Radiation Physics and Chemistry 140 (2017) 112–115

Contents lists available at ScienceDirect

Radiation Physics and Chemistry

journal homepage: www.elsevier.com/locate/radphyschem

Simulation of internal contamination screening with dose rate meters

T.C.F. Fonseca[a,*], B.M. Mendes[a,b], J.G. Hunt[c]

[a] Prog. Pós Graduação Ciência e Tecnologia das Radiações, Minerais e Materiais, CDTN/CNEN, Belo Horizonte, MG, Brazil
[b] Dep. de Engenharia Nuclear – DEN / Universidade Federal de Minas Gerais – UFMG Campus da UFMG, Belo Horizonte, MG, Brazil
[c] Instituto de Radioproteção e Dosimetria - IRD/CNEN, Rio de Janeiro, RJ, Brazil

A B S T R A C T

Assessing the intake of radionuclides after an accident in a nuclear power plant or after the intentional release of radionuclides in public places allows dose calculations and triage actions to be carried out for members of the public and for emergency response teams. Gamma emitters in the lung, thyroid or the whole body may be detected and quantified by making dose rate measurements at the surface of the internally contaminated person. In an accident scenario, quick measurements made with readily available portable equipment are a key factor for success. In this paper, the Monte Carlo program Visual Monte Carlo (VMC) and MCNPx code are used in conjunction with voxel phantoms to calculate the dose rate at the surface of a contaminated person due to internally deposited radionuclides. A whole body contamination with ^{137}Cs and a thyroid contamination with ^{131}I were simulated and the calibration factors in kBq per μSv/h were calculated. The calculated calibration factors were compared with real data obtained from the Goiania accident in the case of ^{137}Cs and the Chernobyl accident in terms of the ^{131}I. The close comparison of the calculated and real measurements indicates that the method may be applied to other radionuclides. Minimum detectable activities are discussed.

1. Introduction

The massive release of radionuclides from a nuclear power plant (NPP) or spent fuel pool or from a radiological dispersion device (RDD) may result in the intake of fission and activation products by members of the public and emergency workers. The resulting body burdens may reach levels where medical treatment and follow-up is required. As part of emergency response planning, persons who may have inhaled or ingested radionuclides should be screened as a part of the “public processing” for internally deposited radionuclides (IAEA, 2005).

The screening protocol should take into consideration that the measurements should be made simply and quickly due to the normally large numbers of people to be screened. This can be performed with readily available portable hand-held equipment. The objective of the screening is to determine which individuals should be indicated for more detailed internal individual monitoring and possible medical treatment.

In this paper, the internal contamination of individuals with ^{137}Cs or ^{131}I such as that seen after a large scale accident at a nuclear Power plant (NPP) or spent fuel pond is simulated, and the calibration factors for hand-held dose rate meters in kBq per μSv/h in a given organ or tissue were calculated using the Monte Carlo method. The MCNPx code (Pelowitz, 2011) and the freely available Monte Carlo program Visual Monte Carlo (VMC) *in-vivo* (Gómez-Ros et al., 2008; Hunt et al., 2002) were used for the modelling.

2. Materials and methods

2.1. VMC and MCNPx

Two Monte Carlo programs were used in this work, VMC *in-vivo*, see http://www.vmcsoftware.com/Index.html and MCNPx. In this paper VMC and MCNPx were used to simulate the emission of photons by fission products deposited in the thyroid, lung and the whole body of voxel phantoms, transport the photons through the phantom and “detect” them in a virtual H*(10) per hour dose rate meter. For the virtual detector in VMC the photon energy fluence Ψ over the relevant energy range for the photons that pass through a 1 cm radius sphere positioned at the point of interest are binned. The photon energy fluence is then converted into H*(10) using the values given in Table A.21 of ICRP 74 (ICRP, 1996). In MCNPx the tally F4 was used to bin the photon energy fluence and multiply by the conversion coefficients for the ambient dose equivalent, H*(10) from photon fluence given in Table A.21 of ICRP 74 as well. The resulting values (in Sv/particle) were converted to kBq per μSv/h. The Simulations were done using the MCNPX code version 2.7.d running under MPI (Message Passing

* Corresponding author.
E-mail addresses: tcff01@gmail.com, tcff@cdtn.br (T.C.F. Fonseca).

http://dx.doi.org/10.1016/j.radphyschem.2017.03.047
Received 20 June 2016; Received in revised form 27 March 2017; Accepted 30 March 2017
Available online 04 April 2017
0969-806X/

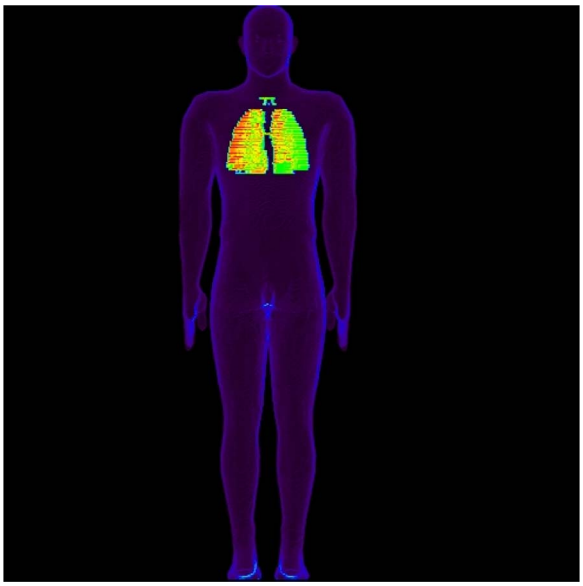

Fig. 1. MaMP Male Mesh Phantom with thyroid and lungs.

Interface) on a computational cluster with 120 processors of the Neutron Laboratory of IRD/CNEN in Brazil.

2.2. The phantoms used in the simulation

The voxel phantoms used in the VMC simulations were the 10 year and 15 year old voxel phantoms produced by University of Florida of body mass 32 kg and 56 kg respectively (Lee et al., 2010) and the ICRP 110 adult male reference phantom of body mass 73 kg (ICRP, 2009).

The MCNPx simulations used the MaMP (Male Mesh Phantom) of 1.76 m and 73 kg of body mass (Fonseca et al., 2014). The freely available library of MaMP and FeMP voxel phantoms were created for virtual Whole Body Counter calibrations. The first versions of these phantoms were without internal organs. Later versions of the MaMP and FeMP voxel phantoms include the thyroid and lungs that allow *in-vivo* calibration calculations to be performed for these organs. Fig. 1 shows the MaMP male phantom with lungs and thyroid. The thyroid of the ICRP male reference phantom has a mass of 20 g and a volume of 19.2 cm^3 however the MaMP voxel phantom has a thyroid of mass 7.3 g and volume of 7.1 cm^3.

2.3. Data from Goiania and VMC simulation

During the 1987 Goiânia accident (IAEA, 1988) daily dose rate measurements were made at a number of predetermined positions on the internally contaminated patients aged from 8 years to adult (Oliveira et al., 1988). Six weeks after the internment whole body measurements for ^{137}Cs were also performed (Hunt and Oliveira, 1990), allowing a comparison to be made between the dose rate at the skin surface and the estimated internal activity. The dose rate measurements were made using a variety of portable equipment which required careful post-accident equipment response studies. In future cases of internal contamination it is recommended that standardized equipment with recent calibration certificates be used. Fig. 2 shows a measurement being made at the neck of a patient at the Goiânia General Hospital. The Whole Body measurements were made by a dedicated set-up at the same hospital, see Fig. 3.

At the time of the Goiânia incident, there was no National Nuclear Energy Commission (CNEN) with resources and training for dealing with this type of incident. The choice of this type of handheld H*(10) dose rate monitor for this evaluation was subject to the availability of suitable equipment and the level of contamination on affected people.

Fig. 2. Dose rate measurement of a patient at the Goiânia General Hospital.

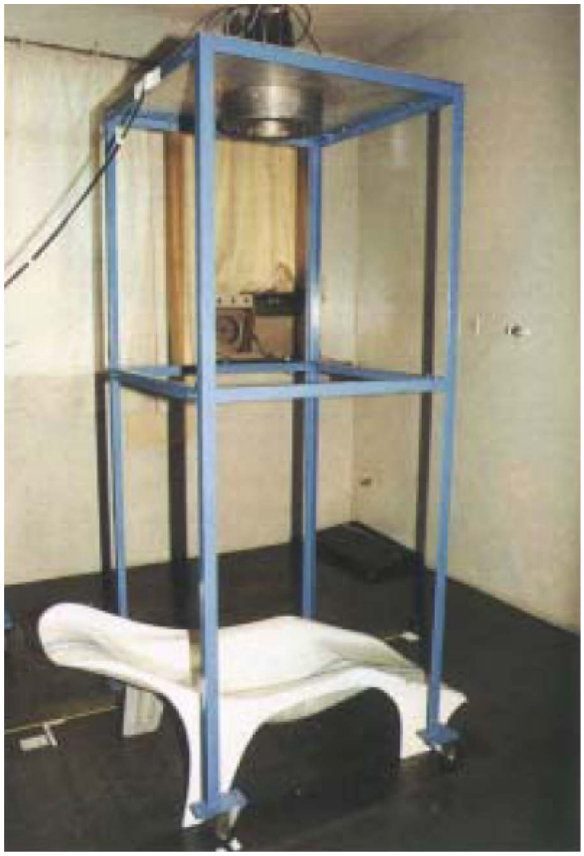

Fig. 3. The Whole Body Counter set-up in the Goiania General Hospital.

For the mass screening of contaminated persons following a radiological accident, a portal monitor would be more effective, but these were not available at the time. Handheld H*(10) dosimeters were the only ones available at this time and they were sufficiently sensitive for the

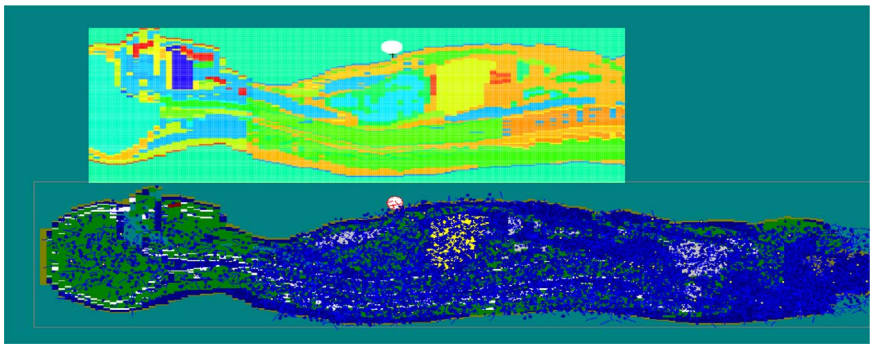

Fig. 4. MCNPx (upper) and VMC (lower) geometry for simulation of dose rate measurement at adult thorax. The fluence was binned at the white spheres.

screening process set up to monitor the population.

For all patients, the body region with the highest dose rate measurements was at the axilla (armpit), followed by the center of the thorax, measured at the front. The dose rate data made at the front thorax were used in this comparison with VMC and MCNPx. The geometry for the VMC simulation is shown in Fig. 4. The simulated dose rate detector (white sphere) was placed at the mid-point of the thorax 2 mm above the skin surface. ^{137}Cs deposited uniformly through all the soft tissues of the phantom was simulated.

Measurement of the axillia was carried during the Goiânia incident due to the legions formed from internal contamination from ^{137}Cs. To measure using the anthropomorphic voxels phantoms, it would require intensive manipulation of the phantom. A standard thorax measurement geometry was chosen representative of an actual measurement geometry and could be easily set up using the existing supine voxel phantoms.

2.4. Dose rate measurements for ^{131}I in thyroid and VMC simulation

Two papers (Tanaka and Kawamura, 1978; REMnet, 2015) used real measurements with dose rate meters and physical phantoms of the thyroid containing known activities of ^{131}I. The VMC simulation was made with the same model of the phantom and detector, however with the 1 cm radius sphere placed over the thyroid at 2 mm from the skin surface, see Fig. 5.

3. Results and discussion

3.1. Validation results for ^{137}Cs

The comparison between the measured and simulated calibration factors is presented in Table 1. For the simulations with MCNPx the result obtained with male AM_ICRP phantom and Cs-137 distributed in the whole body was 8% higher than average measured calibration factor for a 70 kg patient. When simulated with MaMP phantom the value obtained was 26% higher (Table 2).

A possible explanation for the difference in the results comparing the MaMP and the ICRP phantoms is the source distribution throughout the phantom. The MaMP phantom had the ^{137}Cs activity in the phantom distributed throughout the whole body whilst the ICRP phantom had the activity distributed in the soft-tissues. The results are also shown graphically in Fig. 6 below.

3.2. Validation results for ^{131}I

Two publications with real measurements of dose rate at the thyroid cite a calibration factor for ^{131}I in the thyroid of around 30 kBq per μSv/h for the adult (Tanaka and Kawamura, 1978; REMnet, 2015). The VMC simulation of the dose rate at the same geometry is 31 kBq per μSv/h for the adult. For the simulations with MCNPx the result obtained with the ICRP male reference phantom is 13% and when simulated using MaMP phantom is −10%.

The difference between the results for the MaMP phantom when comparing the results from VMC and ICRP phantoms may be due to the difference between the volume, mass and density of the two thyroids in each phantom. The depth of the thyroid from the front of the neck in the phantom may also be a factor.

4. Conclusions

The Monte Carlo programs VMC and MCNPx can be used proactively for emergency planning and preparedness to calculate the dose rate due to internal contamination due to ^{137}Cs and ^{131}I. This information can then be used as an immediate public triage method in the case of widespread dissemination of radionuclides in the environment. VMC *in vivo* is available for free download on the site http://www.vmcsoftware.com/in%20vivo.html. The MaMP and FeMP phantoms are available upon request.

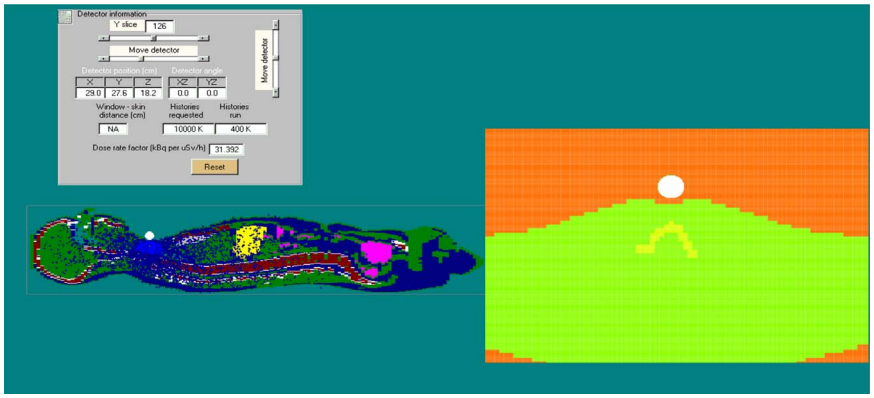

Fig. 5. Graphics of VMC (saggital projection) and MCNPx (axial projection) of ^{131}I distributed uniformly in the thyroid with the dose rate meter (white sphere) placed over the thyroid.

Table 1
Measured and simulated calibration factors in μSv/h/MBq for uniform internal contamination with ^{137}Cs.

Average weight of patient	Number of patients	Average measured calibration factor	One standard deviation of measured calibration factor	VMC calculated calibration factor	MCNPx calculated calibration factor with ICRP reference male phantom	MCNPx calculated calibration factor with MaMP phantom
kg		kBq per μSv/h	kBq per μSv/h	kBq per μSv/h	kBq per μSv/h	kBq per μSv/h
33	2	449	98	490	–	–
60	3	710	220	740	–	–
70	3	770	66	850	830	971

Table 2
Measured and simulated calibration factors in kBq per μSv/h for thyroid contamination with ^{131}I.

Average weight of patient	Average measured calibration factor	VMC Simulated calibration factor	MCNPx Simulated calibration factor ICRP adult male	MCNPx Simulated calibration factor MaMP
kg	kBq per μSv/h	kBq per μSv/h	kBq per μSv/h	kBq per μSv/h
73	30	31	34	27

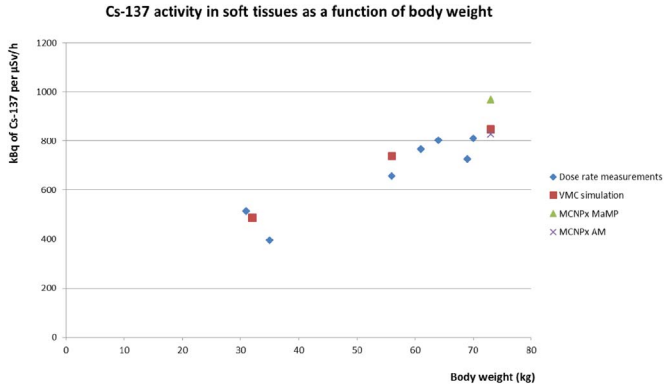

Fig. 6. Graph showing the measured and simulated dose rates at the thorax due to internally deposited ^{137}Cs as a function of body weight.

References

AnonRadiation emergency medicine information network (REMnet), 2015. Measurement of radioactive iodine deposited on cervical thyroid. ⟨https://www.remnet.jp/english/lecture/b03_01/e_04-03-03.html⟩.

Fonseca, T.C.F., Bogaerts, R., Hunt, J., Vanhavere, F.A., 2014. Methodology to develop computational phantoms with adjustable posture for WBC calibration. Phys. Med. Biol. 59 (22), 6811–6825.

Gómez-Ros, J.M., de Carlan, J.M., Franck, D., Gualdrinid, G., Lis, M., López, M.A., 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 modeling 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.

Hunt, J., Dantas, B.M., Lourenço, M.C., Azeredo, A.M.G.F., 2002. Voxel phantoms and Monte Carlo methods applied to *in vivo* measurements for simultaneous ^{241}Am contamination in four body regions. Radiat. Prot. Dosim. 105, 549–552.

Hunt, J.G., Oliveira, C.A.N., 1990. A method for estimating ^{137}Cs body burdens under emergency conditions. Radiat. Prot. Dosim. 30 (4), 275–277.

International Atomic Energy Agency (IAEA), 1988. The Radiological Accident in Goiania. International Atomic Energy Agency, Vienna, VA.

International Atomic Energy Agency (IAEA), 2005. Development of an Extended Framework for Emergency Response Criteria. IAEA-TECDOC-1432. International Atomic Energy Agency, Vienna, VA.

International Commission on Radiological Protection (ICRP), 1996. Conversion Coefficients for use in Radiological Protection against External Radiation. ICRP Publication 74. Ann. ICRP. 26(3-4), 1-205.

International Commission on Radiological Protection (ICRP), 2009. Adult Reference Computational Phantoms. ICRP Publication 110. Ann. ICRP. 39(2), 1-166.

Lee, C., Lodwick, D., Hurtado, J., Pafundi, D., Williams, J.L., Bolch, W.E., 2010. The UF family of reference hybrid phantoms for computational radiation dosimetry. Phys. Med. Biol. 55 (2), 339–363.

Oliveira, C.A.N., Lipsztein, J.L., Lourenco, M.C., Dantas, B.M., Lucena, E.A., 1988. A whole body counter installation for attending to casualties of the accident in Goiania. Health Phys. 54 (Suppl. 1), S61–S63.

Pelowitz, D.B., 2011. MCNPX User's Manual, Version 2.7.0. Los Alamos National Laboratory Report LA-CP-11-00438.

Tanaka, G., Kawamura, H., 1978. Measurement method of radioactive iodine in emergency case. J. Radiat. Res. 19, 78–84 (last accessed March 2015).