External radiation doses to biota:
Monte Carlo dose model calculations

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Abstract. Realistic and reliable dose models are required to estimate the radiological risks to non-human biota, in regions contaminated by radioactivity. To facilitate detailed dose calculations, a graphical user interface has been developed to the Monte Carlo N-Particle Transport code (MCNP): the TADPOLE editor (Terrestrial and Aquatic Dose assessment Program for Organisms in their Local Environment). The editor is intended for site and biota specific analyses of absorbed dose from external γ- and β- radiation.

An experiment was performed in controlled, laboratory conditions as a first validation of the calculation models assigned by the editor. Measurements with TL-dosimeters yielded lower doses than was calculated by MCNP5 through the editor.

KEYWORDS: Radioecology; Monte Carlo; MCNP; Non-human biota; Software tool

INTRODUCTION

Release of anthropogenic radionuclides into the environment constitutes a risk for populations of animals and plants. Assessments of radiological risks to biota in areas with high levels of radioactivity, call for reliable and realistic calculation models.

The Monte Carlo N-Particle Transport Code (MCNP) is a commonly used, general purpose Monte Carlo code system for radiation transport (X-5 Monte Carlo Team, 2003). It features a geometry package that enables complex problems to be modelled. The performance of MCNP has been thoroughly benchmarked with experiments and other calculation methods (Brown, Sweezy, Bull, & Sood, 2008) (Mosteller, 2003). Due to the generality of MCNP, some effort and experience may be required to define a specific problem accurately and efficiently.

The TADPOLE editor (Terrestrial and Aquatic Dose assessment Program for Organisms in their Local Environment) is a graphical user interface for MCNP5. It has been developed to make the advantages of Monte Carlo calculations more accessible to non-experienced users in the field of radioecology.

The editor enables site-specific absorbed dose calculations from external radiation, with no requirements of prior Monte Carlo experience. The user has large freedom of choice in specifying problem geometry, materials and the energy spectra of the radioactive soil or sediment.

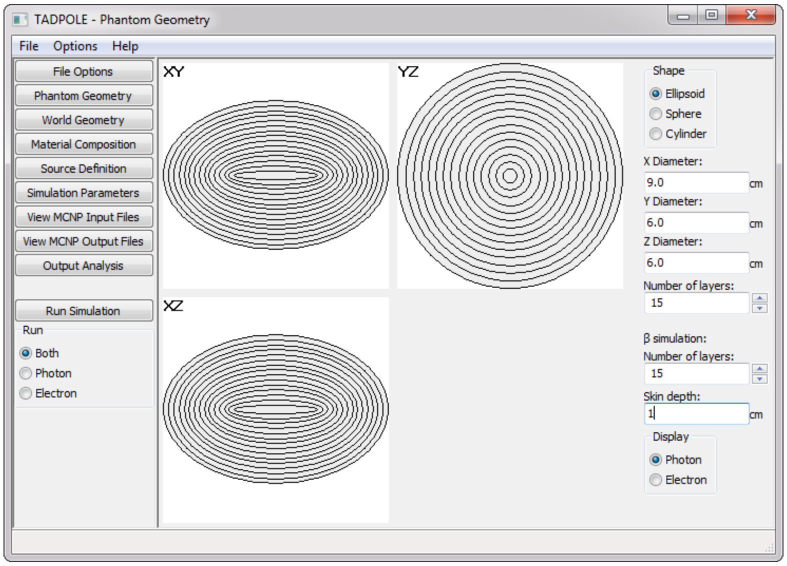
THE TADPOLE EDITOR FOR MCNP5

The purpose of the TADPOLE editor is to facilitate radioecological Monte Carlo dose calculations. It has been developed with the aim to preserve as much as possible of the generality of MCNP5, without compromising with usability.

Parameters that define the problem are prepared in a text file which is used as input to the MCNP code system. The editor is capable to produce input files, initiate calculations and process the output files to yield depth doses in the organism. It is written in the Python programming language, using the wxPython toolkit. This makes the editor platform independent; it works on Windows as well as Linux based systems. No installation is required other than possible adjustments of paths to decay data files.

The editor models an exposure situation with an organism positioned in or upon a radiation emitting medium, e.g. soil or sediment. The structure of TADPOLE is a menu system, where the user defines problem parameters. Input files to MCNP5 are then produced based on these choices.

Figure **1** shows the Phantom Geometry menu. This is where the shape and size of the organism is defined. The shape can be a sphere, ellipsoid or cylinder of any size. To calculate the absorbed dose as a function of depth, the organism is divided in an optional number of shells. For each shell, a mean value of deposited energy will be scored with the pulse-height tally, *F8 in MCNP5. Based on the energy deposition, TADPOLE derives absorbed dose per day as a function of depth. The example in *Figure* **1** shows an ellipsoidal organism with 10 symmetrical shells.



Run
● Both
○ Photon
○ Electron

Shape
● Ellipsoid
○ Sphere
○ Cylinder

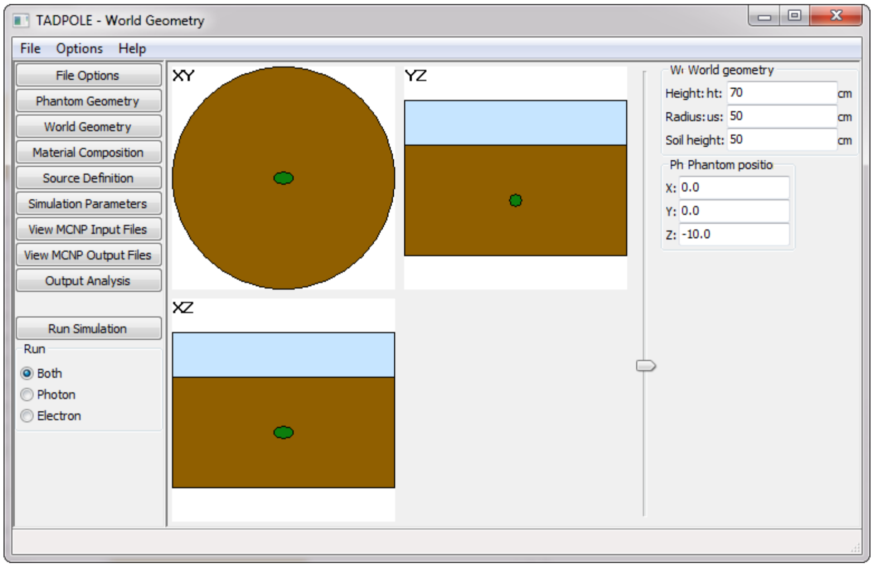
X Diameter: 9.0 cm
Y Diameter: 6.0 cm
Z Diameter: 6.0 cm
Number of layers: 15

β simulation:
Number of layers: 15
Skin depth: 1 cm

Display
● Photon
○ Electron

Figure 1. The Phantom Geometry menu of the TADPOLE editor.

Figure 2 illustrates the simulation geometry. This is the World Geometry menu where the size of the surrounding medium and the position of the organism are selected. The world geometry can be seen in the graphics window where the surrounding medium (i.e. soil or sediment) is brown, the organism is green and the upper portion of the medium (i.e. air or water) is blue.



Run
● Both
○ Photon
○ Electron

W‹ World geometry
Height: ht: 70 cm
Radius: us: 50 cm
Soil height: 50 cm

Ph Phantom positio
X: 0.0
Y: 0.0
Z: -10.0

Figure 2. Screenshot from the World Geometry menu.

Interaction of ionizing radiation with matter depends, among other things, on the atomic composition and mass density of the matter. These properties are set in the Material Composition menu, for all the materials present in the problem. It is possible to vary the material properties of the radioactive medium with depth.

Absorbed dose calculations are performed for both γ-rays and β-particles. However, MCNP5 cannot start two different particle types in the same run (as to version 1.51). Therefore, two different input files are generated; one to estimate the dose contribution from γ-rays and one for β-particles. The results from the two calculations can be combined and viewed in the Output Analysis menu.

In reality, the activity concentration in soil or sediment is rarely homogenous. Anthropogenic radionuclides may have a different depth distribution than naturally occurring radionuclides. These aspects can be considered in the Source Definition menu; see **Error! Reference source not found.**. Here, all the radionuclides that are present and their activity concentrations are defined for different depths. The photon emitting radionuclides that are possible to choose comprise those 1252 listed in Publication 107 from the International Commission on Radiological Protection (ICRP, 2008). Beta spectra are taken from the Radiation Dose Assessment Resource, RADAR[1] (Stabin & Lydia, 2002), which contains 850 radionuclides. Besides particular radionuclides, also entire decay chains can be selected.

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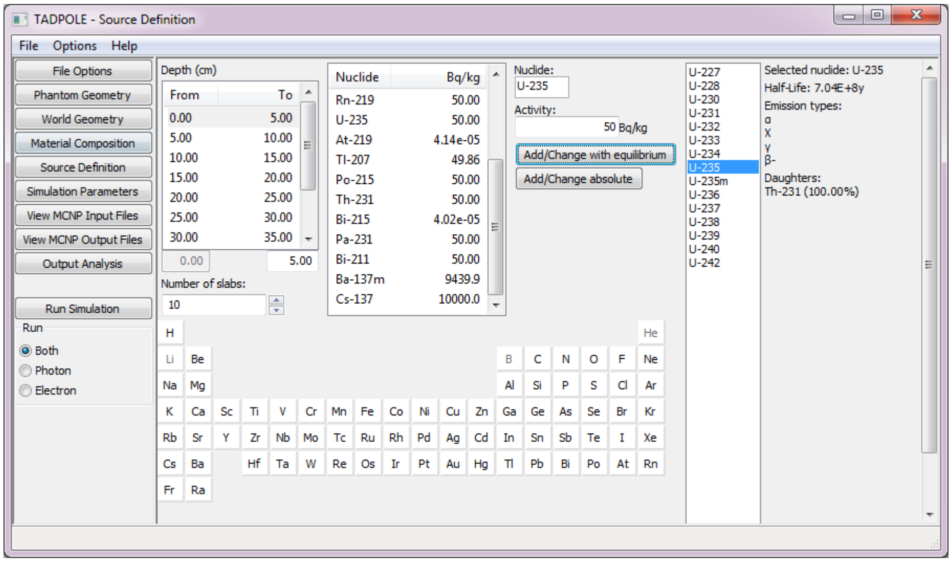
[1] http://www.doseinfo-radar.com/



Depth (cm)

From	To
0.00	5.00
5.00	10.00
10.00	15.00
15.00	20.00
20.00	25.00
25.00	30.00
30.00	35.00

0.00 5.00

Number of slabs: 10

Run

● Both
○ Photon
○ Electron

Nuclide	Bq/kg
Rn-219	50.00
U-235	50.00
At-219	4.14e-05
Tl-207	49.86
Po-215	50.00
Th-231	50.00
Bi-215	4.02e-05
Pa-231	50.00
Bi-211	50.00
Ba-137m	9439.9
Cs-137	10000.0

Nuclide: U-235

Activity: 50 Bq/kg

U-227
U-228
U-230
U-231
U-232
U-233
U-234
U-235
U-235m
U-236
U-237
U-238
U-239
U-240
U-242

Selected nuclide: U-235
Half-Life: 7.04E+8y
Emission types:
α
X
γ
β-
Daughters:
Th-231 (100.00%)

Figure 3. Source Definition menu, where the activity concentrations of different radionuclides can be defined as a function of depth in the radioactive medium.

VALIDATION EXPERIMENT

To validate the Monte Carlo calculation model used by the TADPOLE editor, an experiment was performed under controlled conditions. Ellipsoidal, frog-like phantoms, made of PMMA[2] were prepared with TL-dosimeters. Close to the surface of the phantom, stacks of four 0.13 mm thin TL-chips (LiF:Mg,Ti + PTFE, diameter 4.5 mm, Teledyne Isotopes) were used to evaluate absorbed dose from β-particles. At larger depth, thicker TL-chips were used (LiF:Mg,Ti, diameter 4.5 mm, thickness 0.9 mm, Mirion Technologies (Rados) Oy). *Figure* ***4*** shows a photograph and a schematic image of the phantom.

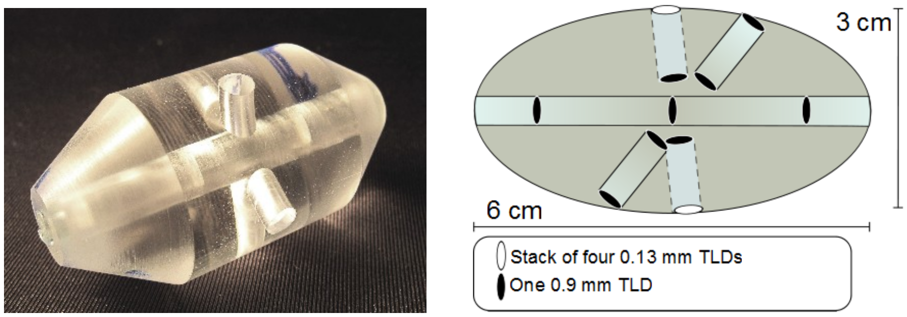


Figure 4. Left: Photograph of a frog phantom that was used in the validation experiment. *Right:* Schematic illustration of the frog phantom with TLD positions indicated.

Three frog phantoms were positioned at various depths in a homogenous medium of KNO_3. According to the manufacturer, the activity concentration of ^{40}K in the medium was 12.1 kBq/kg. Figure 5 shows the experimental setup with the barrel that contained the radioactive medium. The radius of the barrel was 28.35 cm and it contained KNO_3 up to 62 cm height. The irradiation lasted 50 days after which the TL-dosimeters were read out.

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[2] Poly(methyl methacrylate)

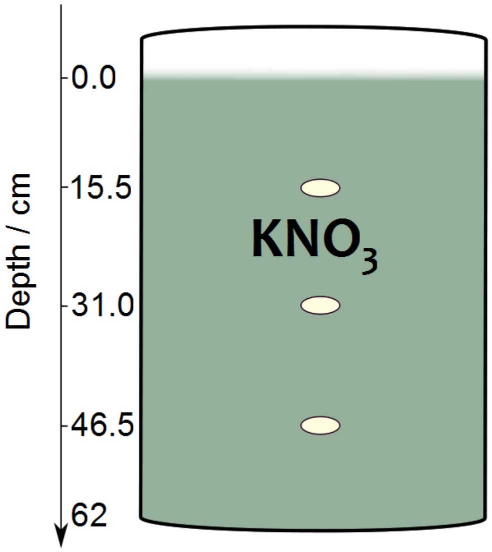

Figure 5. Schematic illustration of the setup used in the validation experiment. Three PMMA phantoms (white ellipses) were positioned at different depth in the homogeneous medium (green).

The experiment was reproduced with the TADPOLE editor and the doses calculated with MCNP5. A homogeneous medium of KNO_3 was defined, ignoring the surrounding steel barrel. The phantoms were modelled as ellipsoids of PMMA. The energy deposited was tallied in 10 symmetrical shells in the γ-calculation. In the β-calculation, 25 shells were used for the outermost 0.5 cm, and 1 shell from 0.5 to 1.5 cm. The β-simulation was performed with the organism in the centre of a soil cylinder of 6 cm radius and 9 cm height, providing a medium layer of approximately 7 to 8 CSDA-ranges for the highest β-energy of ^{40}K. For each of the three phantoms, the calculated dose contributions from β-particles and γ-rays were combined and compared to doses derived from TLD measurements.

RESULTS

Figure 6 shows a comparison between absorbed doses derived by TLD measurements, and those calculated with MCNP5 through the TADPOLE editor for the phantom at 46.5 cm depth. The results for the other two phantoms showed similar results.

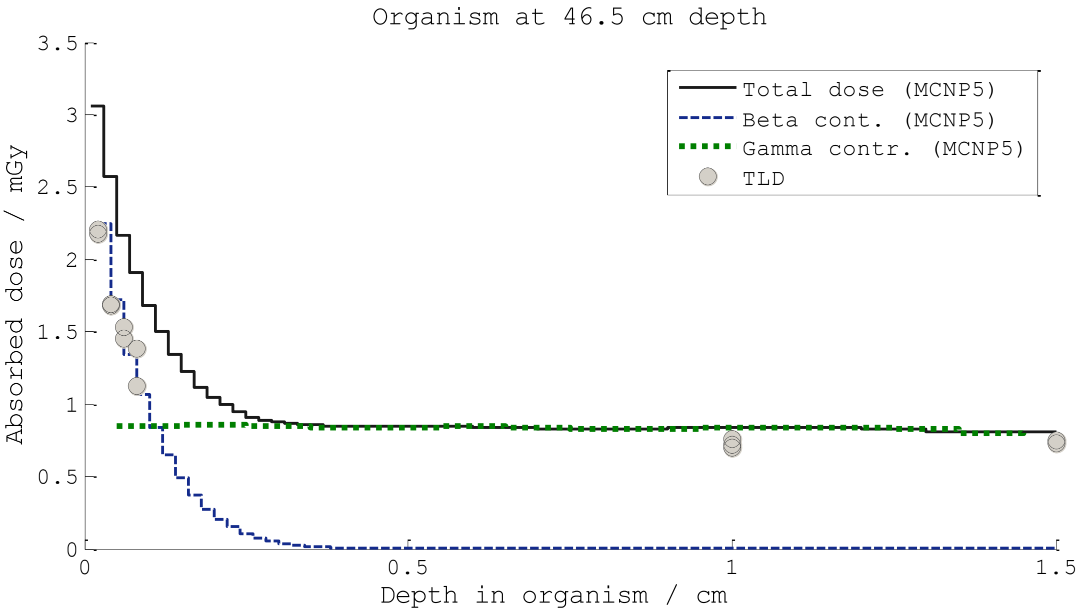

Figure 6. Comparison between calculated depth doses and doses derived from TLD measurements, for the phantom at 46.5 cm depth. The dose contributions from β-particles and γ-rays are also plotted separately.

DISCUSSION

In the experiment that was performed to validate the dose models produced by TADPOLE, the TLD measurements resulted in lower doses than the calculation. For the outermost skin layer, from 0.00 to 0.02 cm, the TLD measurements yielded 2.4 mGy, while the corresponding calculated value was 3.1 mGy.

A contributing reason to this deviation may be the thin plastic film that was wrapped around the phantoms in order to fix the positions of the shallow dosimeters. This layer of film was not taken into account in the Monte Carlo calculations. The deviating results could also be due to that the activity concentration of ^{40}K was derived from the potassium content stated by the manufacturer. Gamma spectrometry is planned to control the ^{40}K activity concentration, but not yet performed.

The editor calculates absorbed doses from external radiation. In reality, contributions to absorbed dose will also come from inhaled or ingested radionuclides. Thus, it may also be relevant to consider internal doses when assessing radiological hazards to biota. The possibility to estimate internal doses is a feature that may be implemented in future versions of the editor.

Besides the validation experiment reported here, another more extensive experiment has been performed but not yet analysed. Frog and worm phantoms of PMMA were exposed in the soil of Utnora, Sweden. This area was exposed to high levels of radioactive fallout after the Chernobyl accident. During this second experiment, activity concentrations of ^{137}Cs up to 20 kBq/kg have been quantified from gathered soil samples.

A more in depth comparison of the TADPOLE editor with other software for dose calculations for non-human biota is planned for the autumn of 2011.

CONCLUSIONS

A graphical user interface has been developed to MCNP5 to facilitate dose calculations from external, radioactive sources to organisms in environments contaminated with radioactivity. The editor produces input files, initiates calculations and assists in normalization and analysis of the calculation results.

In the first validation experiment, the doses derived from TLD-measurements were lower than the calculated doses. A second, more extensive, validation experiment has been performed and is under analysis.

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