Dose calculations of anthropomorphic voxel-based phantom for Americium-241/Beryllium neutron source

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Abstract. The knowledge of dose rates around the radioactive sources is very important for radiation protection purposes. In this study, it is aimed perform dose mapping of 3 Ci Americium-241/Beryllium neutron source at the Istanbul Technical University (ITU) Energy Institute. For this purpose, Serpent 2 Monte Carlo code and ZUBAL voxel-based phantom model were used. Since the Serpent code is a burnup code, this study created an opportunity to test Serpent at radiation protection field. Benchmarking was performed before dose mapping calculations with similar neutron sources in simple geometry from the literature. After confirm the methodology, the neutron fluxes and the neutron dose rates were calculated on the anthropomorphic phantom at 4 different locations. Dose conversion factors from ICRP Publication 21 and ICRP Publication 116 were used and results were compared. There is about 15% difference between the two results. About 50 cm from the source, the maximum neutron effective dose rate is approximately 0.04 mSv/h which is 0.02% of the yearly limit of 20 mSv in one hour. At the same location, equivalent dose for the lens of the eye was calculated as 0.14 mSv that fills 0.01% of the 150 mSv annual dose limit.

Keywords: ^{241}Am-Be neutron source, Serpent, Monte Carlo, ZUBAL voxel phantom, neutron dosimetry

1. Introduction

Simple mathematical models or voxel phantoms are used to calculate and determine the reference doses in organs of human body. Voxels are images which represents phantom organ compositions or content. The main advantage of this type of phantoms is that they can simulate organ geometries consisting of a large number of small components. Using voxel phantoms in Monte Carlo programs requires a radiation transport method and calculations are more demanding compared to analytic phantoms [1].

Radioisotope neutron sources are used for many purposes. It is the main source of neutrons for facilities not having neutron generators, research reactors or other advanced neutron sources. Therefore, it is vital to investigate the neutron source energy spectrum and corresponding dose to comply with the dose limits.

The purpose of this work is to provide dose rate data for radiation protection and safety officers at Istanbul Technical University (ITU) Energy Institute due to 3 Ci 241Am/Be neutron source present at the Institute. Serpent Monte Carlo code Version 2 [2] and voxel-based ZUBAL torso phantom [3] was used for this purpose. Since Serpent is a burn-up code, this study provided an opportunity to test its abilities in the field of radiation protection as well.

In terms of guidance in dose calculations, International Commission on Radiological Protection (ICRP) dose definitions and related limits [4] has been taken into account.

1.1 Dose definitions

Dose definitions such as effective, absorbed, or equivalent dose plays an important role in radiation protection. ICRP Publication 60 [5] described primary dose-limiting quantity as effective dose, E (units in Sievert, Sv), which is the summation of weighted equivalent doses (H_T) in critical organs of the body and additional organs.

$$E = \sum_T w_T H_T \quad (1.1)$$

w_T is weight factor for organ/tissue T and H_T is the equivalent dose in organ/tissue T.

Equivalent dose in an organ/tissue, H_T (units in Sievert, Sv), is defined as

$$H_T = D_T w_R \quad (1.2)$$

D_T is absorbed dose in organ/tissue and w_R is radiation weight factor for R radiation (neutrons in this study). The w_R function depends on incident neutron energy as [6];

$$w_R = \begin{cases} 2.5 + 18.2e^{\frac{-[\ln(E_n)]^2}{6}} & E_n < 1\,MeV \\ 5.0 + 17.0e^{\frac{-[\ln(2E_n)]^2}{6}} & 1MeV < E_n < 50\,MeV \\ 2.5 + 3.25e^{\frac{-[\ln(0.04E_n)]^2}{6}} & E_n > 50\,MeV \end{cases} \quad (1.3)$$

Organ/tissue absorbed dose D_T (units in Gray, Gy) is ,

$$D_T = \overline{d\epsilon}/dm \quad (1.4)$$

In the equation $\overline{d\epsilon}$ is the average energy of ionizing radiation delivered to an organ/tissue in the mass of dm.

2. Models and methods

2.1 ZUBAL voxel-based anthropomorphic torso phantom

The human phantom consisting of head and torso was generated by using ZUBAL phantom data which is generated by Yale University, US. The vertical section of phantom is shown in Figure 1. Each voxel is 0.4x0.4x0.4 cm dimension cube and the whole geometry consist of 128x128x243 voxels at x/y/z directions. In total, there are 3,981,312 voxels at the phantom representing 54 organs and/or tissues.

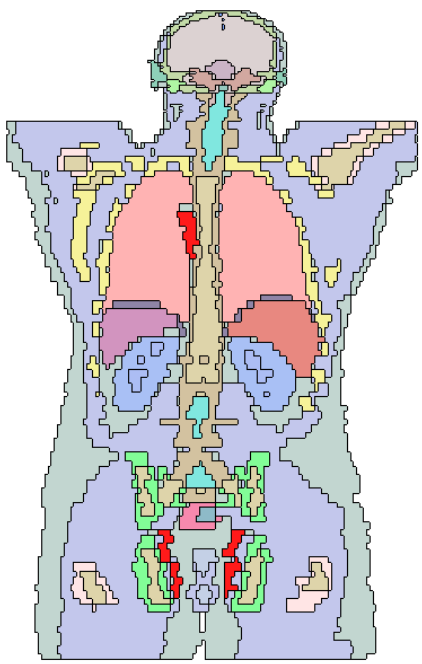

Figure 1. The printed section of ZUBAL voxel phantom using Serpent Code.

This volume array represents high resolution model of the human anatomy and can serve as a voxel-based anthropomorphic phantom suitable for many computer-based modeling and simulation calculations.

2.2 Serpent Monte Carlo Code

The Serpent Monte Carlo code is currently used in more than 150 organizations in 37 countries and has an international user basis of more than 500 users for reactor physics applications ranging from homogenized group constant generation to burnup calculations and the modeling of research reactor cores. Serpent has been developed at VTT Technical Research Centre of Finland since 2004 and the current development version, Serpent 2, has notably diversified the applications of the code. A considerable effort in the current development is devoted to multi-physics, i.e., the coupling of continuous-energy Monte Carlo neutron transport simulation to state-of-the art methods in fields such as thermal–hydraulics and fuel research. In the area of dose calculations, medical physic and radiation physics code have not enough publication but features can also be improved in this direction [7].

2.3 ^{241}Am-Be neutron source

3Ci ^{241}Am-Be neutron source in X.4(code AMN23)[8] has been used at ITU Energy Institute. The capsule is a cylinder of 2.2 cm base diameter and 4.8 cm height. The ^{241}Am-Be neutron source has stainless steel double encapsulation and it contains Americium oxide with Beryllium powder. The neutron source produces neutrons of wide energy spectrum up to 11 MeV as shown in Figure 2 [9]. Average neutron energy is approximately 4.5 MeV. The neutron emission from the source is taken as 6.3 x 10^6 n$s^{-1}Ci^{-1}$.

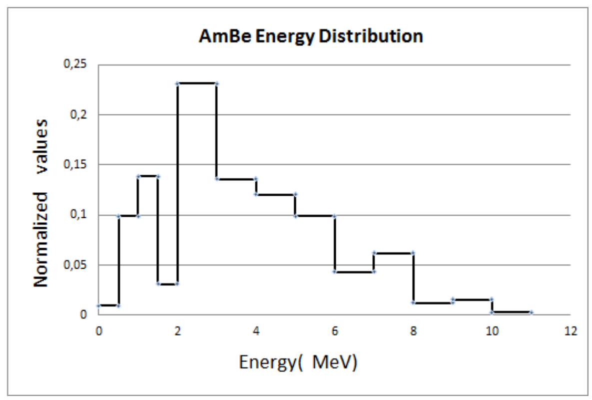

Figure 2. Neutron source energy distribution used in this study.

2.3. Monte Carlo calculations

2.3.1 Benchmark experiment

Before performing the simulations for the purpose of this study, methodology and the code was tested with a benchmark experiment. For the benchmark experiment, the work of Institute for Transuranium Elements [10] was selected. The Geometry B model describes a Pu/Be external source in 3x4x1.5 m room with 30 cm concrete walls. After the geometry creation, source energy distribution was identified with histograms to Serpent code. At a distance of 1m from the source, neutron flux values multiplied with flux to dose conversion factors from Publication 21 of ICRP [11] and results were compared with MCNP4C code results. At specified distance neutron dose rate was calculated with Serpent as 987μSv/h which is 1024.24 μSv/h in the benchmark report. The difference may be caused by errors in neutron energy histogram created for this study and instrumenting different x-section libraries. After the flux counting method of Serpent and conversion factors were verified, the same method was used for ZUBAL phantom case.

2.2.2 Dose calculation for ITU neutron source

The source is assumed to be in 3x2.3x2.1 m room with 15 cm walls. The room is divided into 2 parts with an additional wall of 15 cm thickness to provide protection to staff during experiments. The ZUBAL voxel phantom was generated in a cell with the vertical lattice option. 4 different locations (L1, L2, L3, L4) were considered to investigate the effect of position and wall on the dose rate as shown in Figure 3. Distances to the source are respectively 0,5m, 1,5m, 1,25m and 1,65m. Tissue elemental compositions were obtained from ZUBAL data. Densities of organs were calculated by Serpent. The source described in Section 2.3 was used. 10^7 particles per cycle (except Location 2)

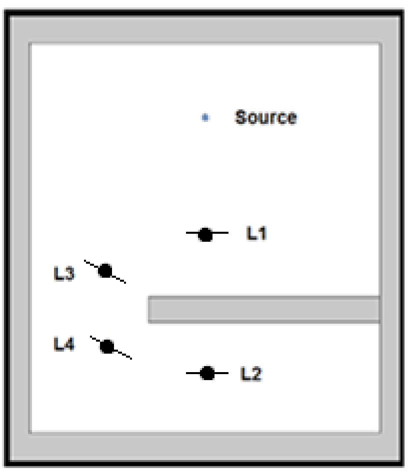

Figure 3. XY cross-section of room and four irradiation points for voxel phantom.

Serpent simulations were performed with 6 core processor to reduce computational time. The simulations took about 17 hours to complete. In Location 2, there was a significant increase in relative errors in detector counts, since there is a wall between the source and the phantom, and the distance between them was greater than that of other locations. To reduce these error rates, the counts at Location 2 were repeated with 1.8×10^8 particles per cycle and took about 30 hours to complete. The S(α, β) scattering was considered for low energy neutrons and cross sections for light water at 300 K were taken from ENDFB-VII library data.

3. Results and Discussions

Detector counts contains 40 energy groups for all 54 organs/tissues. Flux counts were taken using dm (material) detector card for neutrons and volume normalization was performed for each organ/tissue. The average neutron fluxes depending on each energy group in organ volumes together with relative errors for all locations are calculated and shown in Table 1. Percent drop in neutron flux in organs compared to location L1 is around 93% at location L2, 50% at location L3, and 65% at location L4. This is a clear indication of the effectiveness of the shielding. At this stage, it is possible to follow two paths to calculate dose rates as shown in Figure 4. In the first path, the neutron flux values could be multiplied by flux to dose conversion factors listed in ICRP Publication 21 to calculate the equivalent dose rates for each organ. In the second path, neutron fluence values could be calculated by using neutron flux values and the absorbed doses could be calculated for each organ with fluence to dose conversion factors listed in ICRP Publication 116. Then, these organ absorb doses were multiplied with w_R factors by using Equation 3 to achieve equivalent dose values. These two methods are compared at this study to investigate their influence on the resulting dose rates. Sample results of the two methods are seen for basic organs in Table 2. The results in Table 2 shows percent error between method 1 and 2 are around 15% except Testes and Thyroid which are small compared to other organs/tissues. ICRP 116 methodology was selected at this study.

Table 2 Comparison of equivalent doses (H_T) at location L1 for different methods.

	ICRP 21	ICRP 116
Skin	3.95E+00	4.40E+00
Testes	3.51E+00	4.90E+00
Liver	1.60E-01	1.30E-01
Lung	8.70E-02	7.60E-02
Esophagus	2.40E-02	2.00E-02
Stomach	1.73E-01	1.96E-01
Thyroid	7.40E-01	1.09E+00
Bladder	1.80E-01	2.20E-01

As listed in Table 1, organs/tissues like skin, fat, testes, jaw bone and eye have high equivalent doses compare to others. Organ/tissue equivalent doses drops 98% at location L2, 60% at location L3, and 73 % at location L4 compared to L1 values. Finally, effective dose values were obtained by summing the multiplication of equivalent doses with organ weight factors w_T.

Since there are special limits for lens of the eye and skin, equivalent dose values were calculated. Equivalent dose for lens of the eye at location L2 is 0.0029 mSv compared to 0.047 mSv at location L3 and 0.044 mSv for lacation L4. Similarly, equivalent dose for skin at locations L2 is 0.0018 mSv, L3 is 0.018 mSv, and L4 is 0.012 mSv.

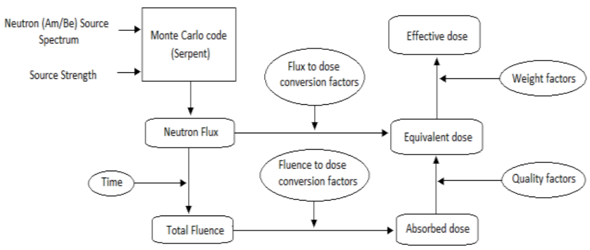

Figure 4. Flow chart of dose calculations for tissue/organ with Serpent code.

4. Conclusions

Dose mapping calculations of 3 Ci ^{241}Am/Be neutron source with ZUBAL voxel-based phantom showed that the maximum effective dose rate obtained is at Location 1 with a value of 0.04 mSv/h. Considering the ICRP's occupational limit of 20 mSv/year, this corresponds to 0.02% of the annual dose limit. And at the same location, 0.14 mSv equivalent dose of lenses of eye fills 0.01% of the 150 mSv annual dose limit in one hour. Effective dose behind the shielding wall is $8x10^{-4}$ mSv (location L2) which is about 50% of the same location in front of the wall (location L1).

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Table 1 Neutron fluxes and equivalent doses results for phantom tissues/organs for different locations

Male organs	Location 1			Location 2			Location 3			Location 4		
	Flux ($cm^{-2}s^{-1}$)	H_T (mrem/h)	Relative error (%)	Flux ($cm^{-2}s^{-1}$)	H_T (mrem/h)	Relative error (%)	Flux ($cm^{-2}s^{-1}$)	H_T (mrem/h)	Relative error (%)	Flux ($cm^{-2}s^{-1}$)	H_T (mrem/h)	Relative error (%)
Skin	1,68E+02	3,95E+00	0,07	2,53E+01	1,80E-01	2,1	1,03E+02	1,81E+00	0,1	7,47E+01	1,16E+00	0,1
Brain	2,58E+01	3,00E-01	1,3	4,44E+00	2,70E-02	6	2,16E+01	2,69E-01	1,3	1,41E+01	1,57E-01	1,6
Skull	1,05E+02	1,43E+00	0,79	2,07E+01	1,30E-01	4,1	8,08E+01	1,06E+00	0,9	5,73E+01	6,73E-01	1,2
Rib cage	3,52E+01	7,70E-01	0,55	1,63E+00	1,10E-02	7,4	1,67E+01	2,97E-01	0,9	1,11E+01	1,83E-01	1,1
Pelvis	9,90E+00	2,00E-01	1,4	6,40E-01	4,10E-03	11,1	6,39E+00	1,19E-01	2	4,32E+00	7,34E-02	2,6
long bones	1,91E+01	2,50E-01	2	3,30E+00	2,14E-02	6,3	1,48E+01	1,84E-01	2,3	9,33E+00	9,86E-02	3,3
Skeletal muscle	4,54E+01	8,50E-01	0,16	4,90E+00	3,05E-02	3,7	2,76E+01	4,22E-01	0,2	1,88E+01	2,60E-01	0,2
Lungs	3,76E+00	8,70E-02	1,1	4,60E-02	4,06E-04	18	1,18E+00	2,45E-02	2,3	8,50E-01	1,73E-02	2,7
Heart	8,43E+00	2,00E-01	2	3,90E-02	2,80E-04	32,4	1,53E+00	2,90E-02	5,5	1,33E+00	2,60E-02	6,1
Liver	7,22E+00	1,60E-01	1,3	4,90E-02	2,62E-04	18,9	4,25E+00	8,73E-02	1,8	2,14E+00	4,36E-02	2,5
Pharynx	7,06E+00	1,61E-01	15	9,20E-02	9,04E-04	46,8	2,62E+00	4,93E-02	29	1,63E+00	3,27E-02	35
Stomach	8,47E+00	1,73E-01	3	6,30E-02	4,18E-04	33,3	1,20E+00	1,94E-02	10,1	1,09E+00	1,77E-02	9,8
Colon/large intestine	1,05E+01	2,53E-01	1,3	1,80E-01	1,42E-03	15,2	2,31E+00	4,55E-02	2,9	1,97E+00	3,81E-02	3,4
Fat	1,87E+02	3,81E+00	1,6	2,87E+01	1,89E-01	10,3	1,42E+02	2,37E+00	2,4	9,89E+01	1,53E+00	2,5
Blood pool	5,74E+00	1,20E-01	1,8	4,40E-01	2,86E-03	12,1	2,61E+00	3,91E-02	3,4	2,01E+00	2,98E-02	3,4
Gas bowel	6,68E+00	2,40E-01	3,3	2,60E-02	2,68E-04	38,5	1,61E+00	5,36E-02	6,6	1,19E+00	3,99E-02	7,9
Testes	1,74E+02	3,51E-00	1,06	1,90E+01	1,11E-01	5,7	1,11E+02	1,63E+00	1,6	9,6E+01	1,39E+00	1,6
Bone marrow	8,66E+00	1,50E-01	1,4	7,00E-01	4,21E-03	11,4	4,67E+00	6,36E-02	2,2	3,26E+00	4,21E-02	2,8
Thyroid	3,38E+01	7,40E-01	9,1	7,90E-01	3,85E-03	53,8	9,13E+00	1,56E-01	21,7	9,19E+00	1,38E-01	21,2
Diaphragm	1,77E+01	4,00E-01	1,8	3,60E-01	2,68E-03	18,6	4,63E+00	8,23E-02	4,1	3,43E+00	5,70E-02	5
Bladder	6,66E+00	1,80E-01	3,6	2,00E-02	1,18E-04	56,7	1,48E+00	3,31E-02	9,6	1,36E+00	3,12E-02	8,5
Jaw bone	1,89E+02	4,17E+00	1,3	1,20E+01	7,46E-02	9,3	9,96E+01	1,66E+00	1,9	7,32E+01	1,08E+00	2,4
Hard plate	6,50E+01	1,29E+00	3,2	2,96E+00	1,86E-02	15,9	3,24E+01	5,68E-01	5,1	2,55E+01	4,14E-01	5,6
Tongue	4,23E+01	8,10E-01	3,5	9,90E-01	5,73E-03	28,4	1,73E+01	2,80E-01	6,2	1,24E+01	1,90E-01	8,3
Sinuses	5,84E+01	1,52E+00	1,7	4,46E+00	3,46E-03	8,9	3,89E+01	8,43E-01	2,4	2,82E+01	5,51E-01	3,2
Eyes	2,48E+02	6,18E+00	2,2	1,90E+01	1,15E-01	11,8	1,33E+02	2,19E+00	3,7	1,11E+02	1,83E+00	3,5
Lenses	4,80E+02	1,44E+01	3,9	4,45E+01	2,94E-01	14,6	2,61E+02	4,65E+00	7,2	2,32E+02	4,36E+00	7
Teeth	1,83E+02	3,88E+00	2,7	9,03E+00	5,41E-02	15,6	8,88E+01	1,51E+00	4,1	6,85E+01	1,07E+00	5,1