Monte Carlo applications in Nuclear Medicine and RT including PET

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- Zhao Mo, Joanne Kim and Saxby Brown – all past or present students from Sydney Uni

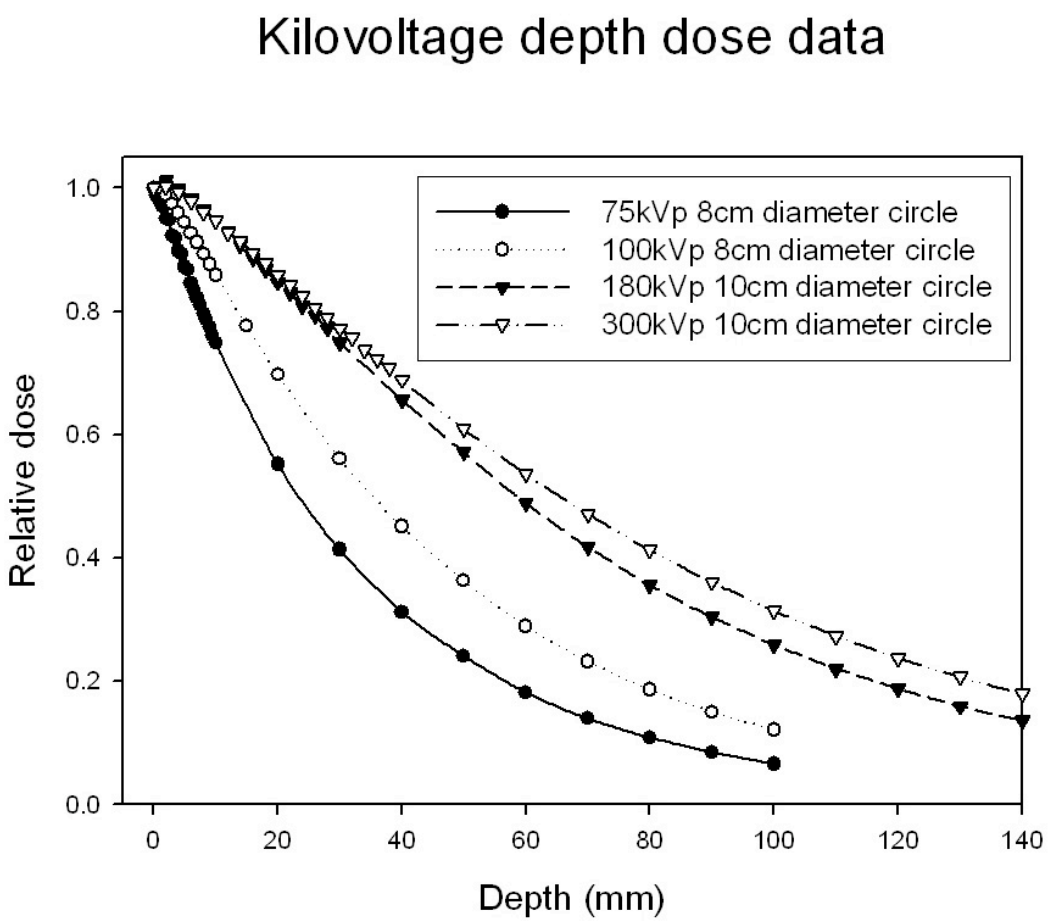
Kilovoltage x-ray beam dosimetry

- These are x-ray units used for therapeutic use such as treating cancer or other skin conditions.

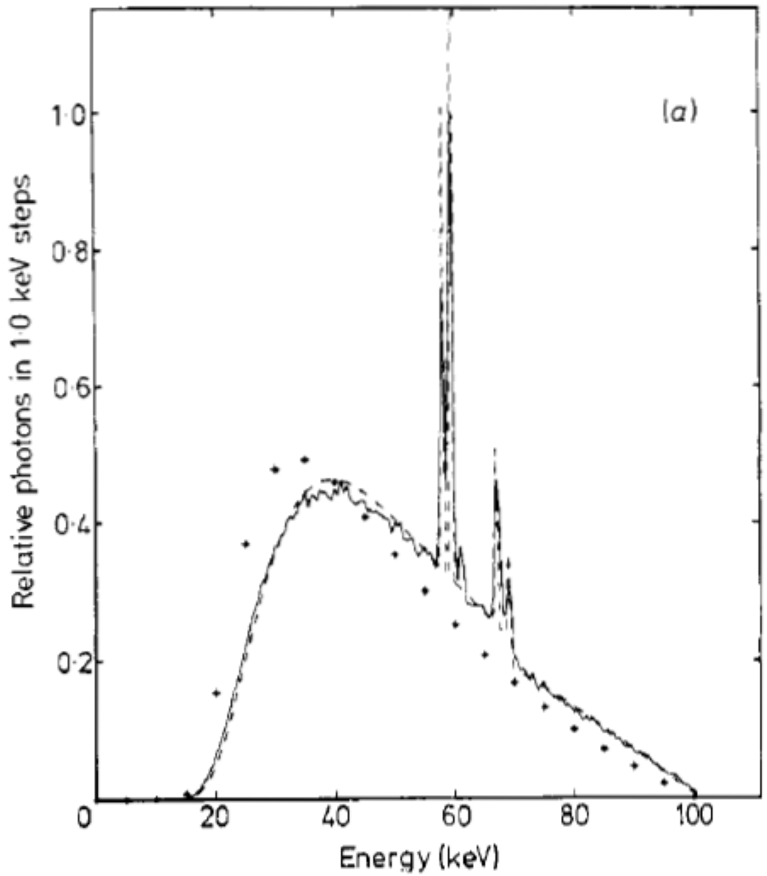
- Energy range: 40 – 300 kVp.

- Energy specified by:
  - HVL (half-value layer) in mm of Al/Cu
  - kVp (peak voltage).

Kilovoltage X-ray beams



X-ray spectrum



Topics to be covered

1. The EGSnrc Monte Carlo code
2. EGSnrc relevant to Nuclear Medicine and PET
3. What you could use?

EGSnrc

- The EGSnrc Monte Carlo system is based on older EGS4 code and developed by the NRC in Canada
- Can model photons and electrons/positrons in the energy range 1 keV to 10 GeV.
- Very well developed and maintained system.
- Incorporated many improvements in both the physics and speed of the system since EGS4
- Website: http://www.irs.inms.nrc.ca/EGSnrc/EGSnrc.html

EGS5 code

- The EGS5 code is based on EGS4 code (EGS3)
- EGS = Electron Gamma Shower, so it only covers photons, electrons and positrons.
- EGS4 code developed at SLAC
- Currently developed at http://rcwww.kek.jp/research/egs/egs5.html

BEAMnrc

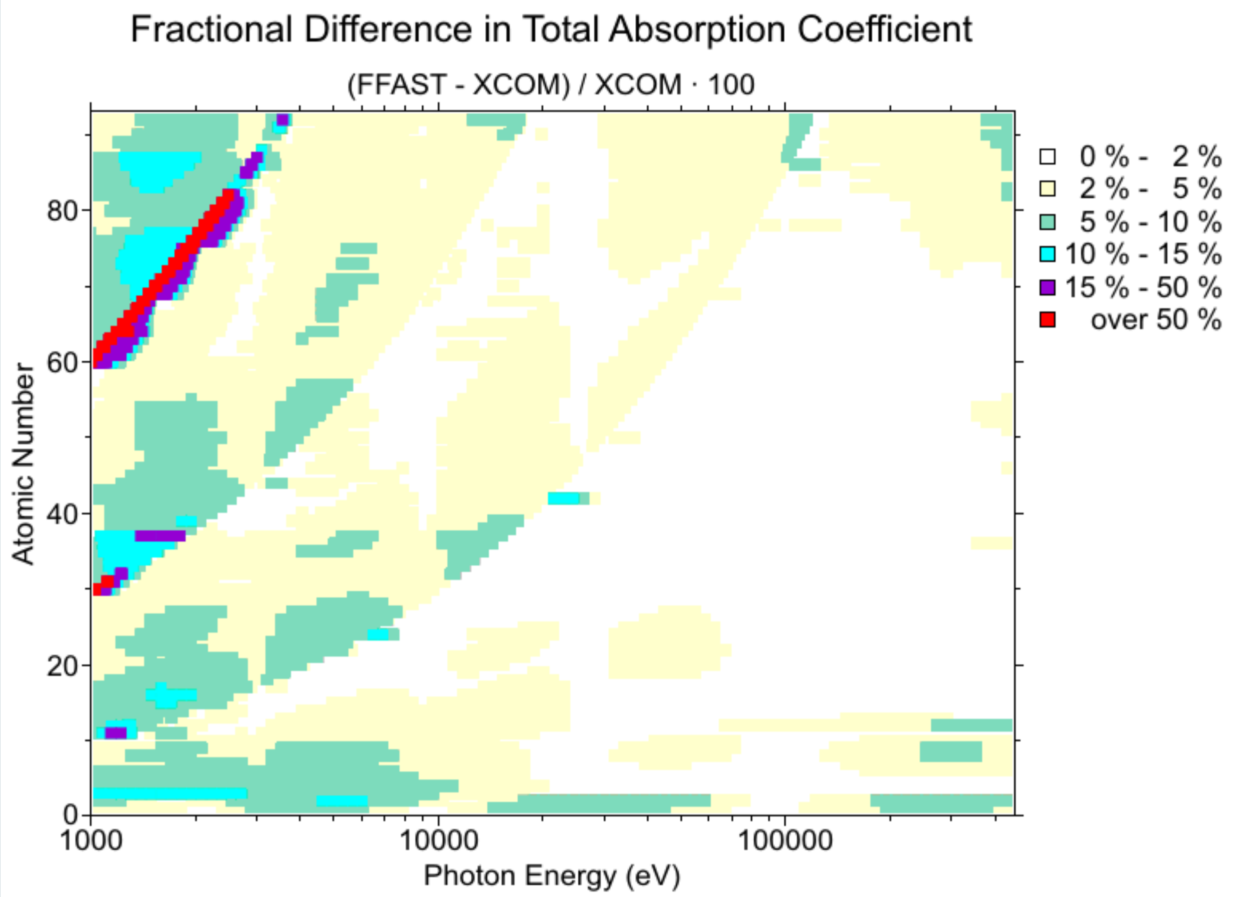
- BEAMnrc is a general purpose Monte Carlo simulation system for modelling radiotherapy sources
- Based on the EGSnrcMP code system for modelling coupled electron and photon transport.
- Provides a whole set of modules in which you can design your linear accelerator or x-ray source.
- Website: http://www.irs.inms.nrc.ca/BEAM/beamhome.html

PENELOPE

- PENELOPE performs Monte Carlo simulation of coupled electron-photon transport in arbitrary materials and complex quadric geometries.
- Written in FORTRAN
- Provides some useful user codes for running your simulations (slab, cylindrical and general geometries)
- Developed from several Spanish universities
- Website:

  http://www.nea.fr/abs/html/nea-1525.html

Cross section data - NIST



http://physics.nist.gov/PhysRefData/Xcom/Text/XCOM.html

EGSnrc and Nuclear Medicine

WHY AND HOW?

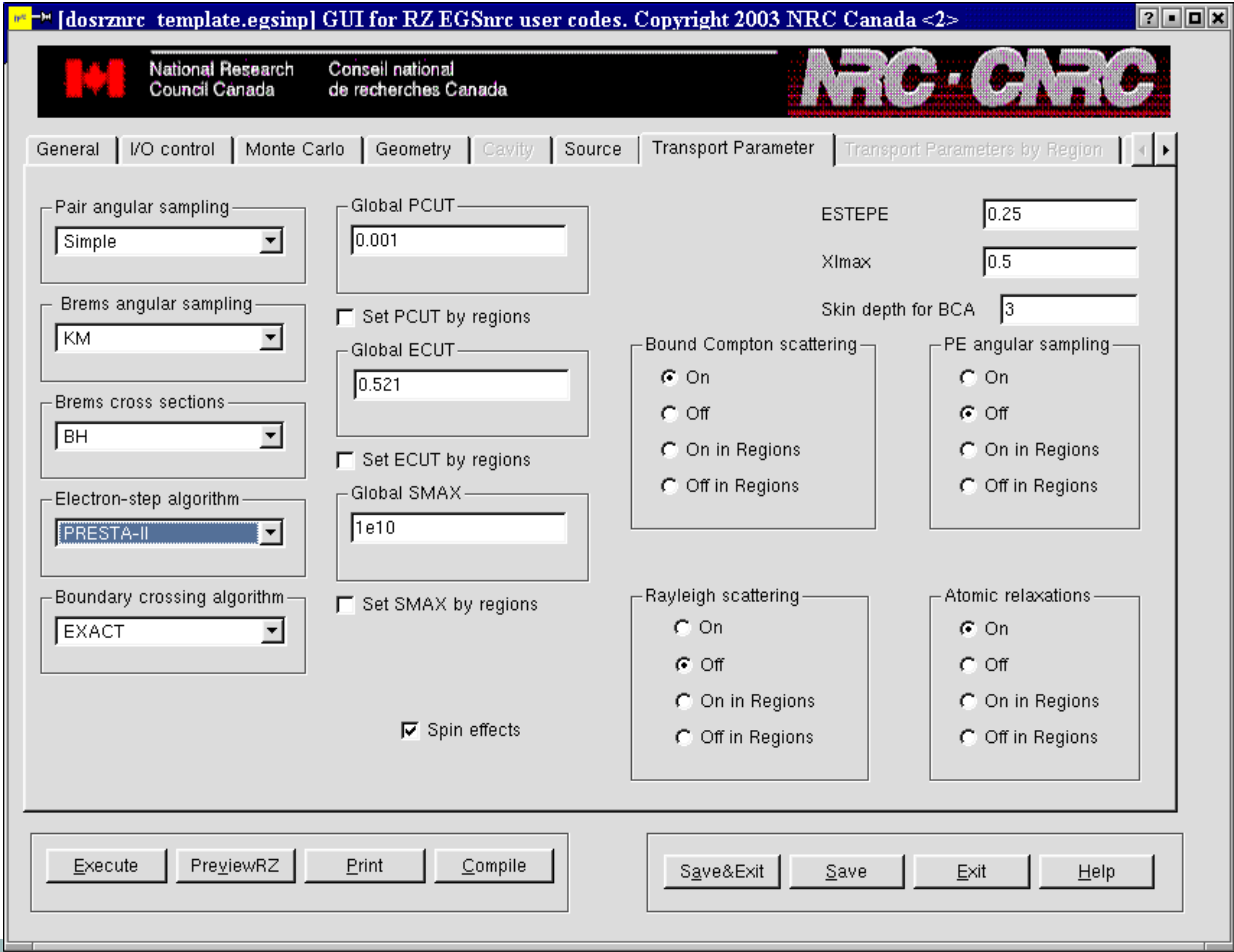
EGSnrc photon calculations

- EGSnrc includes all the relevant interaction processes for low energy photons.
- Has many options available to switch on or off according to the need of the user.
- Does perform the calculations quickly
- See review paper by Verhaegen and Seuntjens in Physics in Medicine and Biology.

EGSnrc photon calculations

- Does not consider radioactive decay.
- Has good documentation and user codes.
- New C++ type library for powerful geometry and source definitions.
- Lots of benchmarking of MC codes

- Note - PENELOPE code is similar, less options and slower.


[dosrznrc_template.egsinp] GUI for RZ EGSnrc user codes. Copyright 2003 NRC Canada <2>
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NRC · CNRC
General
I/O control
Monte Carlo
Geometry
Cavity
Source
Transport Parameter
Transport Parameters by Region
Pair angular sampling
Simple
Brems angular sampling
KM
Brems cross sections
BH
Electron-step algorithm
PRESTA-II
Boundary crossing algorithm
EXACT
Global PCUT
0.001
Set PCUT by regions
Global ECUT
0.521
Set ECUT by regions
Global SMAX
1e10
Set SMAX by regions
Spin effects
ESTEPE
0.25
XImax
0.5
Skin depth for BCA
3
Bound Compton scattering
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Off
On in Regions
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PE angular sampling
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Rayleigh scattering
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PreviewRZ
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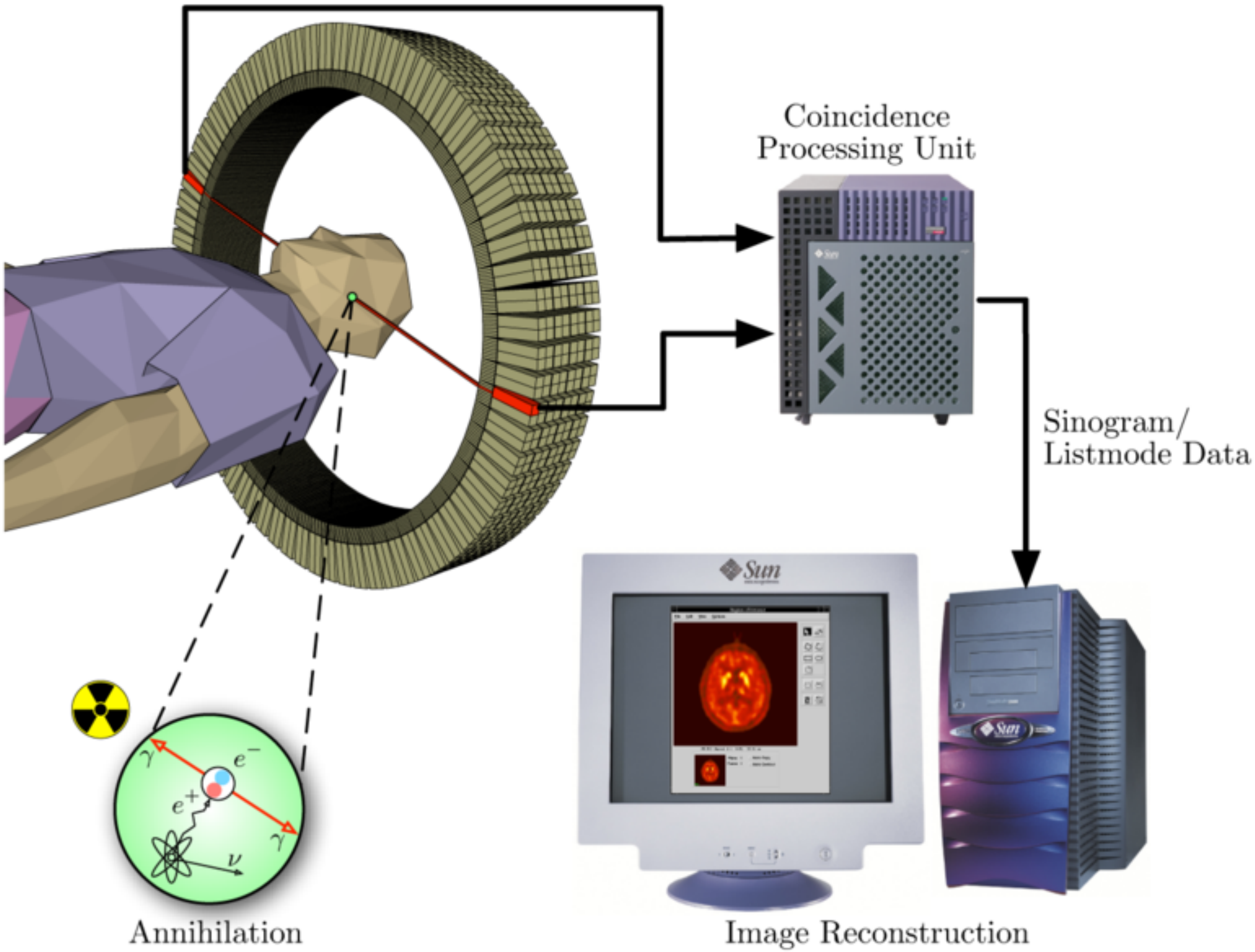
Coincidence
Processing Unit
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e^-
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γ
Annihilation
Image Reconstruction

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Search Terms	Number of hits
EGSnrc and Nuclear Medicine	9
EGS4 and Nuclear Medicine	27
ESGnrc and PET	0
EGS4 and PET	2
EGS4 and Positron Emission Tomography	4
PENELOPE and PET	2

Any relevance?

- Initial impressions are possibly not very good.
- Many publications on detector response using MC techniques.

EGSnrc and Nuclear Medicine

- Accurate dosimetry calculations at lower gamma energies particularly SPECT.
- Similar to low energy x-ray dosimetry in RT.

Table 1

Summary of the radionuclides used and the corresponding gamma-ray emission energies, relative abundance and initial activity

SPECT radionuclide	Half-life	γ-Emission energy (keV), abundance	Initial activity (MBq)
Technetium-99 m (^{99m}Tc)	6.01 h	140 (89%)	396
Iodine-123 (^{123}I)	13.2 h	159 (83%)	60
Iodine-131 (^{131}I)	8.02 d	364 (81%); with additional β^- decay	408
Thallium-201 (^{201}Tl)	3.04 d	75–80[a] (95%), 167 (11%)	102
Indium-111 (^{111}In)	2.80 d	171 (90%), 245 (94%)	269

[a] ^{201}Tl decays by electron capture to mercury-201 (^{201}Hg) with gamma emission energies of 135 keV (3%) and 167 keV (11%). Due to the low abundance of photons, the unresolved ^{201}Hg characteristic X-rays are used for SPECT imaging.

From Brown *et al* (2008) – Applied Radiation Isotopes

Main issues?

- Definition of your source ie. radionuclide within the body.
- How do you specify both the source distribution and subsequent biological changes?
- Unfortunately this is not easily achieved with the current user codes provided with EGSnrc or PENELOPE.

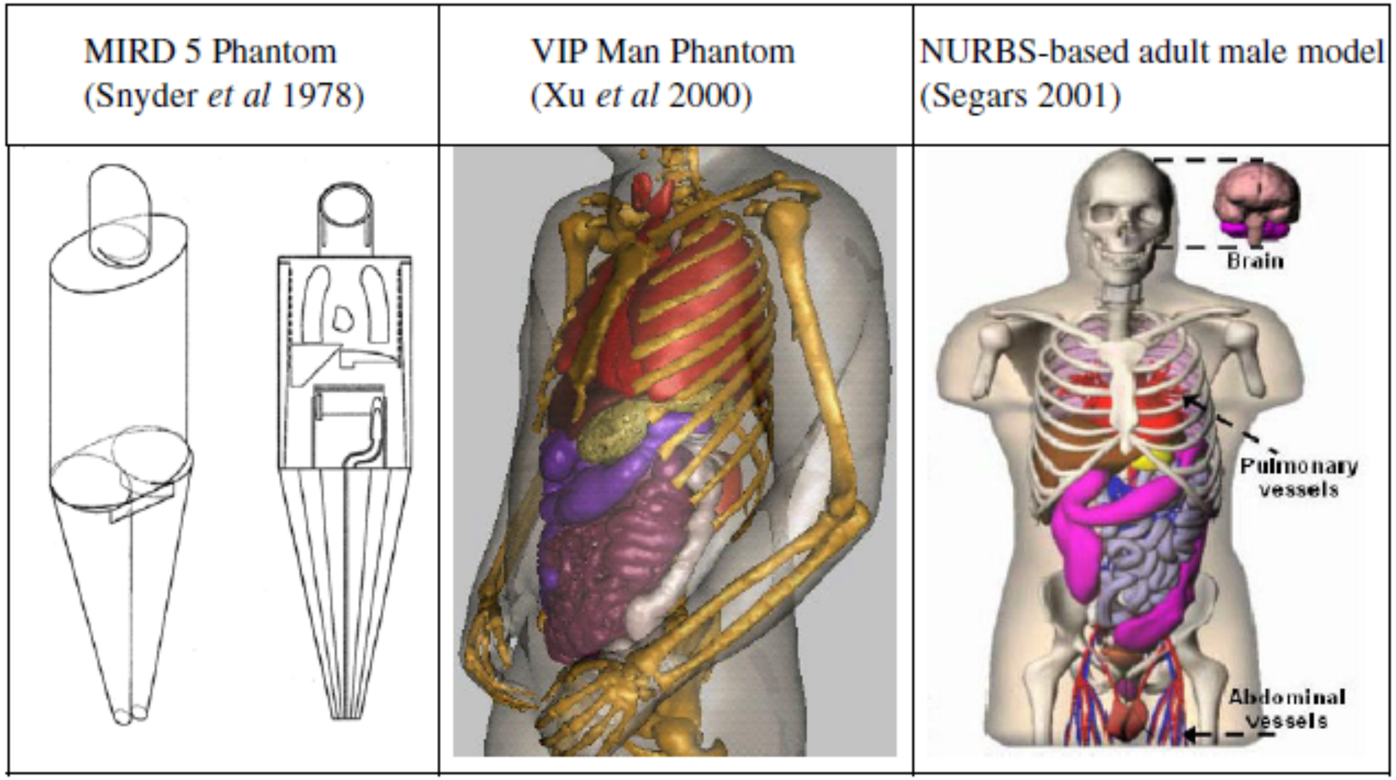


Figure 1. Comparison of the realism of the traditional MIRD body models with those being used to support current dose modelling efforts.

(This figure is in colour only in the electronic version)

Nuclear medicine dosimetry review by Michael Stabin.
Phys. Med. Biol. **51 (2006) R187–R202.**

Current literature

WHAT HAS BEEN ACHIEVED IN THE PAST?

Investigation of scattered radiation in 3D whole-body positron emission tomography using Monte Carlo simulations

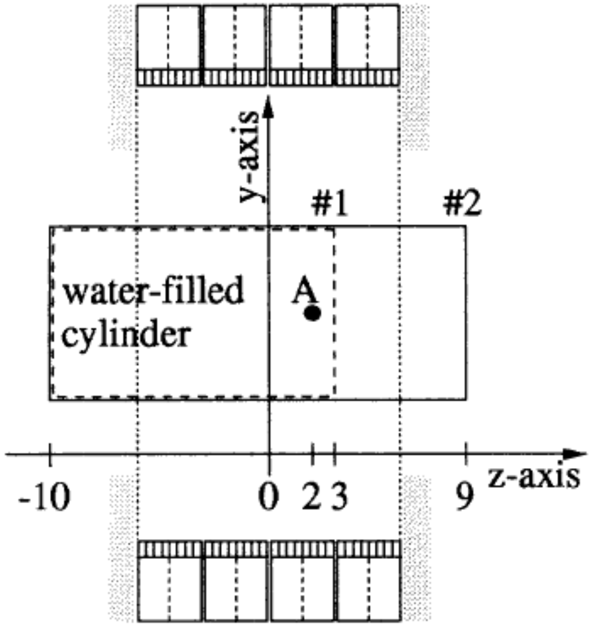


Figure 1. Sketch of the simulated point source in two cylinder phantoms with different axial dimensions. One cylinder (# 1, dashed line) ranges from −10 cm to 3 cm, the other (# 2, full line) from −10 cm to 9 cm. The axial FOV is from −7.76 to 7.76 cm, the source is located at $x = y = 0$ cm and $z = 2$ cm. (Drawing not to scale.)

L-E Adam *et al*, Phys. Med. Biol. **44 (1999) 2879–2895.**

SPECIFIC ABSORBED FRACTION FOR KOREAN ADULT VOXEL PHANTOM FROM INTERNAL PHOTON SOURCE

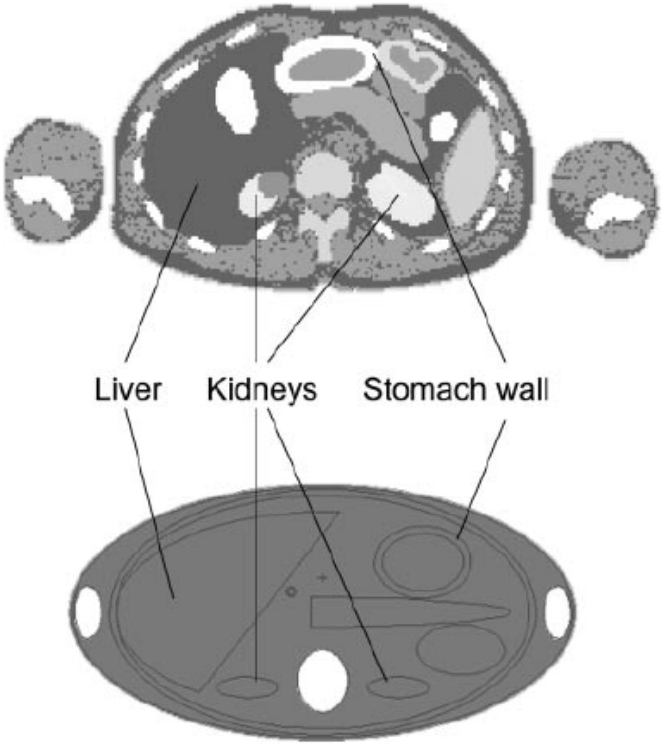
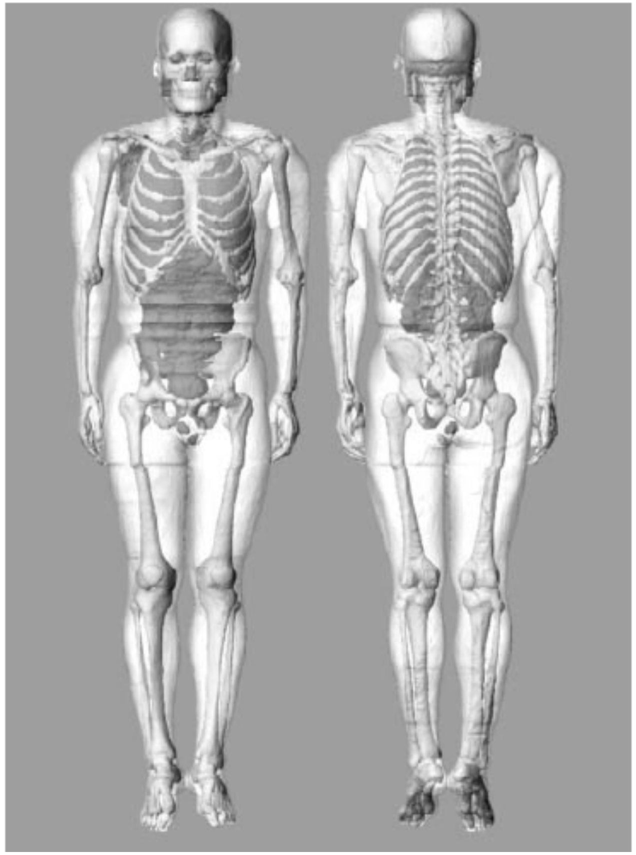


Figure 3. Comparison of inter-organ distance among liver, kidneys and stomach wall in transversal sectioned images obtained from KTMAN-2 and ORNL adult phantom.



C. Lee *et al*, Radiation Protection Dosimetry (2007), Vol. 123, No. 3, pp. 360–368

ESTIMATION OF UNCERTAINTIES ON DOSE CALCULATIONS OF THE 99mTc-MDP-INJECTED PATIENTS IN NUCLEAR MEDICINE

The internal exposures of the patients in nuclear medicine can be calculated based on the equations and data in ICRP Publications 53 and 80. Physical and biological parameters are used for the calculation, and both include uncertainties. Physical parameters can be considered as more precise than biological parameters, so that uncertainties originated from biological parameters are more important. Absorbed fractions (AFs) have been calculated by Monte-Carlo method using medical internal radiation dose (MIRD)-type mathematical phantoms. They depend on the shapes and sizes of the phantoms used in simulations. For estimating shape- and size-related uncertainties, AFs of pairs of source regions and target tissues of the patient-injected ^{99m}Tc-MDP were calculated by using EGS4 codes and a voxel phantom of Japanese male. By simply resizing the voxels of the phantom, the dependencies of size for AFs were calculated, and the uncertainties caused by the cumulated activities in source regions were also estimated by assuming these parameters distributions as Gaussian.

Keiichi Akahane *et al,* Radiation Protection Dosimetry (2007), Vol. 127, No. 1–4, pp. 558–562

A test of water equivalency using gamma ray transmission values

ELSEVIER

Available online at www.sciencedirect.com

ScienceDirect

Radiation Measurements 43 (2008) 1258–1264

Radiation Measurements

www.elsevier.com/locate/radmeas

Evaluation of the water equivalence of solid phantoms using gamma ray transmission measurements

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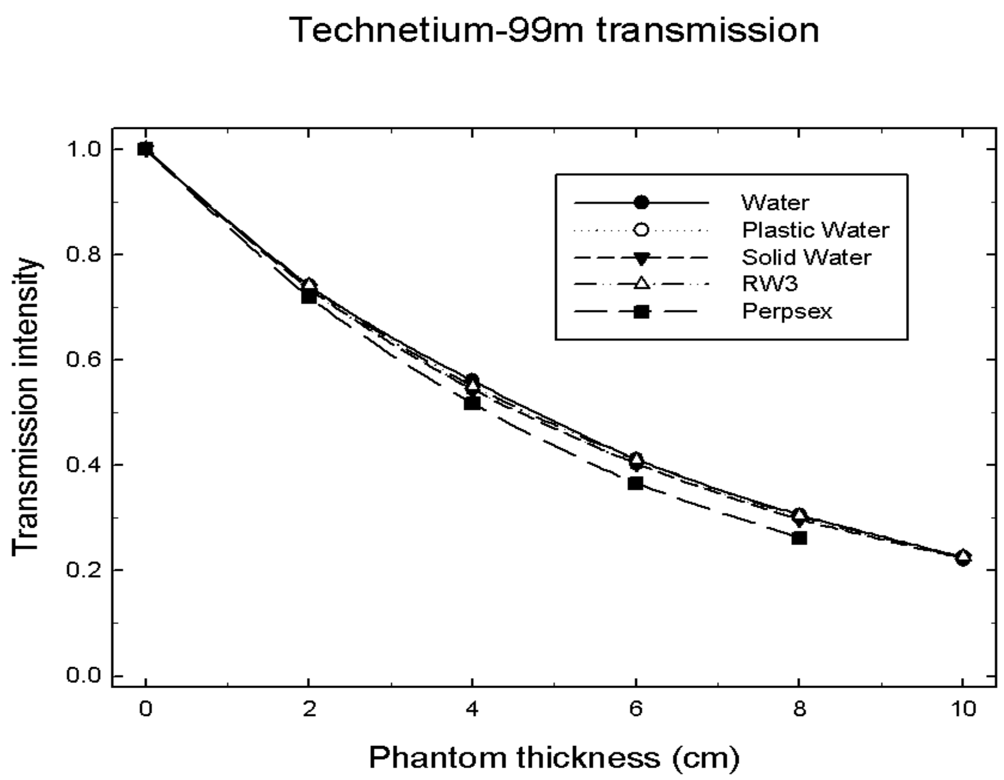
Technetium-99m source

- Tc-99m source: 140.5 keV – main gamma ray
- Phillips Gamma Camera
- ±10% energy window on counting software
- Five phantom materials including water.

Transmission values



- Corrections for decay of source

$$\delta = exp\left(\frac{-t \times ln(2)}{t_{1/2}}\right)$$

- Thickness from 0 – 10 cm.
- Calculated uncertainty: 0.8%

Linear attenuation coefficients

	Water	RMI-457	Plastic Water	RW3	Perspex
$\mu_{Measured}$	0.148	0.151	0.151	0.149	0.166
μ_{EGSnrc}	0.151	0.151	0.152	0.153	0.170
μ_{XCOM}	0.154	0.154	0.155	0.155	0.177

Three sets of linear attenuation coefficient μ:

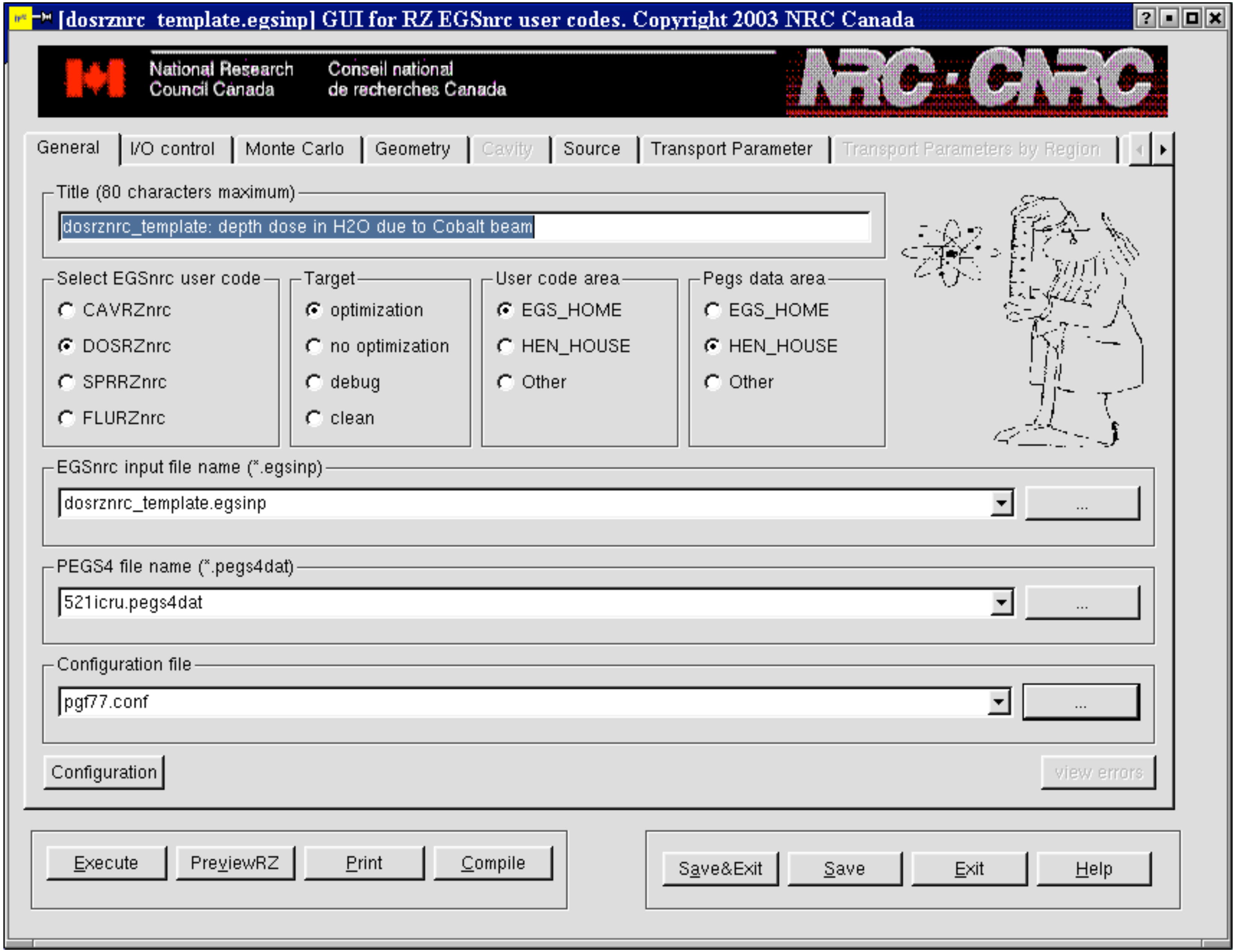
1. Measured
2. EGSnrc calculations
3. XCOM – NIST database

$$I = I_o \times exp(-\mu x)$$

Sigmaplot software used to calculate μ from transmission data.

cf. Midgley paper (Radiation Physics and Chemistry) 2005 – agreed with XCOM.

How to use EGSnrc for Nuclear Medicine applications?



[dosrznrc template.egsinp] GUI for RZ EGSnrc user codes. Copyright 2003 NRC Canada
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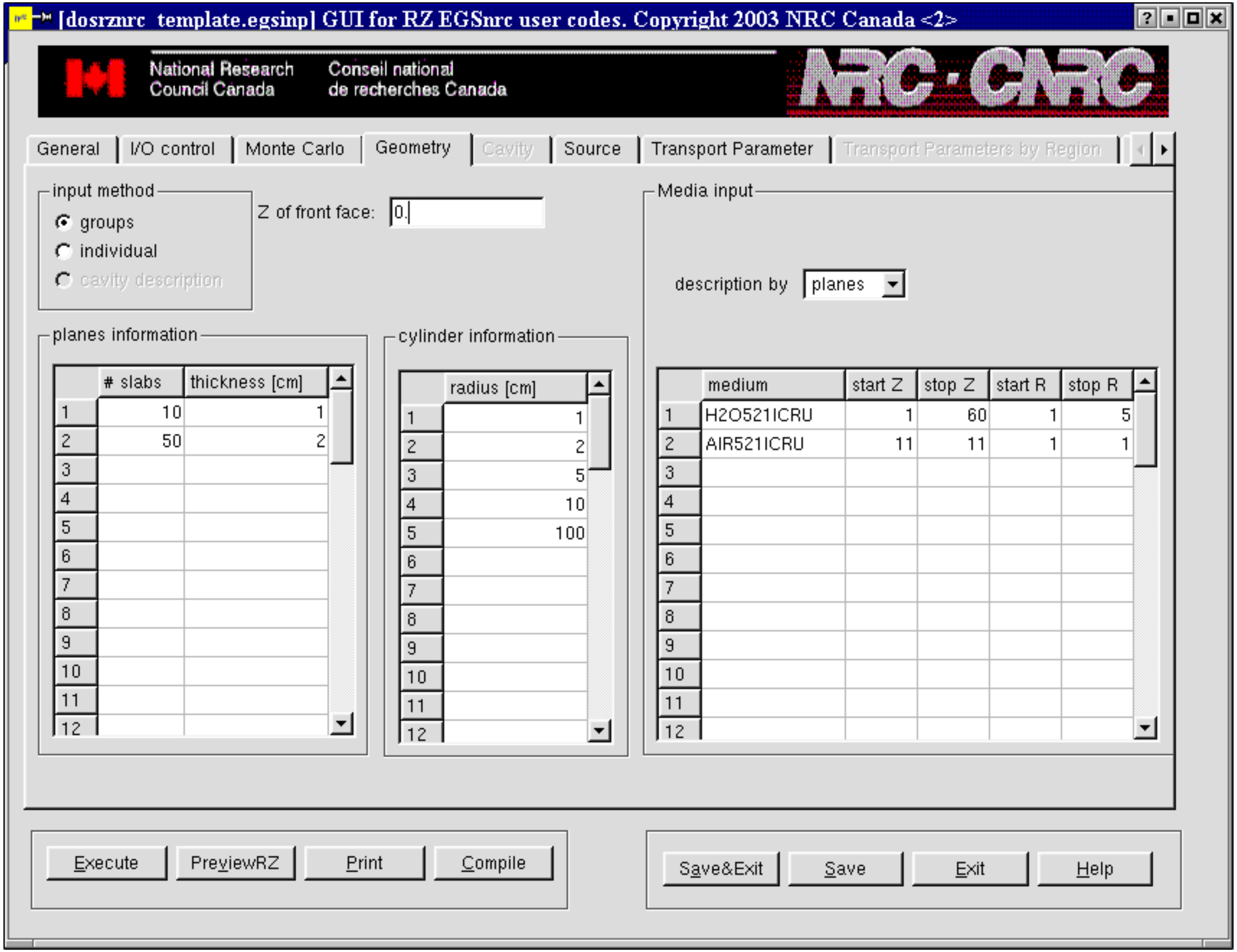
NRC·CNRC
General
I/O control
Monte Carlo
Geometry
Cavity
Source
Transport Parameter
Transport Parameters by Region
Title (80 characters maximum)
dosrznrc_template: depth dose in H2O due to Cobalt beam
Select EGSnrc user code
CAVRZnrc
DOSRZnrc
SPRRZnrc
FLURZnrc
Target
optimization
no optimization
debug
clean
User code area
EGS_HOME
HEN_HOUSE
Other
Pegs data area
EGS_HOME
HEN_HOUSE
Other
EGSnrc input file name (*.egsinp)
dosrznrc_template.egsinp
PEGS4 file name (*.pegs4dat)
521icru.pegs4dat
Configuration file
pgf77.conf
Configuration
view errors
Execute
PreviewRZ
Print
Compile
Save&Exit
Save
Exit
Help



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General
I/O control
Monte Carlo
Geometry
Cavity
Source
Transport Parameter
Transport Parameters by Region
input method
groups
individual
cavity description
Z of front face:
0.
Media input
description by
planes
planes information
slabs
thickness [cm]
1 10 1
2 50 2
cylinder information
radius [cm]
1 1
2 2
3 5
4 10
5 100
medium
start Z
stop Z
start R
stop R
1 H2O521ICRU 1 60 1 5
2 AIR521ICRU 11 11 1 1
Execute
PreviewRZ
Print
Compile
Save&Exit
Save
Exit
Help

egspp: the EGSnrc C++ class library

I. Kawrakow
Ionizing Radiation Standards
National Research Council of Canada
Ottawa, K1A OR6

April 2005

NRCC Report PIRS-899

egspp: the EGSnrc C++ class library

- Development of a C++ library system for EGSnrc
- Allows use of complex geometries
- Allows easy development of your own user code that is applicable to the problem you are solving.

Application of egspp

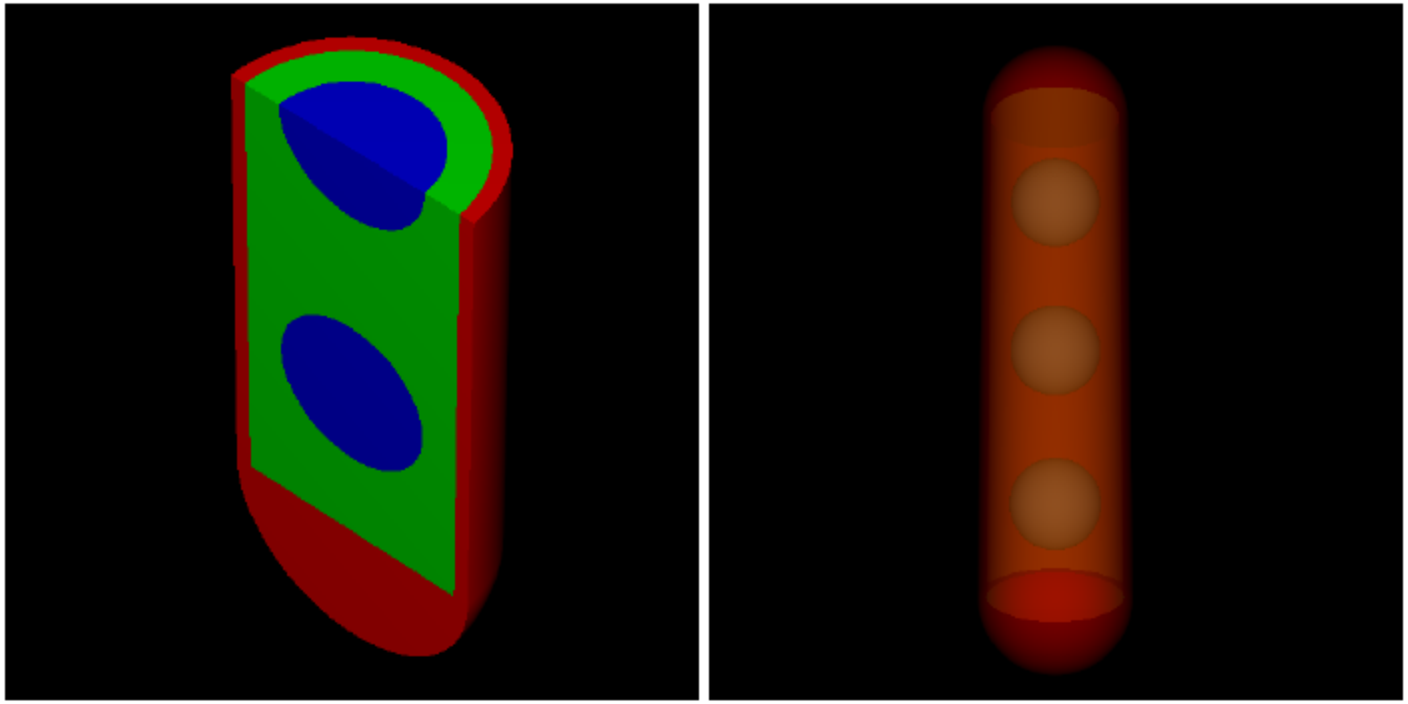

Figure 6: A visualization of the brachytherapy seed geometry defined in I6702.inp. On the left the geometry is cut by a xz- and a yz-plane to be able to see the inside of the seed. On the right a similar effect is achieved by making the seed walls and the air semi-transparent.

- A Gaussian spectrum. Defined via

```
:start spectrum:
    type = Gaussian
    energy = the mean kinetic energy
    sigma = the sigma of the spectrum
    or
    fwhm = the full-width-at-half-maximum of the spectrum
:stop spectrum:
```

```
:start shape:
    library = egs_circle
    radius = the circle radius
    midpoint = Ox, Oy (optional)
    inner radius = the inner radius (optional)
:stop shape:
```

```
:start source:
    library = egs_point_source
    name = some_name
    position = Px, Py, Pz
    :start spectrum:
        definition of the spectrum
    :stop spectrum:
    charge = -1 or 0 or 1 for electrons or photons or positrons
:stop source:
```

Defining your sources

3.11 A source collection

A source collection consists of an arbitrary number N of any other sources $s_1, s_2, ..., s_N$ with weights of $w_1, w_2, ..., w_N$ and delivers particles from s_j with probability w_j. A source collection is defined using

```
:start source:
    library = egs_source_collection
    name = some_name
    source names = list of names of previously defined sources
    weights = list of weights for the sources
:stop source:
```

Defining your sources (2)

3.12 Implementing your own source

If none of the above sources satisfies the needs of your application, you can implement your own source by deriving from the `EGS_BaseSource` or `EGS_BaseSimpleSource` class, implementing the few required methods and compiling your source into a DSO. Any of the above sources can be used as a template. A detailed discussion of all methods that must be implemented goes beyond the scope of this user manual and is left for a separate developers manual (in preparation).