LNF-96/071

Comparison Between Anthropomorphic Mathematical Phantoms Using MCNP and FLUKA Codes

M. Pelliccioni, M. Pillon

Radiation Protection Dosimetry 67, 253-256, (1996), Nuc. Tech. Pub.

Radiation Protection Dosimetry
Vol. 67, No. 4, pp. 253–256 (1996)
Nuclear Technology Publishing

COMPARISON BETWEEN ANTHROPOMORPHIC MATHEMATICAL PHANTOMS USING MCNP AND FLUKA CODES

M. Pelliccioni† and M. Pillon‡
†INFN, Laboratori Nazionali di Frascati
C.P. 13, 00044 Frascati, Italy
‡Associazione EURATOM-ENEA sulla Fusione, Centro Ricerche Frascati C.P. 65, 00044
Frascati, Italy

Received April 9 1996, Amended June 26 1996, Accepted July 1 1996

Abstract — The International Commission on Radiation Protection (ICRP) recommends dose limits for occupational and public exposures in terms of weighted averages of organ and tissue doses. To this end the ICRP introduced the quantity Effective Dose Equivalent in Publication 26, substituted by Effective Dose in Publication 60. Both quantities cannot be measured and are usually evaluated by means of conversion coefficients, calculated using mathematical models of the adult human, the so-called anthropomorphic phantoms. Some of such phantoms exist for various computer codes, but not yet for FLUKA, a Monte Carlo code which simulates the development of showers initiated by high energy particles of energies up to several tens of TeV. An anthropomorphic phantom for the FLUKA code is presented here, together with preliminary results of calculations of the doses produced by photons in the energy range 0.122–90 MeV in a selection of different organs. The results are compared with those obtained for two phantoms running with MCNP: ADAM from GSF and the MCNP version of the FLUKA phantom. In this way, the quality of the FLUKA phantom is tested against the ADAM-GSF phantom and differences of treating physical processes by FLUKA and MCNP are compared.

INTRODUCTION

The International Commission on Radiation Protection recommends dose limits for occupational and public exposures in terms of weighted averages of the dose to the organs and tissues. These weighted averages have been designed as quantities to be limited in radiation protection. It is assumed that the health risk related to an occupational radiation exposure does not exceed certain accepted levels when the legally established limits are observed. The limits were expressed by the ICRP in terms of Effective Dose Equivalent in Publication 26[1] and more recently in terms of Effective Dose in Publication 60[2]. Both quantities are expressed as the sum of a defined set of single organ or tissue doses multiplied by appropriate weighting factors and cannot be measured directly. Thus in many not trivial cases radiation transport calculations using the Monte Carlo method became a basic tool in radiation protection dosimetry. The reason for its growing importance is the fact that such calculations often provide the only means to link the values of measurable quantities with those of radiation protection quantities. Versatile program packages are nowadays available for many problems and have become extensively used in numerical dosimetry. Well-known examples are the codes EGS, ETRAN, MCNP and FLUKA.

Calculations are carried out using mathematical models of the adult human, the so-called anthropomorphic phantoms, derived from the MIRD-5 type[7]. In these models the organs and the body shape are defined by simple geometric bodies, whose volumes and densities are in agreement with the ICRP Reference Man[4].

Anthropomorphic phantoms are in use, for example, for MCNP[5], but not yet for FLUKA, a Monte Carlo code that simulates the development of showers initiated by high energy particles, originally used to design the shielding for high energy proton accelerators. The production and transport of more than 30 different particle types can be followed by this code, in the energy range from thermal energies to several tens of TeV.

Since FLUKA is a very powerful code for high energy particle transport, it was decided to prepare for it an anthropomorphic phantom, in the following called ADAMO. ADAMO is derived from the phantom ADAM, which was prepared by the GSF-Forschungszentrum für Unwelt und Gesundheit (Germany)[6] and can be used by MCNP. To validate ADAMO which differs from ADAM-GSF due to difficulties encountered in geometry translations, it was decided to prepare a version of ADAMO also for MCNP.

ADAMO has been tested calculating the doses to some organs and tissues produced by a broad parallel beam of photons in the energy range 0.122–90 MeV. The results have been compared with those determined by ADAM-GSF and by the ADAMO version for MCNP; in this way ADAMO is tested against ADAM-GSF using the same code MCNP.

COMPUTER MODELS OF THE ADULT HUMAN: ADAMO OR ADAM

Anthropomorphic phantoms have usually been originated by the MIRD-5 type, in which position and shape of the human organs are given in the form of mathematical equations. In the ADAM-GSF phantom organs and tissues relevant for the evaluation of effective dose have been described and the details can be found elsewhere[6]. There are, however, some approximations: there is no specific representation of the bone surface and the whole skeleton is considered as a homogeneous mixture of hard bone and bone marrow, the muscles are represented by that part of the body volume which is not attributed to any other organ or tissue, etc.

ADAMO has been obtained from a translation of the ADAM-GSF phantom and thus the approximations listed above are valid for it also. Work is now in progress to overcome them.

During the translation some difficulties have been encountered, due to the minor number of surface types which FLUKA can handle. As a consequence, the geometry of some organs had to be changed with respect to the surface types used and the way they are combined together to model the organs. The guideline for the translation was therefore to find a reasonable compromise between a simplified geometry and an accurate description of ADAM-GSF (from the dose deposition perspective).

The origin and the coordinate system of the two models were assumed to be identical and, for all the organs, the volume and the centre of gravity were also the same within a few per cent. The shape of the organs is, however, sometimes modified. The surfaces encountered in the ADAM-GSF description which FLUKA cannot handle are the generic ellipsoid with arbitrary length of the three axes, the torus and the frustum of an elliptical cone. The generic ellipsoid is used in ADAM-GSF to represent various organs, like brain, cranium, urinary bladder, stomach, testes, etc. It has been replaced in ADAMO by the ellipsoid of revolution (cigar shape) with major and minor axis respectively equal to the generic ellipsoid major axis and to the square root of the product of the other two generic axes. In this way the volume of the body is preserved. The torus, used in ADAM-GSS to model the clavicles and the sigmoid colon, has been substituted in ADAMO by two concentric cylinders cut by appropriate planes. The frustum of an elliptical cone describes the bones of the arms and the legs in ADAM-GSF. In ADAMO these bones are described by two pieces of an elliptical cylinder of different circumference.

As mentioned in the introduction, a version of the ADAMO phantom was prepared also for MCNP with the aim of comparing the consequences of different ways of treating physical processes in the two code systems. FLUKA and MCNP use union and intersection operators among surfaces (called bodies in FLUKA) to produce the cells (regions in FLUKA language) with the desired shape. The translation between the two codes when the same surface types are used is very easy (it is however necessary to reverse all the signs).

The same material compositions and densities for all the three phantoms (ADAM-GSF; ADAMO/FLUKA; ADAMO/MCNP) have been used. According to ICRP data for Reference Man[4] the density assumed was $0.296\ g.cm^{-3}$ for the lungs, $1.486\ g.cm^{-3}$ for bone, $0.977\ g.cm^{-3}$ for soft tissues, and $1.105\ g.cm^{-3}$ for skin.

The similarity of the geometry between the two versions of ADAMO (for FLUKA and MCNP) has been verified by calculating the organ volumes through a stochastic estimation by ray tracing. For this purpose, a planar gamma ray source has been used to flood the geometry with particles. No material density was introduced for this type of calculation. This produces a uniform fluence throughout the regions. The unit fluence determined by the track length tally, which is inversely proportional to the region volume, results, from the definition of track length, in a tally of volumes. The resulting differences in the calculated volumes of the

Table 1. Absorbed doses in some organs and tissues of the ADAMO phantom per unit photon fluence ($Gy.cm^2$) calculated by FLUKA code for different photon energies.

Tissue or organ	E = 0.122 MeV	rel. unc.	E = 1.25 MeV	rel. unc.	E = 12 MeV	rel. unc.	E = 90 MeV	rel. unc.
Testes	8.36E–13	0.02	6.04E–12	0.06	1.51E–11	0.11	1.75E–11	0.06
Bone	7.22E–13	<0.01	4.92E–12	<0.01	2.33E–11	<0.01	6.33E–11	0.01
Colon	6.86E–13	0.02	5.43E–12	0.02	2.69E–11	0.04	6.30E–11	0.04
Lung	3.00E–13	<0.01	5.28E–12	0.02	2.87E–11	0.02	7.50E–11	0.01
Stomach	7.52E–13	0.01	5.62E–12	0.04	2.48E–11	0.04	4.58E–11	0.01
Urinary bladder	7.39E–13	0.02	5.74E–12	0.06	2.51E–11	0.08	4.97E–11	0.03
Liver	6.42E–13	<0.01	5.39E–12	0.01	2.59E–11	0.01	6.02E–11	0.01
Oesophagus	4.14E–13	0.02	4.43E–12	0.07	2.44E–11	0.09	1.00E–10	0.02
Thyroid	8.47E–13	0.01	6.72E–12	0.08	2.04E–11	0.13	2.81E–11	0.08
Skin	5.17E–13	<0.01	4.10E–12	<0.01	1.25E–11	<0.01	4.41E–11	0.01
Remainder	5.93E–13	<0.01	5.12E–12	<0.01	2.36E–11	<0.01	6.62E–11	<0.01

N.B. E–13 means $\times\ 10^{-13}$

two ADAMO phantoms proved to be much lower than 1%.

RESULTS

Calculations were performed for whole-body irradiation of ADAMO (for FLUKA and MCNP) and for ADAM (for MCNP) with broad parallel beams of monochromatic photons impinging from anterior to posterior. Four photon energies (from 0.122 MeV to 90 MeV) have been used for a more exhaustive comparison. Table 1 shows the FLUKA calculated doses for a selection of organs and tissues that are relevant for the effective dose. The uncertainties quoted are the relative statistical standard deviations of the Monte Carlo simulations. The results of the comparison are summarised in Tables 2–5 where the ratios of the doses calculated by ADAM-GSF and ADAMO phantoms using MCNP and those calculated by ADAMO using MCNP and FLUKA codes are given. The weighted mean and the standard deviation of the results are also given in Tables 2–5. The relative uncertainties of the ratios have been taken as the statistical weights.

The analysis of the data clearly shows that the difference in the weighted mean of the doses for ADAM-GSF and ADAMO is less than 1% for all energies investigated, in spite of the simplifications introduced in the geometry of ADAMO. Greater differences, depending on the photon energy, can be seen, however, between ADAMO-MCNP and ADAMO-FLUKA. The weighted means of the doses estimated by FLUKA calculations are higher than by MCNP up to 5% at 90 MeV. In order to make this aspect clear, the calculation has been repeated at 90 MeV using the kerma approximation for the energy deposition, i.e. without the secondary electron transport. In this case the energy lost by the gamma rays is locally deposited inside the organ or the tissue where the interaction took place. The guidelines for this test were that FLUKA employs the Moliere theory modified by Bethe[7] to treat the charged particle multiple scattering while MCNP uses the theory developed by Goudsmit and Saunderson[8]. The results are shown in Table 6; the fractional uncertainties are smaller than in the previous calculations because the same computer time was used but primary generation is now faster.

Without the electron transport the ratios of the results of MCNP and FLUKA are close to unity also for the primary photon energy of 90 MeV. This is an indication that the gamma ray interaction is treated in a similar way in the two codes at least in the energy range explored, while the different ways of treating the electron transport produces results in terms of deposited energy which are slightly lower for MCNP. This hap-

Table 2. Ratios of calculated doses at 0.122 MeV.

Tissue or organ	ADAM/ ADAMO	rel. unc.	ADAMO MCNP/FLUKA	rel. unc.
Testes	1.05	0.019	0.95	0.026
Bone	1.01	0.007	1.01	0.007
Colon	0.99	0.028	0.98	0.028
Lung	0.96	0.007	1.04	0.007
Stomach	0.97	0.071	1.03	0.013
Urinary bladder	1.04	0.041	0.99	0.025
Liver	0.98	0.007	1.00	0.004
Oesophagus	1.04	0.023	1.03	0.030
Thyroid	1.00	0.036	0.95	0.026
Skin	1.02	0.007	1.00	0.007
Remainder	1.00	0.007	0.99	0.004
Weighted mean	0.999		1.004	
Weighted st. dev.	0.008		0.008	

Table 3. Ratios of calculated doses at 1.25 MeV.

Tissue or organ	ADAM/ ADAMO	rel. unc.	ADAMO MCNP/FLUKA	rel. unc.
Testes	1.06	0.110	1.03	0.094
Bone	1.01	0.007	0.99	0.007
Colon	0.96	0.028	1.02	0.028
Lung	1.07	0.023	0.98	0.022
Stomach	0.91	0.058	1.08	0.051
Urinary bladder	1.01	0.109	1.02	0.093
Liver	0.97	0.017	1.02	0.015
Oesophagus	0.98	0.114	1.01	0.106
Thyroid	0.84	0.153	0.88	0.125
Skin	0.99	0.005	1.00	0.004
Remainder	0.97	0.002	1.00	0.002
Weighted mean	0.990		1.002	
Weighted st. dev.	0.011		0.007	

Table 4. Ratios of calculated doses at 12.0 MeV.

Tissue or organ	ADAM/ ADAMO	rel. unc.	ADAMO MCNP/FLUKA	rel. unc.
Testes	0.80	0.115	1.08	0.141
Bone	1.01	0.009	0.98	0.008
Colon	1.00	0.057	1.00	0.057
Lung	0.96	0.016	0.95	0.024
Stomach	0.95	0.039	1.01	0.051
Urinary bladder	1.06	0.066	0.93	0.096
Liver	1.00	0.012	1.00	0.018
Oesophagus	1.02	0.068	0.98	0.109
Thyroid	1.16	0.124	0.92	0.168
Skin	1.03	0.008	0.99	0.007
Remainder	0.97	0.006	0.99	0.006
Weighted mean	0.998		0.985	
Weighted st. dev.	0.013		0.006	

pens at high primary energy, when the electron paths are an important part of the development of the shower.

CONCLUSION

An anthropomorphic phantom model, ADAMO, has been prepared for FLUKA and MCNP. The new model has been tested against the ADAM-GSF phantom. The results have shown a remarkable agreement of most of the calculated doses to organs and tissues within a few per cent. Work is now in progress to improve the ADAMO phantom, including the addition of some missed tissues important for the effective dose calculations. ADAMO, using the potentiality of FLUKA code, is planned to be used to calculate the conversion coefficients from fluence to effective dose for high energy radiation. Since ADAMO is modelled both for MCNP and FLUKA with identical geometry description, further work will also concern some benchmark calculations between the two codes using the relatively complicated geometry of anthropomorphic phantoms. These benchmarks are interesting for comparison and validation of calculated dosimetric quantities.

ACKNOWLEDGEMENT

The authors express their gratitude to G. Gualdrini (ENEA) for providing the phantom model ADAM for MCNP and for many helpful discussions throughout the course of the work.

Table 5. Ratios of calculated doses at 90.0 MeV.

Tissue or organ	ADAM/ ADAMO	rel. unc.	ADAMO MCNP/FLUKA	rel. unc.
Testes	0.81	0.551	1.47	0.385
Bone	0.97	0.042	0.92	0.024
Colon	1.15	0.066	0.91	0.061
Lung	1.01	0.040	0.93	0.024
Stomach	0.98	0.198	0.95	0.098
Urinary bladder	1.17	0.242	0.95	0.188
Liver	1.05	0.026	0.97	0.021
Oesophagus	1.01	0.132	0.83	0.095
Thyroid	1.20	0.504	0.73	0.262
Skin	1.01	0.037	0.94	0.028
Remainder	0.96	0.014	0.97	0.013
Weighted mean	1.006		0.944	
Weighted st. dev.	0.020		0.020	

Table 6. Ratios of calculated doses at 90.0 MeV using the kerma approximation for the energy deposition.

Tissue or organ	ADAMO MCNP/FLUKA	rel. unc.
Testes	1.09	0.060
Bone	0.98	0.004
Colon	0.97	0.015
Lung	0.99	0.011
Stomach	1.03	0.024
Urinary bladder	1.02	0.042
Liver	0.98	0.007
Oesophagus	1.10	0.050
Thyroid	0.99	0.061
Skin	0.97	0.006
Remainder	0.99	0.005
Weighted mean	0.988	
Weighted st. dev.	0.007	

REFERENCES

1. International Commission on Radiological Protection. *Recommendations of the International Commission on Radiological Protection*. ICRP Publication 26 (Oxford: Pergamon Press) (1977).
2. International Commission on Radiological Protection. *1990 Recommendations of the International Commission on Radiological Protection*. ICRP Publication 60, Ann. ICRP **21**(1–3) (1991).
3. Snyder, W. S., Ford, M. R., Warner, G. G. and Fisher Jr, H. L. *Estimates of Absorbed Fractions for Monoenergetic Photon Sources Uniformly Distributed in Various Organs of a Heterogeneous Phantom*. Medical Internal Radiation Dose Committee Phamphlet No. 5, J. Nucl. Med. **10**, Supplement No. 3 (1969).
4. International Commission on Radiological Protection. *Reference Man: Anatomical, Physiological and Metabolic Characteristics*. ICRP Publication 23 (Oxford: Pergamon Press) (1975).
5. Schultz, F. W., Geleijns, J., Jansen, J. Th. M. and Zoetelief, J. *Calculation of Organ and Effective Doses for PA Chest Radiography Using Anthropomorphic Phantoms and MCNP* (TNO Medical Biological Laboratory, Rijswijk, The Netherlands) Seminar on Advanced Monte Carlo Computer Programs for Radiation Transport, Saclay, France, (April 1993).
6. Kramer, R., Zankl, M., Williams, G. and Drexler, G. *The Calculation of Dose from External Photon Exposures Using Reference Human Phantoms and Monte Carlo Methods. Part I: The Male (Adam) and Female (Eva) Adult Mathematical Phantoms*. (Neuherberg: GSF-Forschungszentrum für Unwelt und Gesundheit) GSF-Bericht S-885 (1982).
7. Bethe, H. A. *Molière's Theory of Multiple Scattering*. Phys. Rev. **89**, 1256 (1953).
8. Goudsmit, S. and Saunderson, J. L. *Multiple Scattering of Electrons*. Phys. Rev. **57**, 24 (1940).