EURADOS Intercomparison on the Usage of the ICRP/ICRU Adult Reference Computational Phantoms

Maria Zankl1,\*, Jonathan Eakins2, José-María Gómez Ros3, Christelle Huet4, Jan Jansen2, Montserrat Moraleda3, Uwe Reichelt5, Lara Struelens6, Tomas Vrba7

1 Helmholtz Zentrum München (GmbH) German Research Center for Environmental Health, Institute of Radiation Medicine, Ingolstädter Landstr. 1, 85764 Neuherberg, Germany

2 United Kingdom Health Security Agency, Chilton, UK

3 CIEMAT – Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas, Madrid, Spain

4 Institut de Radioprotection et de Sûreté Nucléaire, Fontenay-aux-Roses, France

5 Technical University Dresden, Dresden, Germany

6 SCK CEN – Belgian Nuclear Research Centre, Mol, Belgium

7 Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University in Prague, Prague, Czech Republic

\*Corresponding author: zankl@helmholtz-muenchen.de

**Abstract**—The European Radiation Dosimetry Group, EURADOS, has organised an intercomparison study on the usage of the ICRP/ICRU voxel reference computational phantoms together with radiation transport codes. Voluntary participants have been invited to solve specific tasks and provide solutions to the organisers before a certain deadline. The tasks to be solved are of practical interest in occupational, environmental and medical dosimetry. The aims of this training activity were to investigate if the phantoms have been correctly implemented in the radiation transport codes and to give the participants the opportunity to check their own calculations against quality-assured master solutions and improve their approach, if needed.

Keywords — intercomparison; reference computational phantoms; radiation transport codes; training

1. Introduction

EURADOS, the European Radiation Dosimetry Group, is a network of more than 75 European institutions and 600 scientists coordinated in working groups that – among other activities – organises scientific meetings and training activities as well as intercomparison and benchmark studies.

Since most radiation transport codes are rather complex, many – especially novice – users are applying them as “black boxes”, sometimes failing to realise whether the parameters chosen are indeed suitable for the tasks to be solved. This is one of the reasons why EURADOS aims at improving this situation by organising intercomparison studies (Broggio et al., 2012; Gómez-Ros et al., 2008; Gualdrini et al., 2005; Price et al., 2006; Siebert et al., 2006; Tanner et al., 2004; Vrba et al., 2015; Vrba et al., 2014), in which participants are invited to solve proposed computational tasks and check their results against both quality-assured master solutions provided by EURADOS and the solutions of other participants.

EURADOS Working Group 6 “Computational Dosimetry” recently organised an intercomparison study on the usage of the ICRP/ICRU adult reference computational phantoms (ICRP, 2009) that aimed to investigate whether participants were able to correctly combine the phantoms with the radiation transport codes used, and if they were able to correctly apply ICRP guidance on the evaluation of specific dosimetric quantities such as organ equivalent dose (in particular for the red bone marrow) (ICRP, 2010) and effective dose (ICRP, 2007). The purpose of this article is to summarise the general aspects of the intercomparison exercise.

1. Methods and Materials

2.1 Phantoms

Two phantoms of the human body were to be used in the intercomparison exercise. These are the male and female adult reference computational phantoms as described in ICRP Publication 110 (ICRP, 2009). The phantoms are based on the voxel models “Golem” (Zankl and Wittmann, 2001) and “Laura” (Zankl et al., 2005), which are in turn based on medical image data of real people whose body height and mass resembled the reference anatomical and physiological parameters for both male and female subjects given in Publication 89 (ICRP, 2002). For construction of the reference phantoms, several modification steps were applied to the segmented phantoms Golem and Laura. These were:

* voxel scaling to match reference height and reference skeleton mass;
* inclusion of further anatomical details, such as a greater amount of blood vessels, bronchi, and lymphatic nodes;
* sub-segmentation of the skeleton;
* matching the organ masses of both models to the ICRP data on the adult Reference Male and Reference Female without compromising their anatomic realism;
* adjusting the whole-body masses to 73 and 60 kg for the male and female reference computational phantoms, respectively, by “wrapping” the body with additional layers of adipose tissue.

The main characteristics of the adult male and female reference computational phantoms are summarised in Table 1.

Table 1: Main characteristics of the adult male and female reference computational phantoms (ICRP, 2009)

|  |  |  |
| --- | --- | --- |
| Property | Male | Female |
| Height (m) | 1.76 | 1.63 |
| Mass (kg) | 73.0 | 60.0 |
| Number of tissue voxels | 1946375 | 3886020 |
| Slice thickness (voxel height, mm) | 8.0 | 4.84 |
| Voxel in-plane resolution (mm) | 2.137 | 1.775 |
| Voxel volume (mm3) | 36.54 | 15.25 |
| Number of columns | 254 | 299 |
| Number of rows | 127 | 137 |
| Number of slices | 220 (+2)a) | 346 (+2) a) |

a) Additional slices of skin at the top and bottom to cover structures other than skin of the head and feet in the top and bottom slices

The skeleton is composed of cortical bone, trabecular bone, active (red) and inactive (yellow) bone marrow, cartilage and endosteal tissues. The dimensions of internal structures of most of these tissues are in the order of micrometres and therefore much smaller than the resolution of a normal CT (computed tomography) scan (order of millimetres). Thus, these volumes could not be ‘segmented’, i.e. resolved into distinct voxelized regions. Instead, an alternative scheme had to be developed in order to represent the gross spatial distributions of the various bone tissues as realistically as possible for the given voxel resolution (Zankl et al., 2007). For this purpose, the skeleton was divided into those nineteen bones and bone groups for which individual data on red bone marrow content and marrow cellularity are given in ICRP Publication 70 (ICRP, 1995). These bones are: upper halves of humeri, lower halves of humeri, lower arm bones (ulnae and radii), wrists and hand bones, clavicles, cranium, upper halves of femora, lower halves of femora, lower leg bones (tibiae, fibulae and patellae), ankles and foot bones, mandible, pelvis (os coxae), ribs, scapulae, cervical spine, thoracic spine, lumbar spine, sacrum, and sternum. These were then sub-segmented into an outer shell of cortical bone and the enclosed spongiosa part of the bone. The long bones contain a medullary cavity as a third component which is enclosed by cortical bone. This sub-division resulted in 44 different ‘identification numbers’ (i.e. distinct tissue regions) in the skeleton: two – cortical bone and spongiosa – for each of the nineteen bones mentioned above, and a medullary cavity for each of the six long bones (upper and lower half of humeri, lower arm bones, upper and lower half of femora, and lower leg bones). Furthermore, the amount of cartilage that could be identified on the CT images and could, thus, be segmented directly, was attributed to four body parts – head, trunk, arms and legs. Hence, the skeleton covers a total of 48 individual identification numbers.

For each bone (group), the spongiosa region encompasses red bone marrow, yellow bone marrow, and trabecular bone. The reference values of the total amount of red marrow (ICRP, 1995, 2002) and its percentage distribution among individual bones, as given in ICRP Publications 70 and 89 based on earlier data of Cristy (Cristy, 1981), permit evaluation of the amount of red bone marrow in each bone (group). Furthermore, the bone marrow cellularity (Cristy, 1981; ICRP, 1995) in an individual bone, i.e. the red bone marrow fraction, permits the evaluation of the volume of yellow marrow from the red bone marrow volume. The remaining spongiosa volume of each bone is then assigned to trabecular bone. Accordingly, each of the nineteen bones or bone groups has its own unique bone-specific spongiosa composition.

The above process still does not permit a direct evaluation of doses to the red bone marrow or to bone endosteum (i.e., the shallow marrow within 50 µm distance from the bone surface), for example because the lack of fine structure in the homogenised tissues of the model cannot reproduce the correct secondary charged particle fields that are locally incident on the various components of real bone, which leads to problems in determining the correct distributions of dose deposition. As a consequence, a specific method for bone dosimetry has been developed and introduced in ICRP Publication 116 (ICRP, 2010), based on bone- and energy-specific fluence-to-dose response functions for photons and neutrons, or the use of equations to obtain the skeletal-averaged absorbed dose to active marrow and endosteum in the case of directly ionizing radiation (electrons).

The participants were advised to use the bone dosimetry method as suggested by ICRP Publication 116 (ICRP, 2010). Furthermore, they were asked to use the reference computational phantoms with their organ masses and tissue compositions as described in ICRP Publication 110 (ICRP, 2009), in contrast to the organ masses with added blood content as introduced in ICRP Publication 133 (ICRP, 2016).

The phantom data are given as an ASCII file consisting of an array of organ identification numbers listed slice by slice; within each slice, row by row; and within each row, column by column (ICRP, 2009). The elemental composition and density for the material assigned to every organ ID are also provided.

2.2 Skills to be tested

Participants were invited to attempt to solve the tasks and submit their results to the organisers. Besides testing several skills of the participants, further aims of the intercomparison exercise were:

* to provide an opportunity for the participants to improve their computational procedures via feedback,
* to identify common pitfalls, and
* to gain insight into the status of voxel phantom usage in computational dosimetry.

Besides testing the correct usage of the Monte Carlo codes involved, the intercomparison exercise also aimed to find out if the participants

* were able to correctly combine the ICRP/ICRU reference computational phantoms of ICRP Publication 110 (ICRP, 2009) with their radiation transport codes,
* understood a variety of dose quantities, such as
* organ absorbed dose,
* organ absorbed dose rate,
* organ equivalent dose,
* organ equivalent dose rate,
* absorbed fraction,
* specific absorbed fraction,
* S value,
* and effective dose (ICRP, 2007),
* understood the correct application of a variety of normalisation quantities (e.g., air kerma free in air, kerma-area product, activity concentration),
* and were able to correctly apply the methods for red bone marrow and endosteum dosimetry as recommended in ICRP Publication 116 (ICRP, 2010).

2.3 Tasks to be solved

The tasks to be solved considered a variety of exposure scenarios (occupational, environmental and medical) and radiation types (photons, electrons, neutrons). More specifically, these were:

* A photon point source AP at 125 cm from the bottom of the feet and 100 cm from the chest: The aim was to calculate organ absorbed doses for both reference computational phantoms and the effective dose for 1 GBq of Co-60 and ten minutes exposure time.
* A neutron point source AP at 125 cm from the bottom of the feet and 100 cm from the chest: The aim was to calculate organ absorbed doses for both reference computational phantoms and the effective dose for a 1 minute exposure to a 1 GBq source of 10 keV neutrons.
* Am-241 ground contamination: The contamination is assumed to be contained within a disc of radius 2 m, with the anthropomorphic phantom standing at its center, and is deposited on the surface of a concrete floor; a uniform ground contamination is assumed, with an emission rate of 1 photon per cm2 per second. The aim was to calculate organ absorbed dose rates for both reference computational phantoms, as well as the effective dose rate.
* Immersion in a radionuclide source homogeneously distributed inside a room: The ICRP/ICRU adult male reference phantom is located at the center of a confined room filled with N-16 contaminated air. The aim was to calculate organ equivalent dose rates per activity concentration.
* Typical x-ray examinations: The aim of this exercise was to calculate organ absorbed dose conversion coefficients per air kerma and per kerma-area product for the male and female reference computational phantom for two typical x-ray examinations (chest PA and abdomen AP).
* Internal dosimetry: The aims of this exercise were to evaluate (1) absorbed fractions and specific absorbed fractions of energy in specified “target” organs for (1a) monoenergetic photons and (1b) monoenergetic electrons distributed homogeneously in specific “source” organs of both phantoms, and (2) S-values for the same source and target organ combinations for specific radionuclides.
  1. Approach chosen

Each of the tasks was supervised by two or three members of EURADOS WG6. One person was responsible for providing a master solution, the correctness of which had to be ascertained by second/third calculations by the other members supporting the task.

A collection of the task specifications was announced on the EURADOS website (http://www.eurados.org/) and distributed to various mailing lists for recruiting potential participants in May 2018. Each interested participant was free to solve one or several of the problems, according to his/her knowledge, interest, and time to be devoted to the participation.

The participants had to provide their solutions to the person responsible for each specific task by a specified deadline. EXCEL templates for entering the participants’ solutions in a pre-defined format were provided in order to ease evaluation by the responsible persons. The templates contained also a general part asking for personal and affiliation details, as well as information about the transport code and version used, the cross-section libraries, cutoff values chosen, the potential use of kerma approximation, and the method of bone dosimetry applied. In case the latter deviated from the ICRP 116 method (ICRP, 2010), participants were requested to explain their method in detail. The solutions were evaluated, and feedback to the participants was provided in spring and summer 2019; potential mistakes were aimed at being resolved by direct contact between the responsible persons and participants. The final deadline for revised solutions was at the end of May 2020.

Although the results are presented anonymously, all participants were invited to co-author the manuscripts that contain the detailed analyses of the results of the tasks to which they contributed, and some have accepted the offer. The respective articles are part of the present Special Issue of Radiation Measurements.

1. Response and general findings

The Intercomparison Exercise was well-received by the computational dosimetry community. 32 participants from 17 countries submitted solutions to at least one of the proposed tasks; some participants solved several or even all tasks. The agreement of the submitted solutions with the master solutions was very variable – ranging from excellent agreement to discrepancies of several orders of magnitude in single cases. Several participants were found to have had problems in correctly applying the ICRP recommended method of red bone marrow dosimetry using dose response functions (ICRP, 2010). This is the reason why there is a specific article in this Special Issue that describes this method in more detail (Zankl et al., 202x).

Many problems in the initial submissions could be solved by feedback between the participants and the persons responsible for each task. In most cases, the participants then resubmitted a revised set of results. Some initial errors were attributable to simple carelessness, such as copy-and-paste errors or mis-arranging the results in the given template. Sometimes there was a misunderstanding concerning the normalisation quantity, e.g., normalising to the correct quantity but at a different distance from the source than was asked for. These errors were mostly easy to find. There were, however, cases where the participants did not disclose how they changed their computational procedure to arrive at a revised solution; in these cases, no knowledge about the nature of the initial mis-comprehensions can be gained, unfortunately.

One general finding was that some participants provided results that were obviously wrong, although this could have been revealed by simple plausibility checks. Such tests might have been performed directly on the results by checking whether the individual organ dose coefficients showed a reasonable pattern – e.g., for homogeneous irradiation conditions, all of the resulting organ dose coefficients should have a rather similar magnitude. Furthermore, for specific tasks, an indication of the reasonableness of the results might have been obtained by comparing the results with available literature values for exposure conditions that are not too different from the task considered. Such simple measures of quality assurance were sometimes neglected, however.

1. Conclusion

The tasks that were set in the EURADOS intercomparison exercise are of practical interest in the fields of medical physics as well as occupational and environmental radiation protection. A correct simulation of the proposed tasks with computer codes requires an appropriate knowledge of the physical quantities involved and the ability to combine the ICRP/ICRU reference computational phantoms correctly with radiation transport codes.

The main scope of the intercomparison exercise was to offer an open forum for discussion and training in the field of computational dosimetry. In many cases, initial errors made by the participants were easy to find and eliminate. In some other cases, however, no knowledge about potential miscomprehensions could be gained due to the participants not disclosing how they improved their computational procedure.

One general conclusion is also that there was sometimes a lack of awareness of the necessity to quality assure computational results, such as with the help of plausibility checks or comparison with literature data for similar exposure conditions.

The present intercomparison exercise demonstrated once more that these types of study are beneficial to the field of computational dosimetry. Besides training the participants directly by improving their computational procedures via feedback with the task organisers, they lead also to the availability of representative dose values for various exposure conditions that may aid future novice users in the quality assurance of their methods.

Acronyms

ICRP: International Commission on Radiological Protection

ICRU: International Commission on Radiation Units and Measurements

References

Broggio, D., Bento, J., Caldeira, M., Cardenas-Mendez, E., Farah, J., Fonseca, T., Konvalinka, C., Liu, L., Perez, B., Capello, K., Cowan, P., Cruzate, J.A., Freire, L., Gómez-Ros, J.M., Gossio, S., Heide, B., Huikari, J., Hunt, J., Kinase, S., Kramer, G.H., Kurihara, O., Kyrieleis, A., Lebacq, A.L., Leone, D., Li, C., Li, J., Mihailescu, L.C., Moraleda, M., Navarro, J.F., Oliveira, C., Puerta, N., Reichelt, U., Simões, C., Sommer, D., Takahashi, M., Teles, P., Vanhavere, F., Vrba, T., Franck, D., Gualdrini, G., Lopez, M.A., 2012. Monte Carlo modelling for the in vivo lung monitoring of enriched uranium: Results of an international comparison. Radiat. Meas. 47(7), 492-500.

Cristy, M., 1981. Active bone marrow distribution as a function of age in humans. Phys. Med. Biol. 26, 389-400.

Gómez-Ros, J.M., Carlan, L.d., Franck, D., Gualdrini, G., Lis, M., A.M., L., Moraleda, M., Zankl, M., Badal, A., Capello, K., Cowan, P., Ferrari, P., Heide, B., Henniger, J., Hooley, V., Hunt, J., Kinase, S., Kramer, G.H., Löhnert, D., Lucas, S., Nuttens, V., Packer, L.W., Reichelt, U., Vrba, T., Sempau, J., Zhang, B., 2008. Monte Carlo modelling of Germanium detectors for the measurement of low energy photons in internal dosimetry: results of an international comparison. Radiat. Meas. 43(2-6), 510-515.

Gualdrini, G., Agosteo, S., Ménard, S., Price, R.A., Chartier, J.-L., Großwendt, B., Kodeli, I., Leuthold, G.P., Siebert, B.R.L., Tagziria, H., Tanner, R.J., Terrissol, M., Zankl, M., 2005. QUADOS intercomparison: a summary of photon and charged particle problems. Radiat. Prot. Dosim. 115(1-4), 587-599.

ICRP, 1995. Basic anatomical and physiological data for use in radiological protection: the skeleton. ICRP Publication 70. Ann. ICRP 25(2).

ICRP, 2002. Basic anatomical and physiological data for use in radiological protection: reference values. ICRP publication 89. Ann. ICRP 32(3-4), 5.

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

ICRP, 2009. Adult reference computational phantoms. ICRP Publication 110. Ann. ICRP 39(2).

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

ICRP, 2016. The ICRP computational framework for internal dose assessment for reference adults: specific absorbed fractions. ICRP Publication 133. Ann. ICRP 45(2), 1-74.

Price, R.A., Gualdrini, G., Agosteo, S., Ménard, S., Chartier, J.-L., Großwendt, B., Kodeli, I., Leuthold, G.P., Siebert, B.R.L., Tagziria, H., Tanner, R.J., Terrissol, M., Zankl, M., 2006. Pitfalls and modelling inconsistencies in computational radiation dosimetry: lessons learnt from the QUADOS intercomparison. Part II: Photons, electrons and protons. Radiat. Prot. Dosim. 118(2), 155-166.

Siebert, B.R.L., Tanner, R.J., Chartier, J.-L., Agosteo, S., Großwendt, B., Gualdrini, G., Ménard, S., Kodeli, I., Leuthold, G.P., Price, R.A., Tagziria, H., Terrissol, M., Zankl, M., 2006. Pitfalls and modelling inconsistencies in computational radiation dosimetry: lessons learnt from the QUADOS intercomparison. Part I: Neutrons and uncertainties. Radiat. Prot. Dosim. 118(2), 144-154.

Tanner, R.J., Chartier, J.L., Siebert, B.R.L., Agosteo, S., Grosswendt, B., Gualdrini, G., Kodeli, I., Leuthold, G.P., Menard, S., Price, R.A., Tagziria, H., Terrissol, M., Zankl, M., 2004. Intercomparison on the usage of computational codes in radiation dosimetry. Radiat. Prot. Dosim. 110(1-4), 769-780.

Vrba, T., Broggio, D., Caldeira, M., Capello, K., Fantínová, K., Franck, D., Gómez-Ros, J.M., Hunt, J., Kinase, S., Leone, D., Lombardo, P.A., Manohari, M., Marzocchi, O., Moraleda, M., Nogueira, P., Ośko, J., Arron, S., Suhl, S., Takahashi, M., Teles, P., Tremblay, M., Tymińska, K., Lopez, M.A., Tanner, R., 2015. EURADOS intercomparison exercise on MC modelling for the in-vivo monitoring of AM-241 in skull phantoms (Part II and III). Radiat. Phys. Chem. 113, 59-71.

Vrba, T., Nogueira, P., Broggio, D., Caldeira, M., Capello, K., Fantínová, K., Figueira, C., Hunt, J., Leone, D., Murugan, M., Marzocchi, O., Moraleda, M., Shutt, A., Suh, S., Takahashi, M., Tymińska, K., Antonia Lopez, M., Tanner, R., 2014. EURADOS intercomparison exercise on MC modeling for the in-vivo monitoring of Am-241 in skull phantoms (Part I). Radiat. Phys. Chem. 104, 332-338.

Zankl, M., Becker, J., Fill, U., Petoussi-Henß, N., Eckerman, K.F., 2005. GSF male and female adult voxel models representing ICRP Reference Man - the present status, The Monte Carlo Method: Versatility Unbounded in a Dynamic Computing World. La Grange Park, USA: American Nuclear Society, Chattanooga, TN, USA.

Zankl, M., Eakins, J.S., Gómez Ros, J.-M., Huet, C., 202x. The ICRP recommended methods of red bone marrow dosimetry. Radiat. Meas. xx( yy (this issue)).

Zankl, M., Eckerman, K.F., Bolch, W.E., 2007. Voxel-based models representing the male and female ICRP reference adult - the skeleton. Radiat. Prot. Dosim. 127(1-4), 174-186.

Zankl, M., Wittmann, A., 2001. The adult male voxel model "Golem" segmented from whole body CT patient data. Radiat. Environ. Biophys. 40, 153-162.