Source Geometry

- Due to the LLAT and RLAT position having arms angled out, organs in the torso received more dose than they would have otherwise in the upright position where the arms serve as shields pinned to the sides of the body.
- Not much positional variation from 45 to 90 bend (organs see the same solid angle from source)

Results – LLAT and RLAT Source Geometry

- Upright phantom ratio underestimates doses (vs bent) for
  - Low Energies: Testes, Thymus
  - Colon, Lungs, Stomach, Bladder, Liver, Esophagus, Skin, Adrenals, Small Intestine, Kidney, Muscle, Prostate, Gallbladder, Heart
  - LLAT: Spleen and Pancreas by factor of 2-3
- Organs that did exhibit any positional difference at a 45-degree bend (> ~10%) in the LLAT/RLAT irradiation fields:
  - Bladder (0.01 MeV), Adrenals (0.05 MeV), Prostate (1 MeV), Liver, Pancreas, Spleen, Thymus, Gallbladder

LLAT Source Geometry
Organ Dose Ratio in 45-degree Bent/Upright



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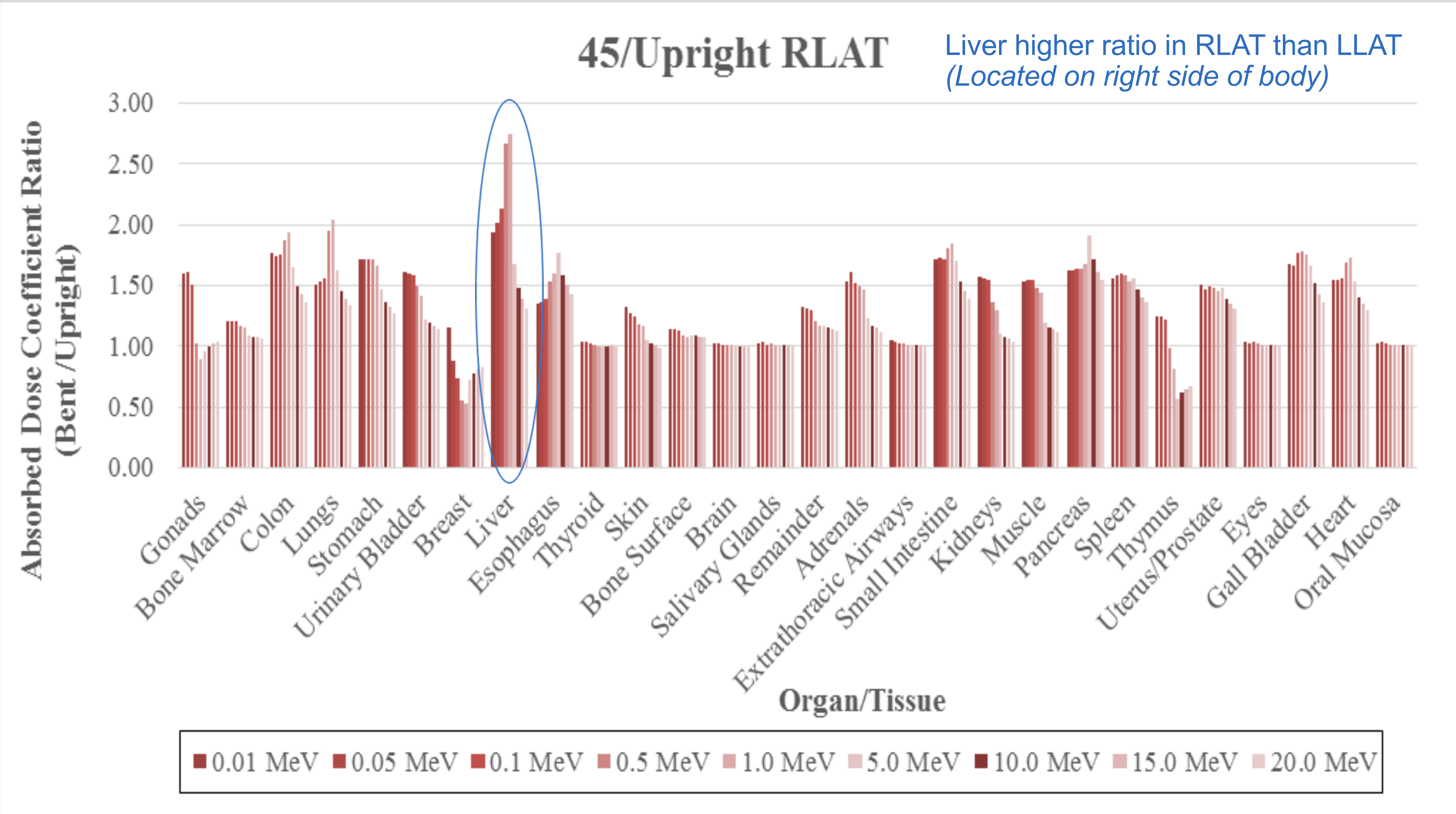
RLAT Source Geometry
Organ Dose Ratio in 45-degree Bent/Upright



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Contribution of Secondary Particles

- Because neutrons are uncharged, energy is imparted to tissues by secondary particles
  - Element composition of tissues can have influence
- Photon dose depends on neutron energy
  - Low energy (e.g. thermal energy): contribution of neutron-liberated photons dominates absorbed dose
    - ICRP 103 neutron radiation weighting factor used to convert absorbed dose to equivalent dose

Effective Dose
Radiation Weighting Factor

$$w_R = \begin{cases} 2.5 + 18.2e^{-[\ln(E_n)]^2/6}, & E_n < 1 \text{ MeV} \\ 5.0 + 17.0e^{-[\ln(2E_n)]^2/6}, & 1 \text{ MeV} \leqslant E_n \leqslant 50 \text{ MeV} \\ 2.5 + 3.25e^{-[\ln(0.04E_n)]^2/6}, & E_n > 50 \text{ MeV} \end{cases} \quad (4.3)$$

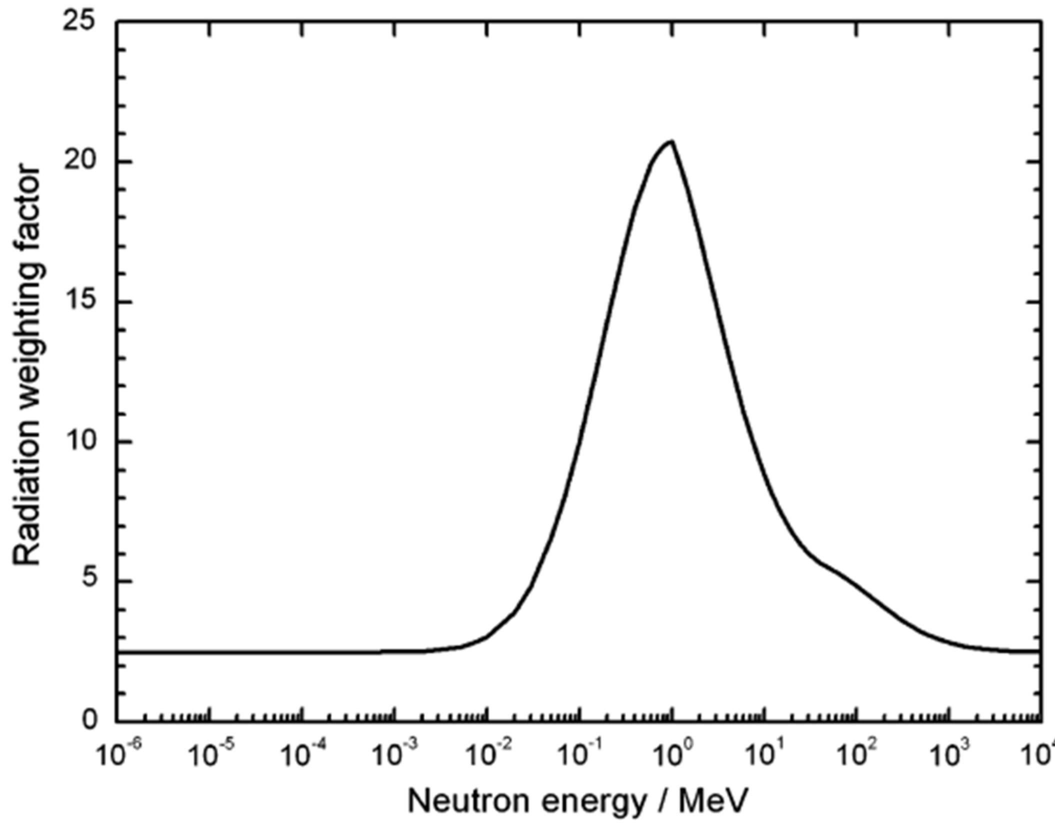

Fig. 1. Radiation weighting factor, w_R, for neutrons versus neutron energy.

Image courtesy of ICRP Publication 103.

Conclusions

- Upright phantom largely underestimates:
  - absorbed dose in the brain for the AP source geometry
  - absorbed dose in testes and prostate for PA source geometry
  - both the half and full bend phantom positions
- Very little positional difference for LLAT and RLAT
- Ratio for ISO was ~ 1.0 for all positions due to uniform irradiation source, as expected
- Future Work
  - Criticality dose reconstruction
    - Information gathered would be helpful in determining impact on human health from neutron dose
      - Tokai-Mura accident
  - Glovebox worker dose reconstruction

References

- Akkurt, Hatice, Kursat Bekar, and K. Eckerman. "Assessment of Organ Doses for a Glovebox Worker Using Realistic Postures with PIMAL and VOXMAT." Trans. of Am. Nuc. Soc 101 (2009): 671-673.

- Dewji, S., et al. "Estimated dose rates to members of the public from external exposure to patients with ^{131}I thyroid treatment." Medical physics 42.4 (2015): 1851-1857.

- S. A. Dewji, K. L. Reed, M. Hiller, Comparison of Organ Doses for PIMAL Stylized Phantoms in Upright and Bent Positions for Standard Irradiation Geometries. *Radiation and Environmental Biophysics (In Press).*

- Cristy, M. and Eckerman, K.F. Specific Absorbed Fractions of Energy at various Ages from Internal Photon Sources Parts I-VII. ORNL/TM 8381/V1-V7 (Oak Ridge National Laboratory, Oak Ridge, TN) U. S. Environmental Protection Agency, Washington, DC (1987).

- ICRP, 2007. The 2007 Recommendations of the International Commission on Radiological Protection. ICRP Publication 103. Ann. ICRP 37 (2-4).

- ICRP, 2010. Conversion Coefficients for Radiological Protection Quantities for External Radiation Exposures. ICRP Publication 116, Ann. ICRP 40(2-5).

- NRC. PIMAL source. <https://www.usnrc-ramp.com>

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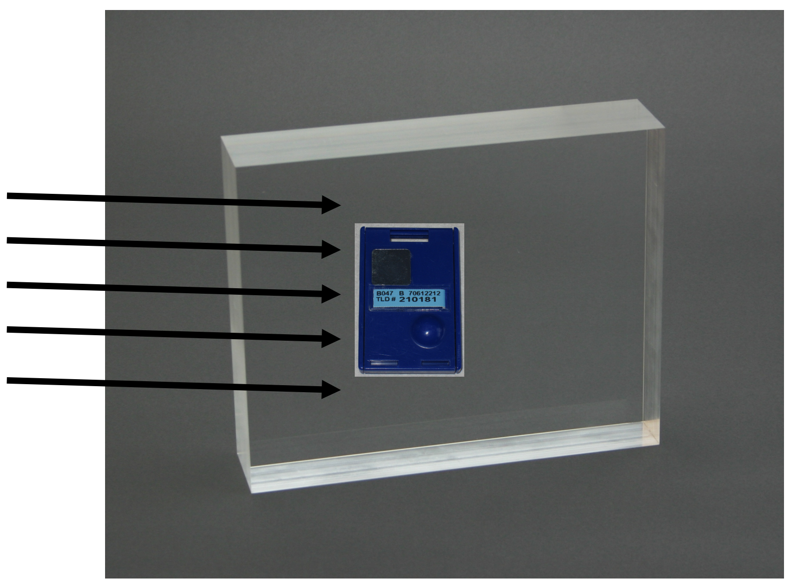
Examples

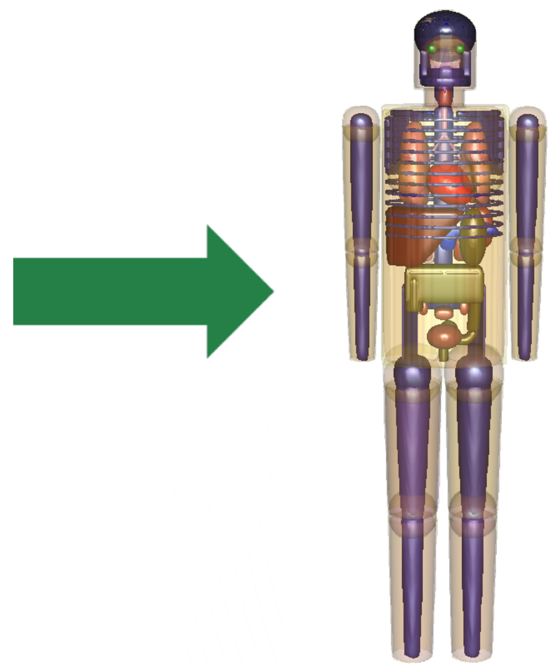
1. Glovebox Worker
2. I-131 Patient Release Study
3. **Upright vs. PIMAL Bent for ICRP 116 Geometries**
   - Photon
   - Neutron
   - **TLD**

PIMAL Correlation with TLDs (Sanchez et al, 2017)

- Assumptions about dosimeter placement and posture of wearer inherent in personal dosimetry.
- Protection quantities (i.e., Effective Dose) assume vertical, upright posture. Placement of dosimeter not considered.



Operational Quantities – $H_p(10)$



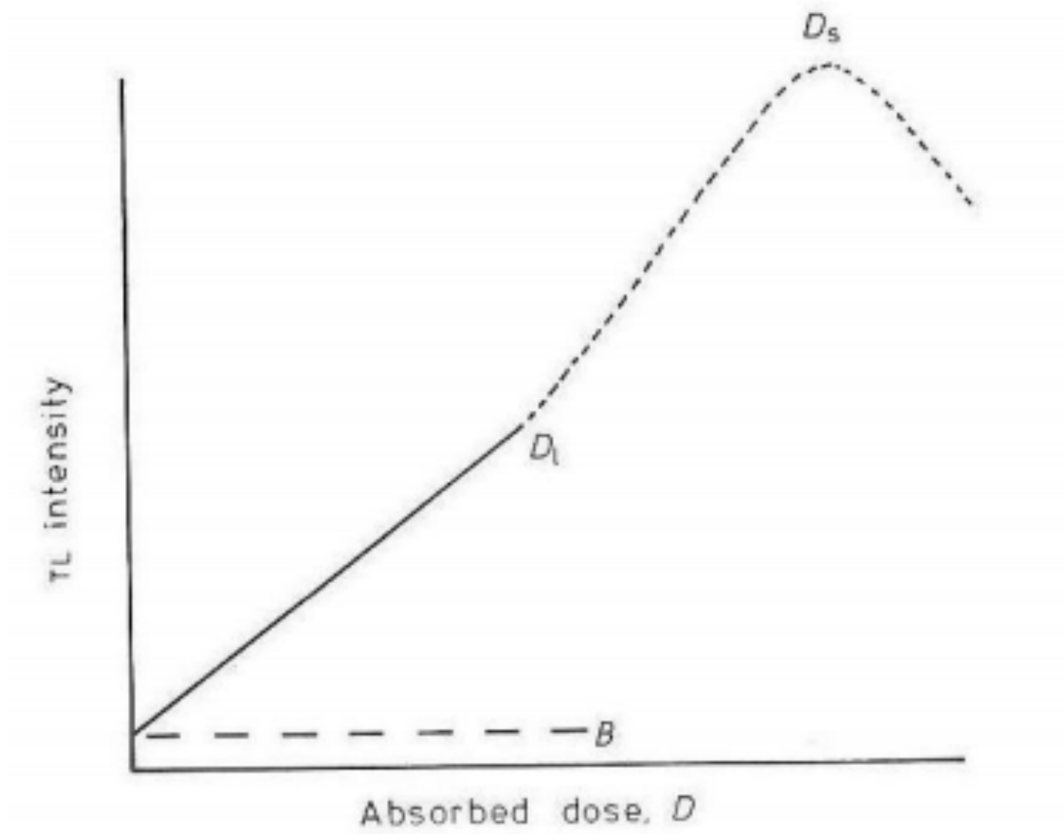
Protection Quantities – E

Introduction

$$r_i(d) = \frac{L_i}{H_p(d)}$$

- r = TLD Response-to-dose factor
- L_i = Normalized response of ith TLD element
- H_p = Personal dose equivalent
- d = depth of penetration

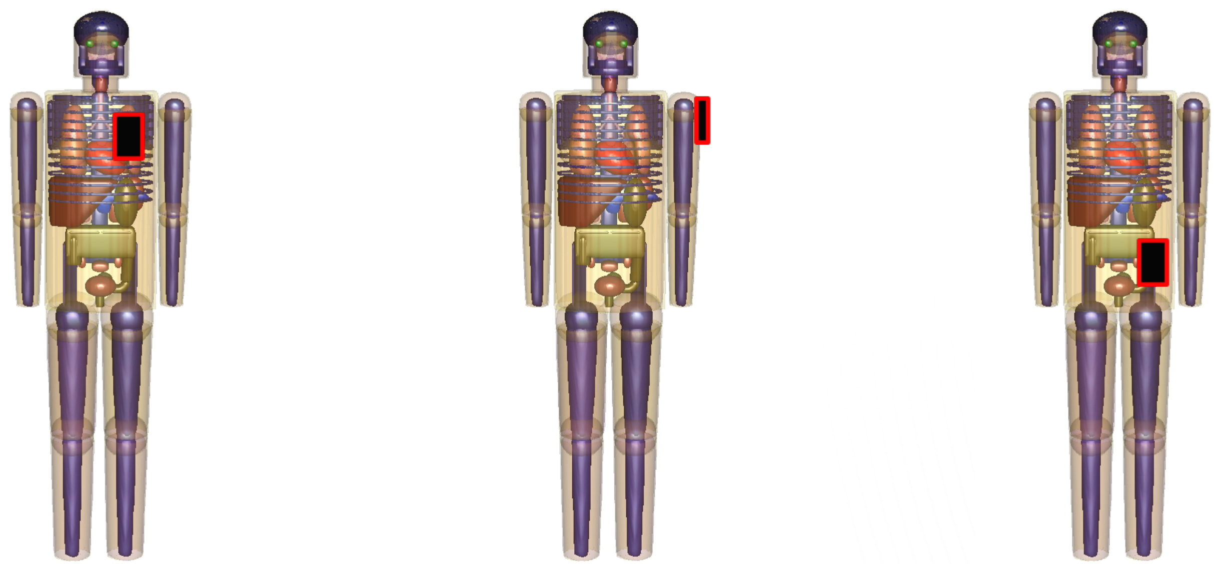
Response-to-Dose Factor



TLD Response Curve

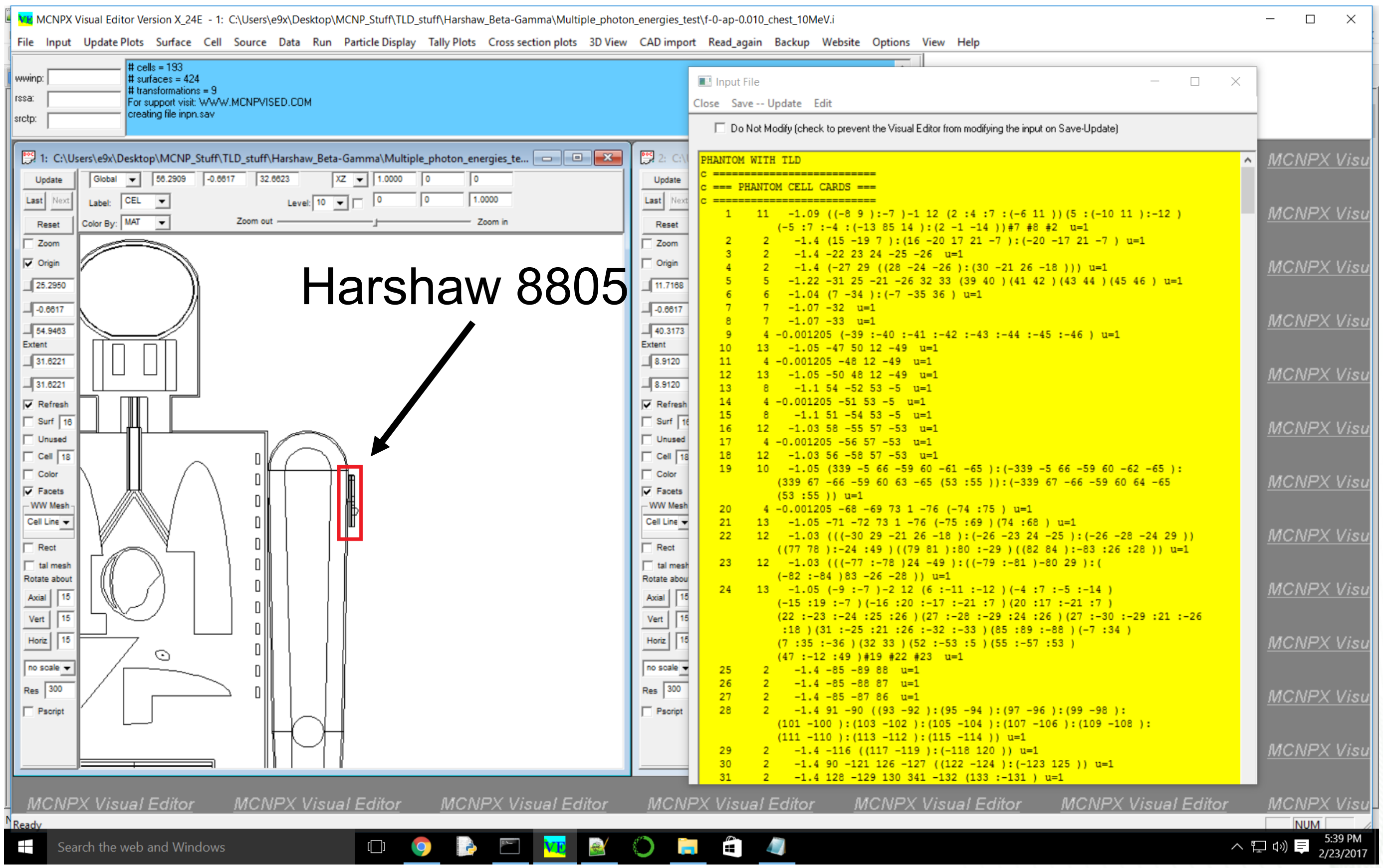
Methodology – Monte Carlo Simulation

- Phantoms equipped with 6.2 x 3.2 x 0.6 cm^3 ABS plastic rectangular prisms on chest, shoulder and waist.
  - Energy flux and particle fluence tallies taken over outward-facing surfaces of rectangles.
  - Ratio of energy flux to effective dose to phantom used as surrogate for TLD response-to-dose factor



Methodology – Monte Carlo Simulation

- Why plastic rectangles?
  - Realistic TLD models yielded poor statistics
  - TLD elements <0.005 cm^3



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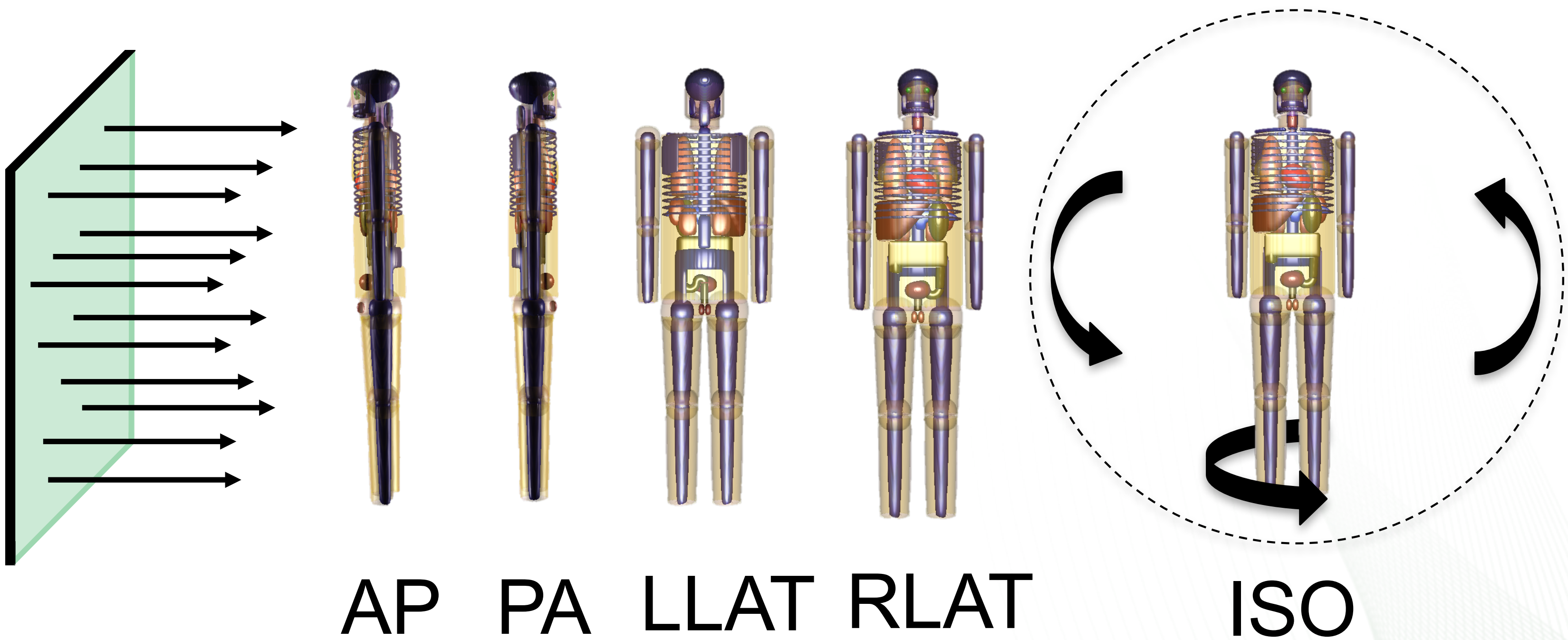
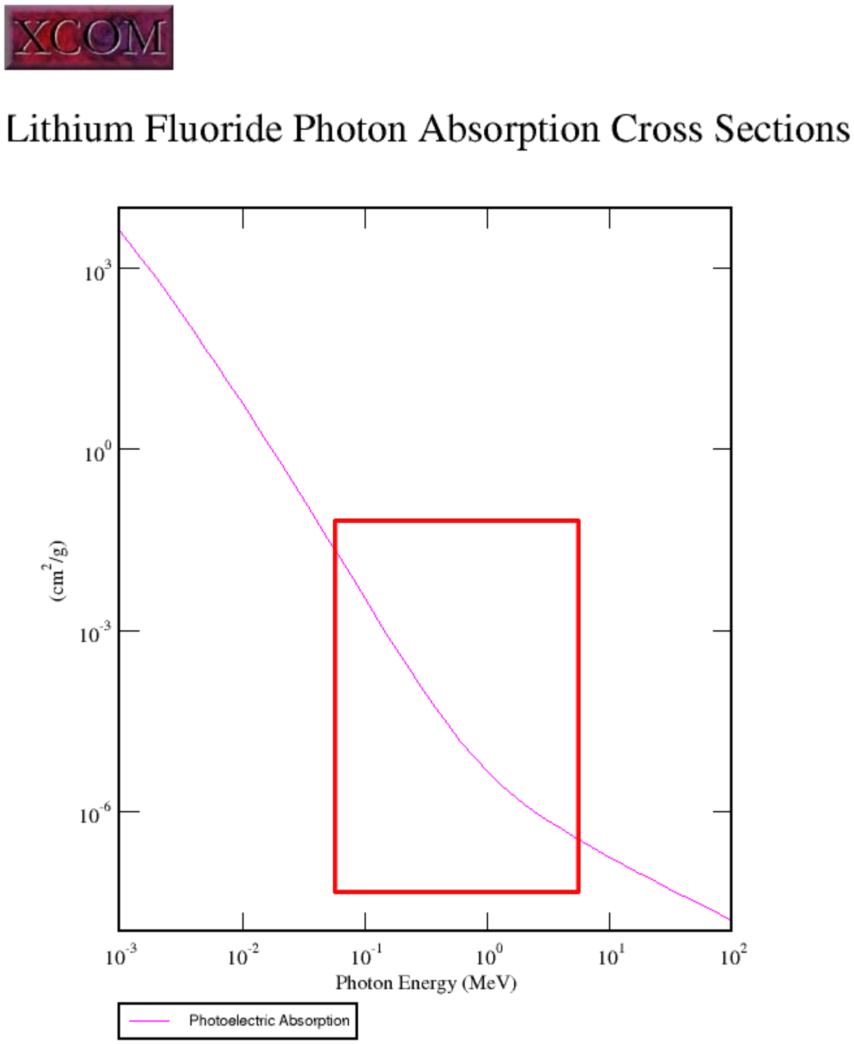
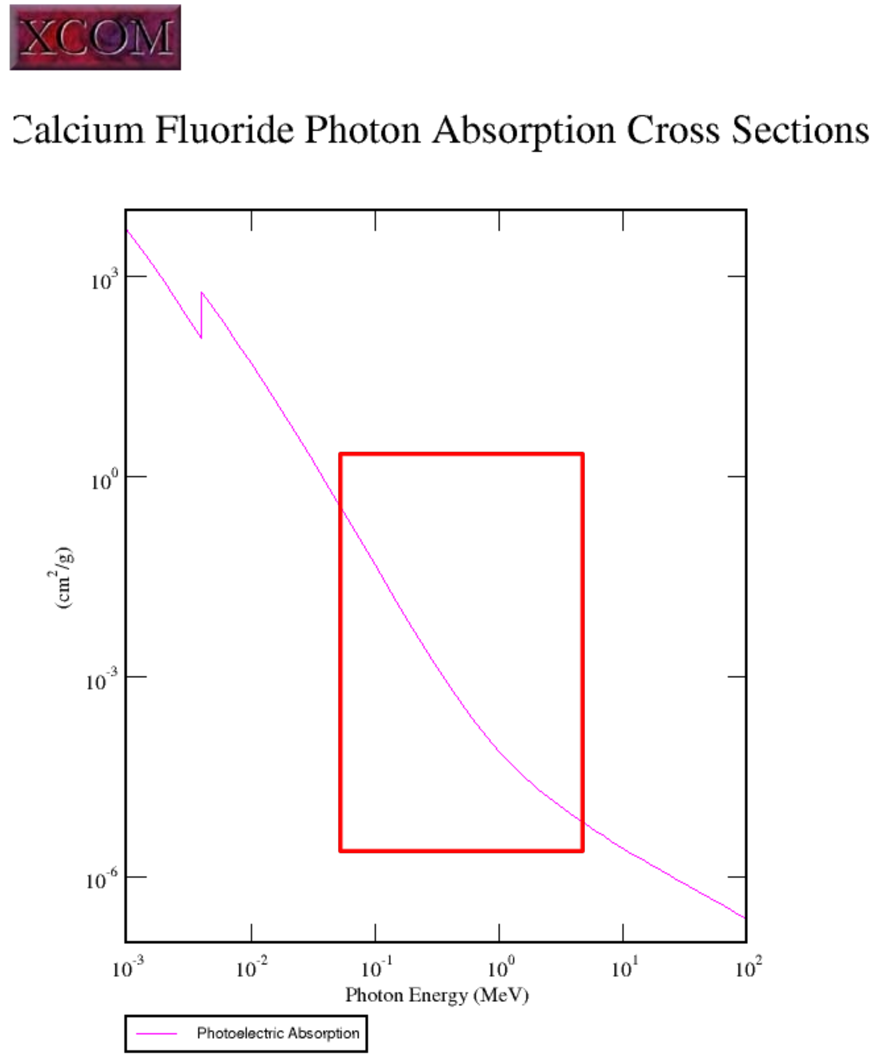
Methodology – Monte Carlo Simulation

- Upright and repositioned phantoms were irradiated using 5 International Commission on Radiation Protection Publication 116 irradiation geometries
  - Anterior-posterior (AP), Posterior-anterior (PA), Left lateral (LLAT), right lateral (RLAT), and isotropic (ISO)



Results





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Conclusions

- Energy flux-to-effective dose factors highly sensitive to TLD placement and phantom posture.
  - LLAT many times greater than AP, PA and RLAT for shoulder placements
  - AP and PA greater than LATs for upright chest and waist placements, but comparable for fully-bent phantoms
- Response curves often do not exhibit monotonic increase over full range of energies

Conclusions

- Configuration of body and dosimeter placement may be significant considerations for personal dosimetry and dose reconstruction
- May warrant update of personal TL dosimetry methodologies:
  - Develop realistic TLD models
  - Allow for situation-specific posture considerations
  - Correlate doses to at-risk organs to TL response

References

- Savva, A. Personnel TLD Monitors: Their Calibration and Response. M.S. Dissertation, University of Surrey, Guildford, Surrey, 2010.
- Berger, M.J., Hubbell, J.H., Seltzer, S.M., Chang, J., Coursey, J.S., Sukumar, R., Zucker, D.S., and Olsen, K. (2010), *XCOM: Photon Cross Section Database* (version 1.5). [Online] Available: http://physics.nist.gov/xcom [Sunday, 25-Jun-2017 22:52:39 EDT]. National Institute of Standards and Technology, Gaithersburg, MD.
- ICRP, 2007. The 2007 Recommendations of the International Commission on Radiological Protection. ICRP Publication 103. Ann. ICRP 37 (2-4).
- ICRP, 2010. Conversion Coefficients for Radiological Protection Quantities for External Radiation Exposures. ICRP Publication 116, Ann. ICRP 40(2-5).
- NRC. PIMAL source. <https://www.usnrc-ramp.com>

Questions?

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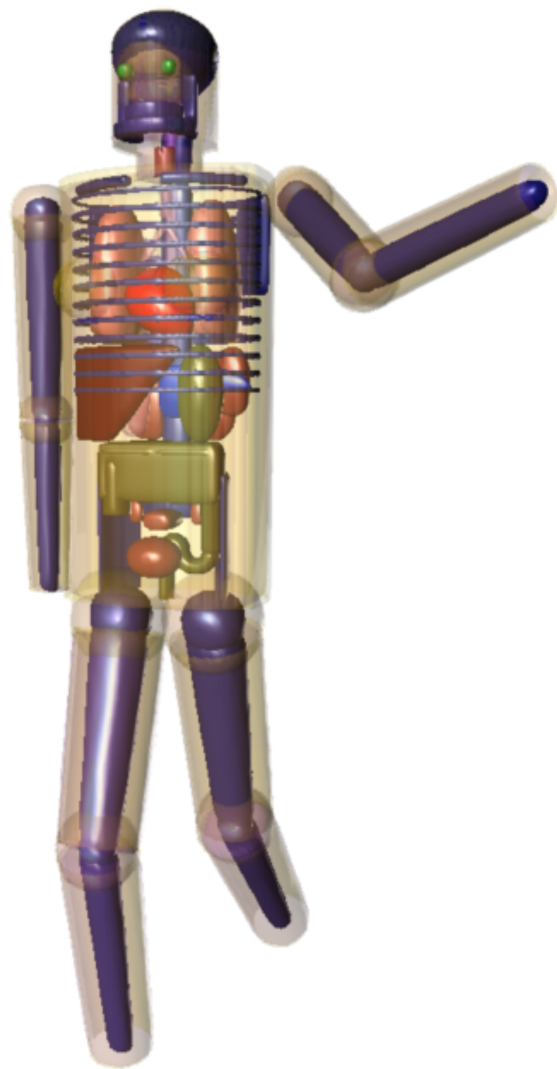
Thank you for your attention!



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Basic PIMAL GUI

Center for Radiation Protection Knowledge

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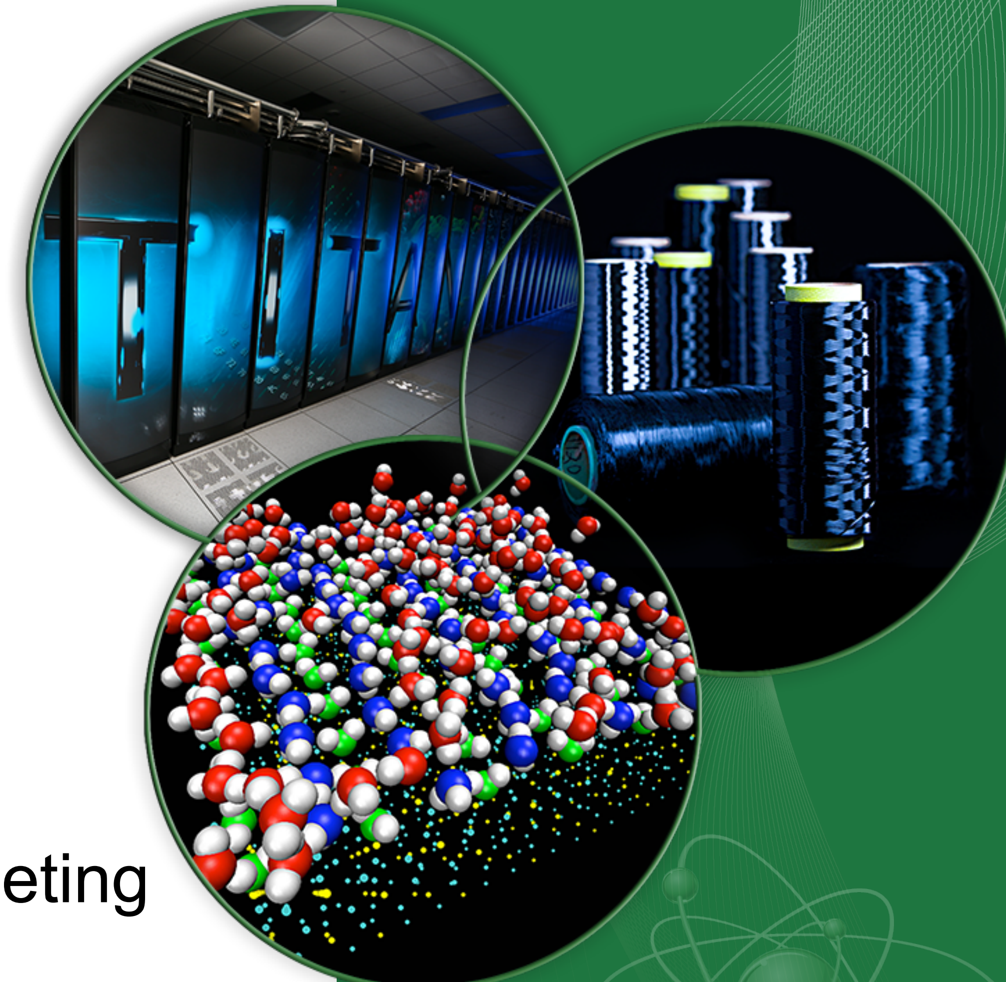

Prepared for:
2017 RAMP Users' Group Meeting
October 16-20, 2017

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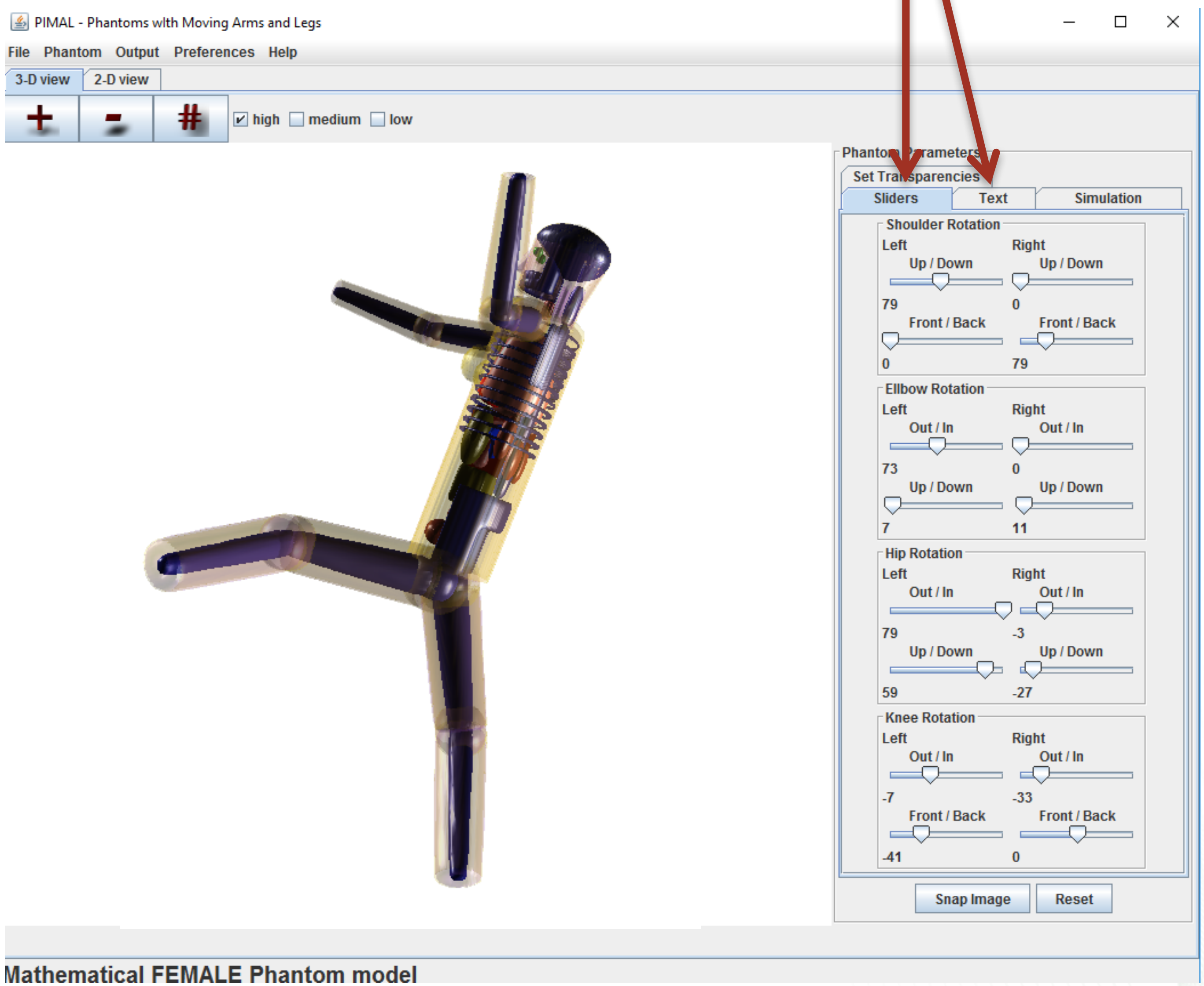
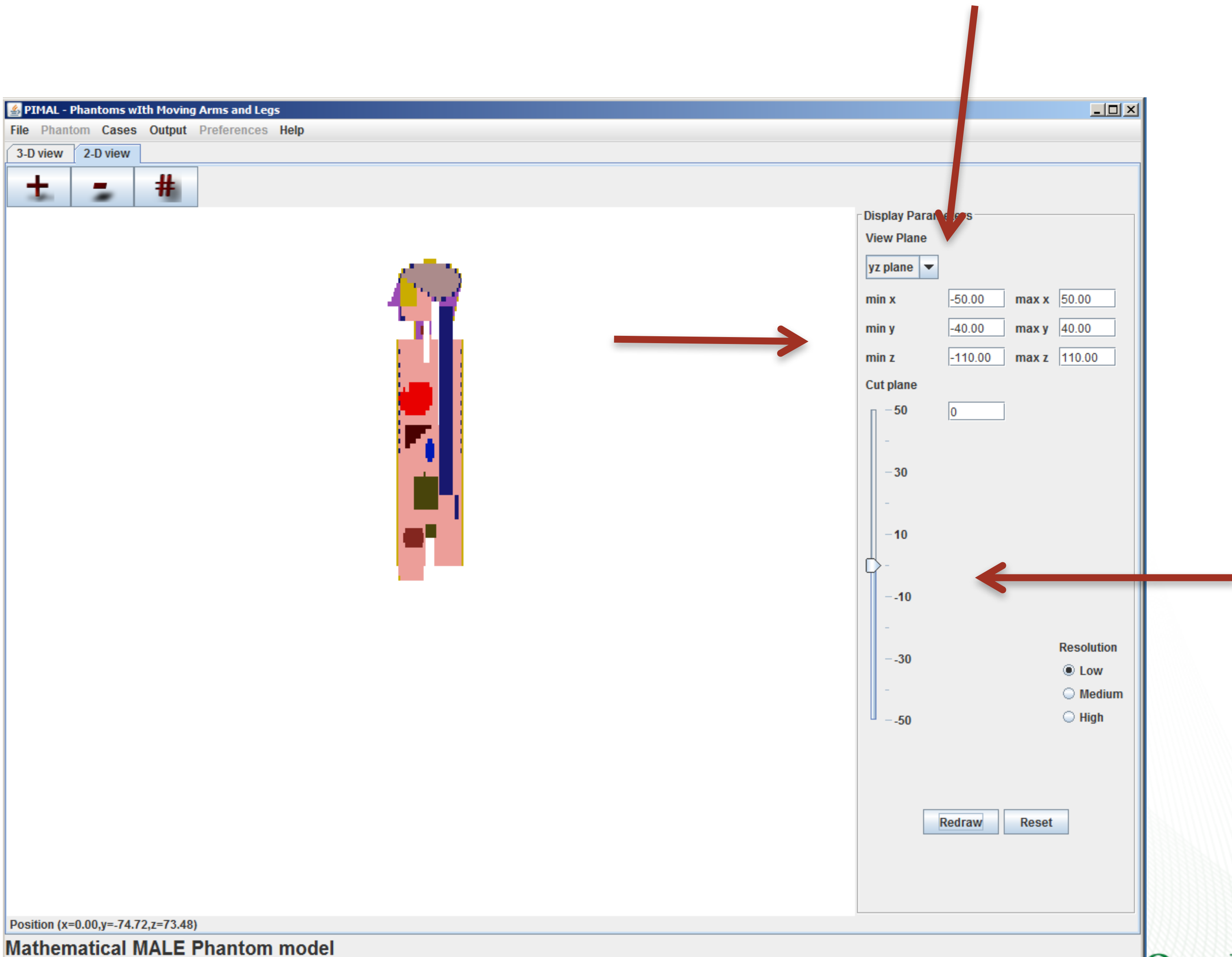
Adjust phantom



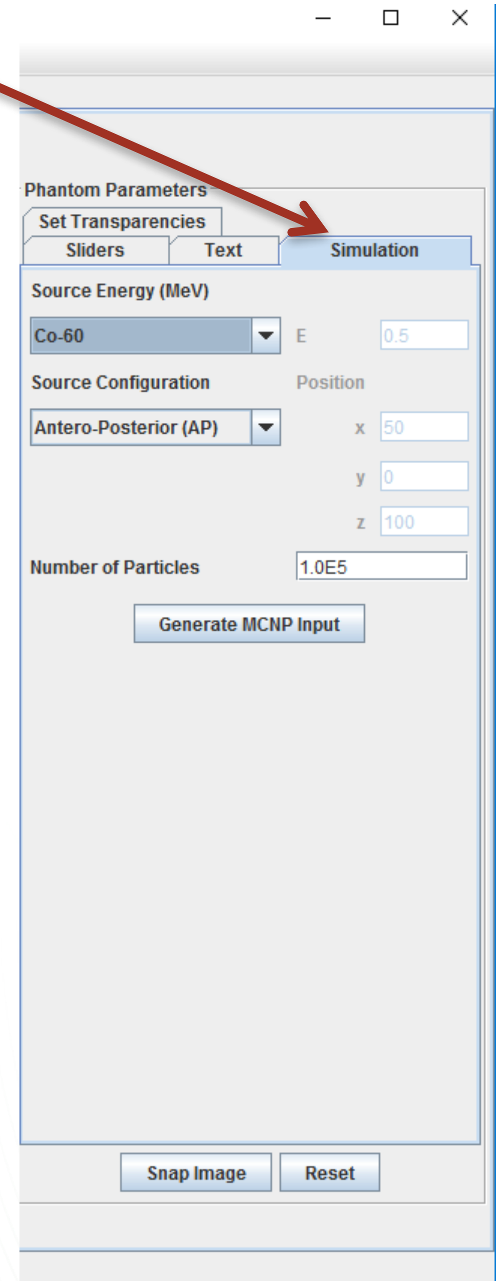
2D view



PIMAL - Phantoms wIth Moving Arms and Legs
File Phantom Cases Output Preferences Help
3-D view 2-D view
Display Parameters
View Plane
yz plane
min x -50.00 max x 50.00
min y -40.00 max y 40.00
min z -110.00 max z 110.00
Cut plane
50 30 10 -10 -30 -50
0
Resolution
Low
Medium
High
Redraw Reset
Position (x=0.00,y=-74.72,z=73.48)
Mathematical MALE Phantom model

Start the simulation

Select Simulation Tab



Adjust Simulation Input Parameters

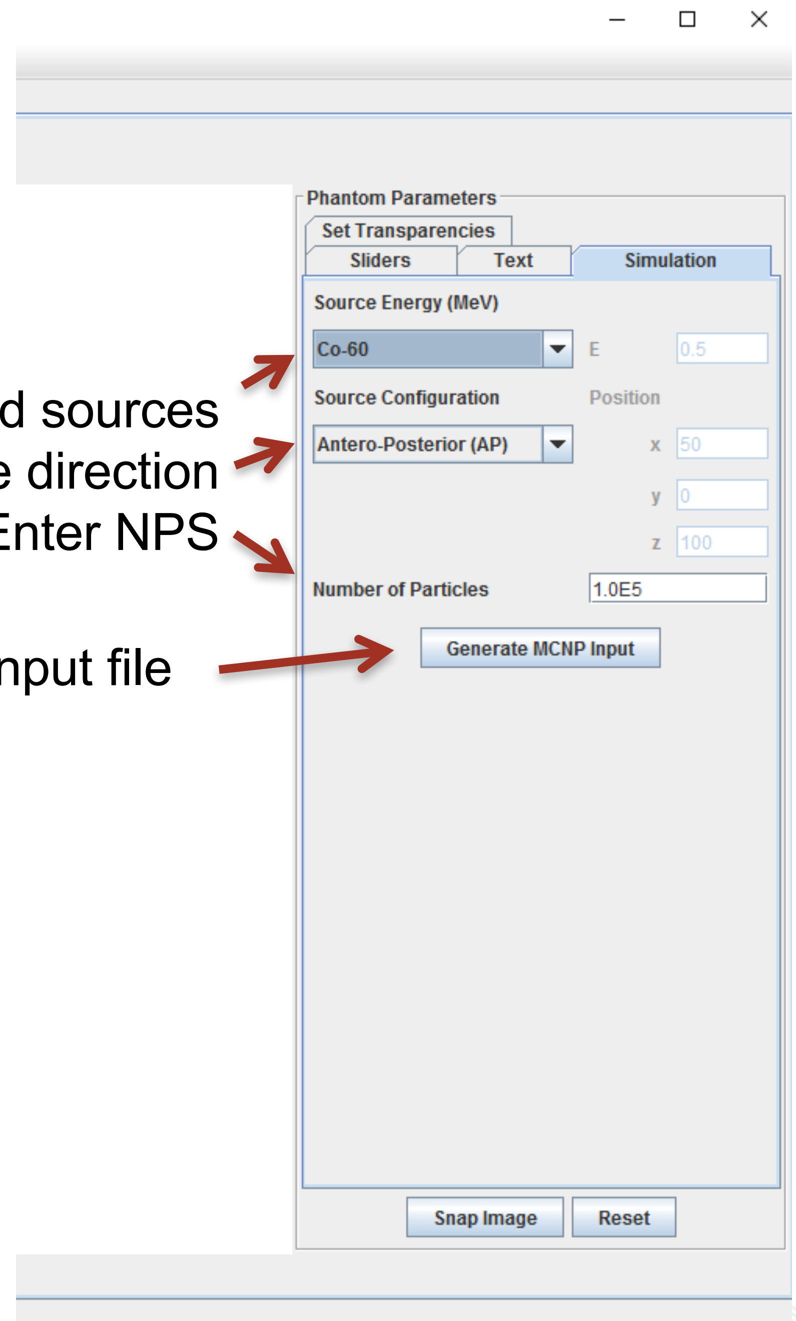
All simulation parameters can be changed later in the MCNP input file

Select Source: Monoenergetic or Various pre-defined sources

Select source direction

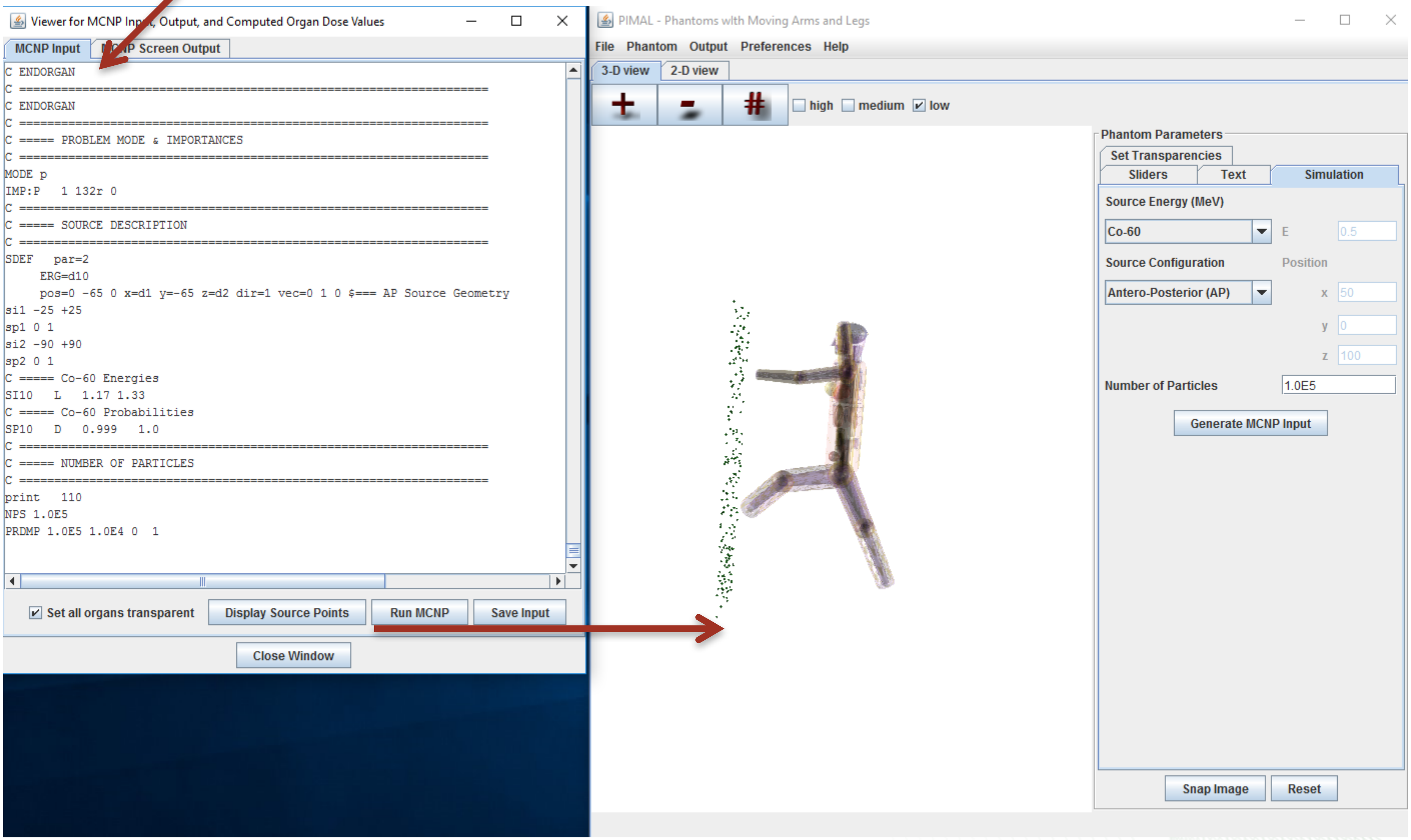
Enter NPS

Generate input file

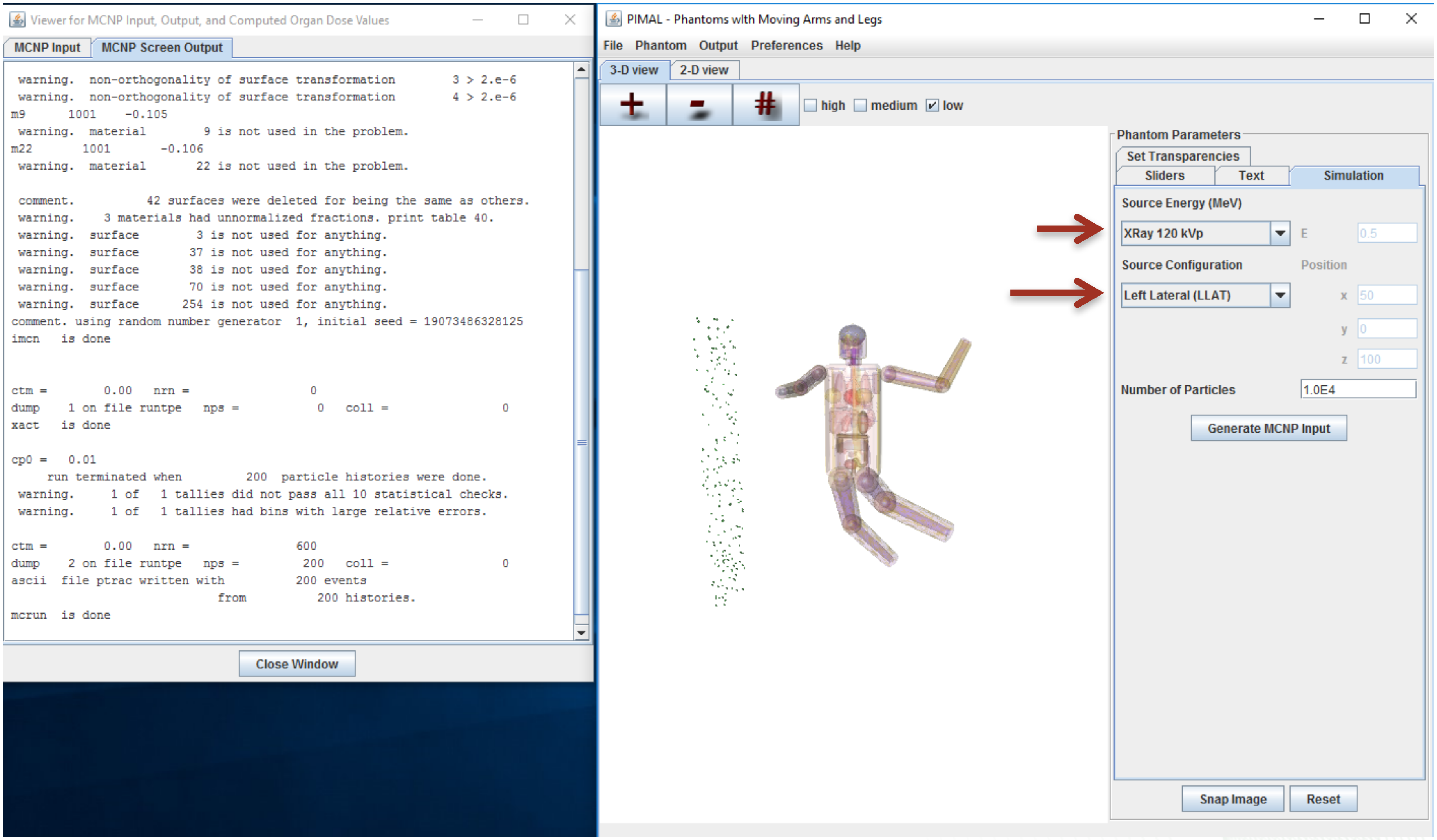


Start the simulation

PIMAL MCNP control window



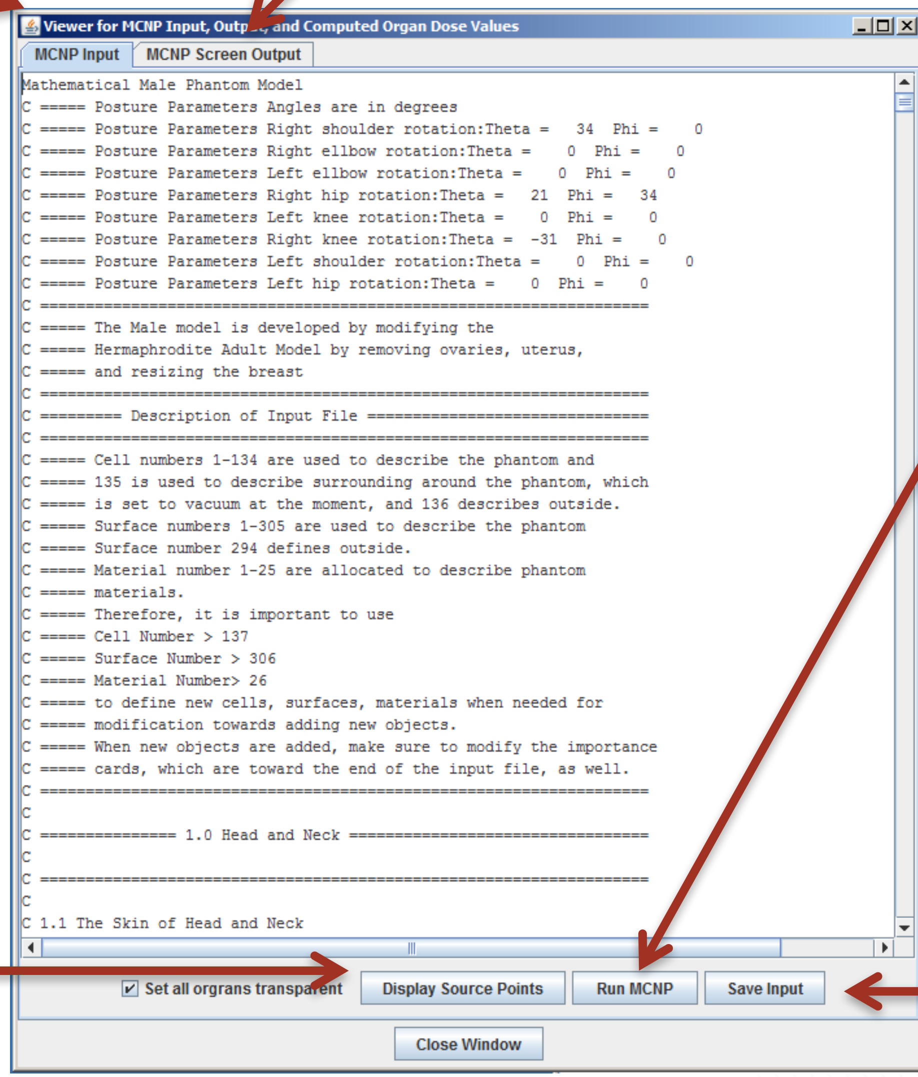
Alternative simulation setup



PIMAL MCNP control window

View MCNP inp. file

See MCNP output



Start MCNP run

Display source in the PIMAL window

Save MCNP **AND** PIMAL input files to disk

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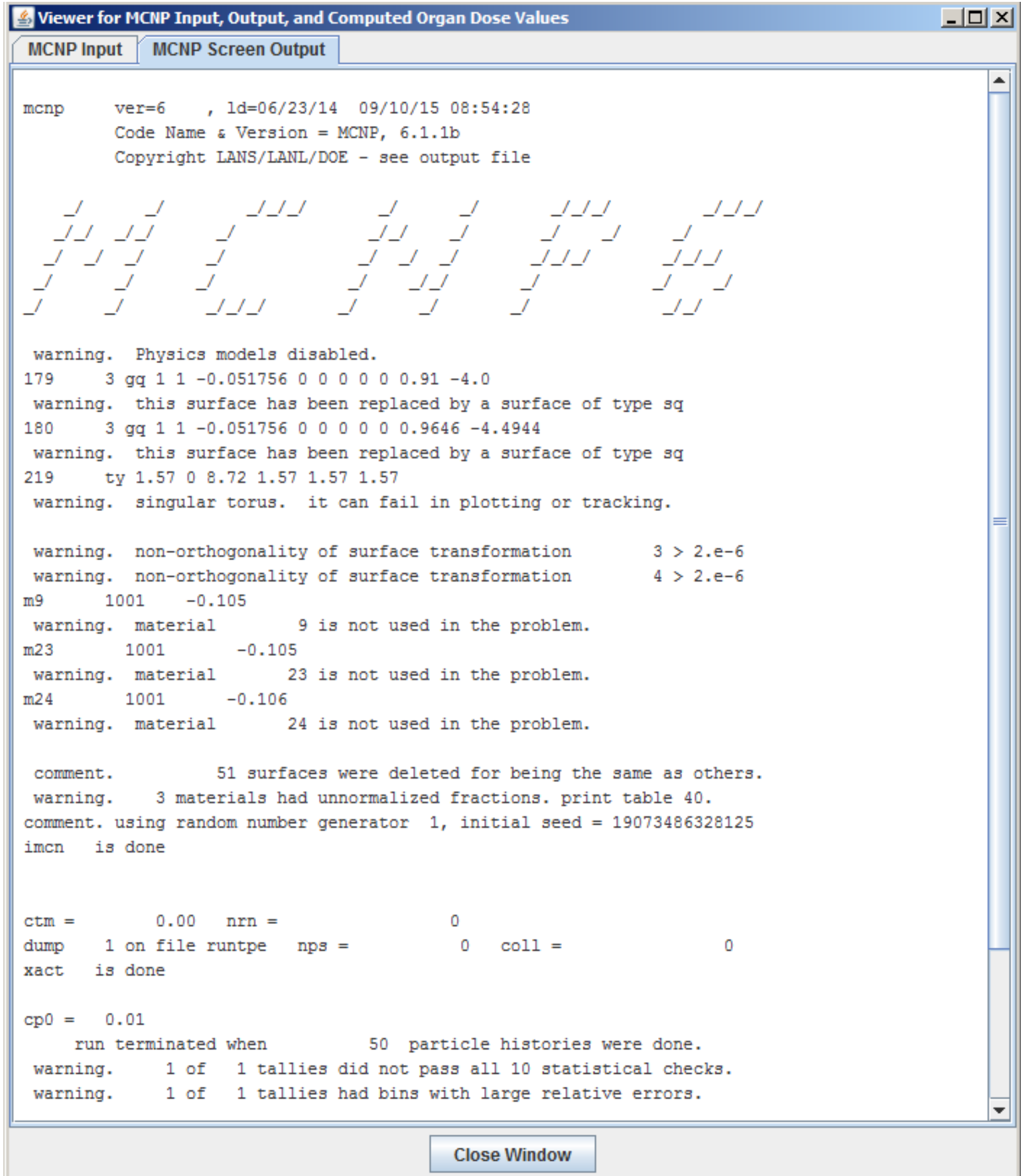
Run the MCNP simulation



Output after MCNP run

Full Output

Organ Doses

Viewer for MCNP Input, Output, and Computed Organ Dose Values

MCNP Input | MCNP Screen Output | MCNP Full Output | Computed Organ Dose Values

Math_Male_0.o

Absorbed Dose (Gy/Source Particle) for NPS=1.0E6

Organs	Photon Dose Tally: 216	Relative Error (1 sigma) Tally: 216
testes	1.1923E-17	0.0600
bone marrow	4.1915E-17	0.0058
colon	7.0621E-18	0.0230
lungs	8.8378E-18	0.0142
stomach	2.4212E-18	0.0606
urinary bladder	9.8118E-18	0.0372
breast	6.0469E-17	0.0234
liver	1.2738E-17	0.0145
esophagus	4.3882E-18	0.0643
thyroid	3.1350E-17	0.0394
skin	2.5751E-17	0.0039
bone surface	2.9816E-17	0.0070
adrenals	6.6135E-18	0.0865
brain	2.1963E-17	0.0127
Extrathoracic airways	2.8539E-17	0.0256
small intestine	5.7636E-18	0.0253
kidneys	1.0708E-17	0.0288
muscle	1.1500E-17	0.0041
pancreas	2.7678E-18	0.0720
spleen	9.3344E-19	0.1295
thymus	8.4414E-18	0.0713
prostate	7.6569E-18	0.1006
eyes	3.1813E-17	0.0431

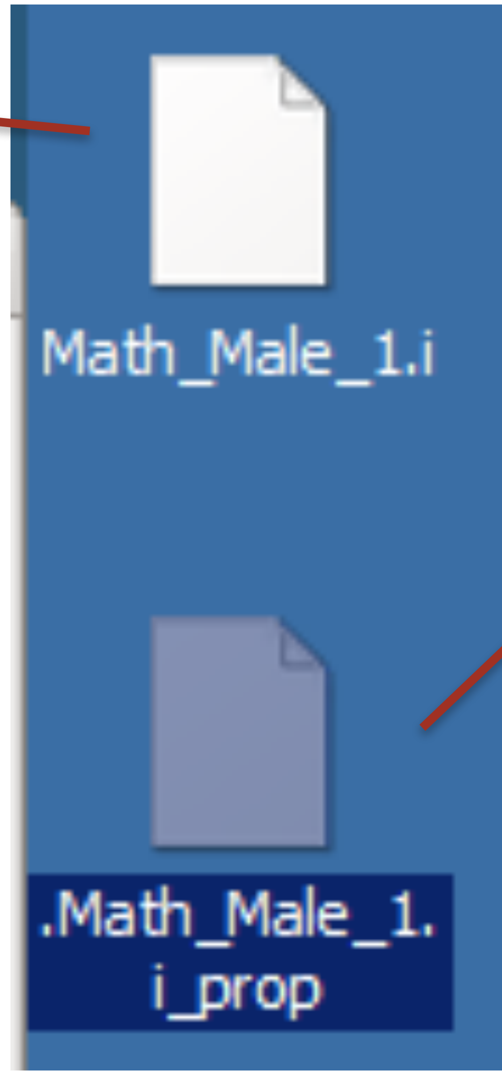
Export to ASCII | Close

Close Window

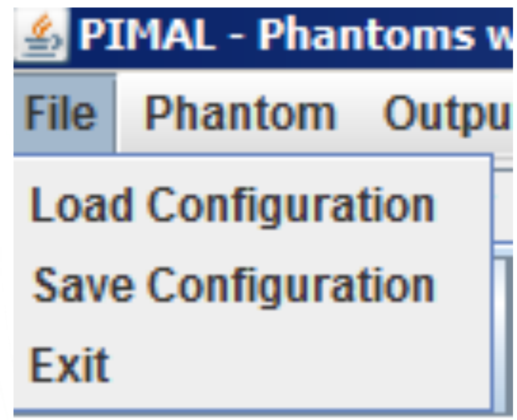
Input Files on disk

MCNP input file generated by PIMAL.

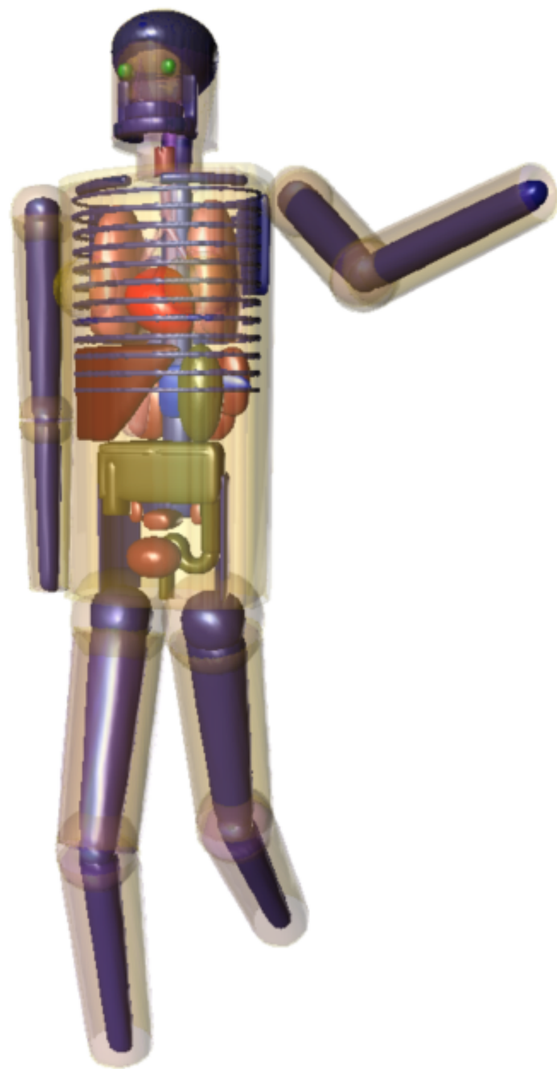
Open in text editor to modify the MCNP simulation and run from the MCNP command line.



PIMAL configuration file.
Select File -> Open Input and that file to load your previous generated PIMAL models



Thank you for your Attention



MCNP® Resources

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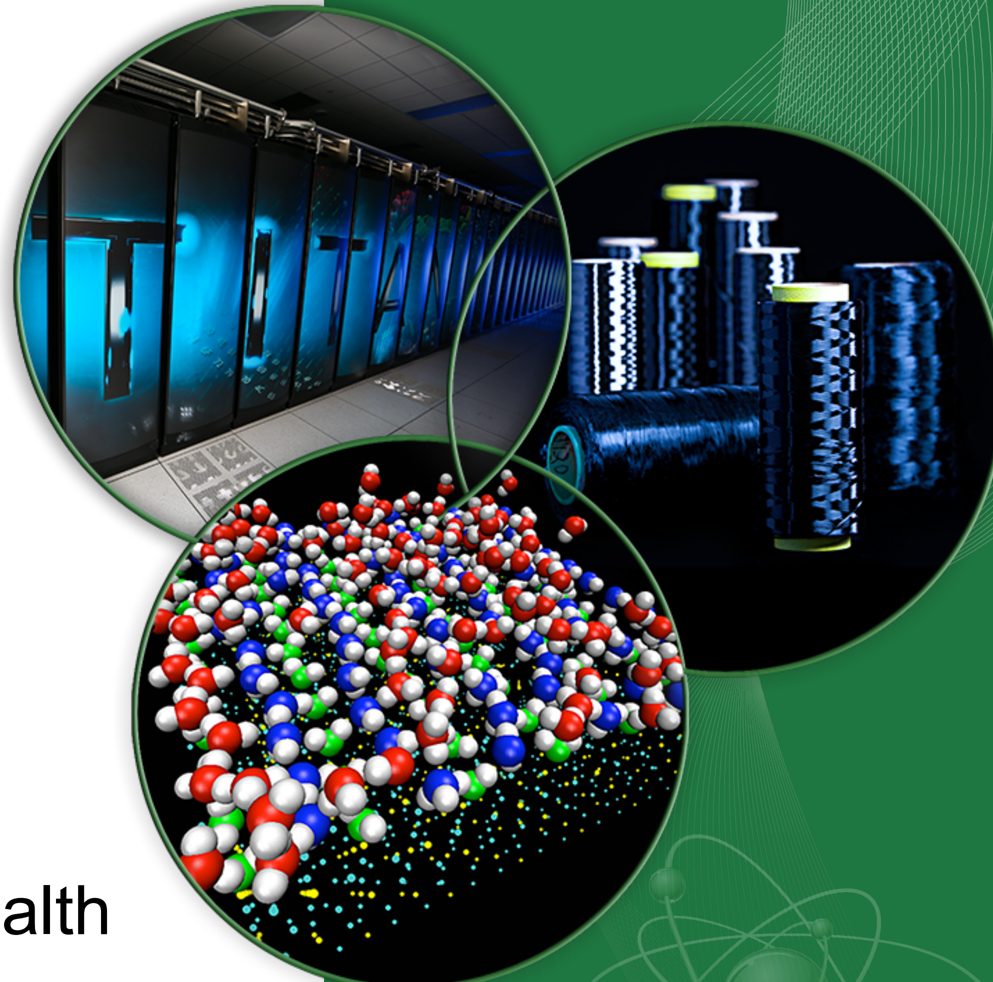
Prepared for:

62nd Annual Meeting of the Health Physics Society

July 9-13, 2017, Raleigh, NC



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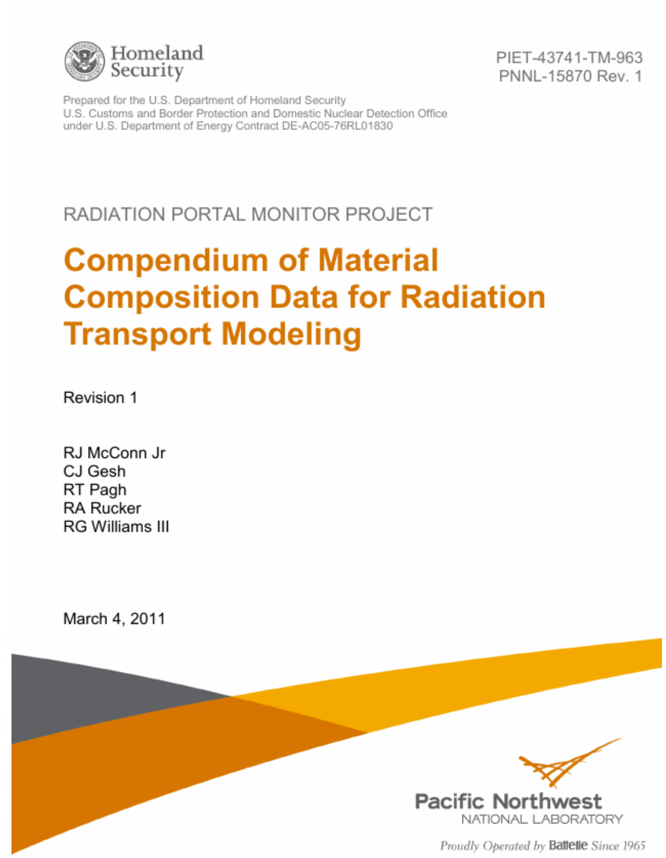
MCNP® Manuals

- The MCNP® Manual is included with the software package
- Part 1 of the MCNP® 5 manual gives a good overview of theory
- Refer to MCNP® 6.1.1 Manual Chapter 5 for examples

MCNP® Resources

- Shultis & Faw, MCNP® Primer https://www.mne.ksu.edu/~jks/MCNP® prmr.pdf
- LANL Reference Collection https://laws.lanl.gov/vhosts/mcnp.lanl.gov/references.shtml
- Materials, PNNL-15870 Rev. 1 http://www.pnnl.gov/main/publications/external/technical_reports/PNNL-15870Rev1.pdf


Homeland Security

PIET-43741-TM-963
PNNL-15870 Rev. 1

Prepared for the U.S. Department of Homeland Security
U.S. Customs and Border Protection and Domestic Nuclear Detection Office
under U.S. Department of Energy Contract DE-AC05-76RL01830

RADIATION PORTAL MONITOR PROJECT

Compendium of Material Composition Data for Radiation Transport Modeling

Revision 1

RJ McConn Jr
CJ Gesh
RT Pagh
RA Rucker
RG Williams III

March 4, 2011

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MCNP® Training

- LANL (Mostly at Los Alamos) https://laws.lanl.gov/vhosts/mcnp.lanl.gov/classes/classinformation.shtml
- Visual Editor Consultants (Worldwide) http://www.mcnpvised.com/
- OECD NEA (usually Paris) http://www.oecd-nea.org/dbprog/trainingcourses.htm
- RSICC Newsletter announces Training https://rsicc.ornl.gov/RSICCNewsletters.aspx

PIMAL References

- **PIMAL Manual v. 4.1.0**
  - Publication Pending on RAMP site
  - Draft e-mailed/posted
  - Pre-draft available with installer

- **Oak Ridge National Laboratory Center for Radiation Protection Knowledge (CRPK)**
  - Specializing in advanced/customized computational phantom modeling and training crpk@ornl.gov
  - General PIMAL questions pimal@ornl.gov