DOSE ASSESSMENT FOR RADIOACTIVE SKIN CONTAMINATION OF A CHILD

A Thesis

by

JEFFREY AARON KOWALCZIK

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

May 2008

Major Subject: Health Physics

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Approved by:

Chair of Committee,	John W. Poston, Sr.
Committee Members,	John Ford
	Thomas W. Adair III
Head of Department,	Raymond Juzaitis

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ABSTRACT

Dose Assessment for Radioactive Skin Contamination of a Child. (May 2008)

Jeffrey Aaron Kowalczik, B.S., Texas A&M University

Chair of Advisory Committee: Dr. John W. Poston, Sr.

Dose assessments produced using the computer code MCNP are important to simulate events that are difficult to recreate experimentally. An emergency scenario involving whole-body skin contamination is one example of such an event. For these scenarios, an anthropomorphic phantom of a 10-year-old male with uniform skin contamination was created and combined with MCNP for dose calculations. Activity on the skin was modeled with gamma-ray sources at energies of 50 keV, 100 keV, 250 keV, 500 keV, 750 keV, 1 MeV, 1.25 MeV, 1.5 MeV, and 2 MeV. The radionuclides ^{60}Co, ^{137}Cs, and ^{131}I were also modeled. The effective dose to the body and major organs was calculated for each scenario. Exposure rate contour lines were also produced around the body.

The activity required to result in a dose equal to the legal limit of 0.1 mSv for minors was calculated for each scenario. The highest activity required to produce this limit was from the 50 keV gamma-ray source. This activity was increased by an arbitrary value, approximately tenfold the current value, to represent an emergency scenario. This new activity concentration of 1 mCi per 100 cm^2 was used to produce doses for each of the scenarios. The lowest effective dose for the body was 0.82 mSv,

produced from the 50 keV source. The highest effective dose was 19.59 mSv, produced from the 2 MeV source. The exposure rates nearest the body were approximately 1.25 R/h, decreasing to100 mR/h approximately 60 cm from the body. The data points were found to be dependent on the energy of the gamma ray. These data can also be improved by deriving solutions previously assumed in this scenario. For example, the skin may be broken down into multiple regions to allow for independent calculations for regional contamination. The activity on the skin can also be derived from air concentration models, allowing for the use of other models to be used in conjunction with this research.

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I would like to thank my committee chair, Dr. Poston, and my committee members, Dr. Ford and Dr. Adair, for their guidance and support throughout the course of this research. I have gained much knowledge under their direction not only in this research, but in the classroom as well.

I would like to extend many thanks to my parents for their encouragement and their unending support throughout my college career. I would also like to thank Megan for providing me with strength and support throughout the past several years.

NOMENCLATURE

Bq	becquerel
^{60}Co	cobalt-60
^{137}Cs	cesium-137
^{131}I	iodine-131
keV	kiloelectron volts
MeV	megaelectron volts
mCi	millicurie
mSv	millisievert
μCi	microcurie
NPS	Number of Histories Computed
ICRP	International Commission on Radiological Protection
MCNP	Monte-Carlo N-Particle Transport Code
R	roentgen
RDD	Radiological Dispersal Device

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CHAPTER I

INTRODUCTION

With the growing threat of radiological terrorism, assessment techniques need to be developed to establish standards for use in the event of an emergency. Dose models and computer codes are powerful tools to assess these potential emergencies that are unable to be experimentally tested, such as those in a radiological release. This scenario may be caused from a radiological dispersal device, or RDD, but also include non-terrorism events, such as reactor or material accidents. An RDD differs from a nuclear weapon in that it uses conventional explosives or other mechanisms to spread radioactive contamination (NCRP 2005). These methods include explosive devices such as the dirty bomb shown in Figure 1. An RDD could also be as simple as dispersing radioactive material into a ventilation system that will spread into a building. The airborne radioactive contamination created by such an event would imbed radioactive particles in the clothing and skin of nearby persons.

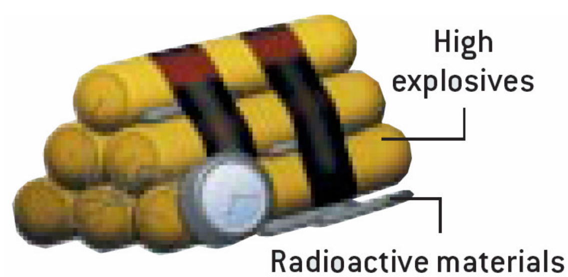

Figure 1. Simplified example of an RDD, or dirty bomb (Levi and Kelly, 2002).

This thesis follows the style of Health Physics Journal.

In a radiological release emergency, there is the potential for skin contamination, inhalation, or ingestion; the worst case would involve a combination of the three. Many inhalation and ingestion models are used throughout the industry today (IRCP 1979, ICRP 1995); however, there are few dose assessment models used for skin contamination. This research will address dose assessment models for uniform skin contamination of a 10-year-old male using various gamma-emitting nuclides.

HISTORY OF INCIDENCE

While no RDD has ever been detonated in the United States, they are especially dangerous because they require no knowledge of nuclear technologies; such a device simply involves the spread of radioactive contamination. This threat is exponentially increased due to the ease of acquisition of many types of radioactive sources. This ease is illustrated in events such as the Goiânia incident (although this was not a terrorist incident) that resulted in radiological contamination of a large number of people and a large area.

In 1987, in Goiânia, Brazil, two men broke into an abandoned medical center, housing an old radiotherapy machine with a sealed ^{137}Cs source. The men stole the capsule and managed to remove the 50.9 TBq source from its housing, not knowing its danger. They broke the seal on the source allowing a blue fluorescence to be visible. This light created an immense interest in the cesium chloride compound inside. The material exchanged hands numerous times, increasing the number of people it affected. After it was determined to be dangerous over two weeks later, 249 people had been contaminated; five were dead (Zimmerman and Loeb, 2004). This event, while not identical to a terrorism incident, can be directly compared to one due to the unintentional radiological contamination on the skin.

CURRENT MODELS

Because many of the calculations and standards in use are for occupational workers over the age of eighteen, there is little information for younger population groups. While the likelihood of industry incidents is small, there are still emergency scenarios that would involve minors. The dose models used in this research will address a specific scenario to a minor of a certain age: uniform skin contamination to a 10-year-old male. While this model is only a very small part of the many dose models essential for emergency response, it will provide an important data point for future work and understanding.

PROBLEM STATEMENT

The purpose of this research was to obtain the dose to organs of the body of a 10-year-old child exposed to radioactive material resulting in uniform skin contamination. This assumption of uniform activity on the skin is a conservative approach to assume the worst-case scenario involving skin contamination. Three radionuclides, ^{60}Co, ^{137}Cs, and ^{131}I, and a spectrum of monoenergetic photons from 50 keV to 2 MeV will be tested. The equivalent dose will be calculated in the major organs of the body, as well as the effective dose. A contour plot of the isodose curves around the body will be produced for three planes through the body. These plots will give exposure rates at locations around the body and are useful, qualitatively, to shown the areas of high and low exposure rates.

CHAPTER II

PROCEDURE

PHANTOM

An anthropomorphic phantom obtained from White Rock Science[†] was used to create a mathematical model for a 10-year-old male. This computer program built a three-dimensional geometry of a 10-year old male based on descriptions given previous reports from Oak Ridge National Laboratory (Cristy 1980, Cristy and Eckerman, 1987, Snyder 1974). The Body Builder program used to model the child phantom generated an output in the format of an MCNP deck.

The phantom of the 10-year-old male had a mass of 32.69 kg (72.07 lbs) and a height of 139.97 cm (4 feet, 7 inches). The width across the torso was approximately 28 cm and the depth from chest to back was approximately 17 cm. An example of an anthropomorphic phantom is shown in Figure 2. This phantom provides an approximation of the size and position of each organ in the body. These organs are listed in Table 1 with their volumes and masses. The organs listed all had individual cells created by Body Builder in MCNP.

† White Rock Science, PO Box 4729, Los Alamos, NM 87544

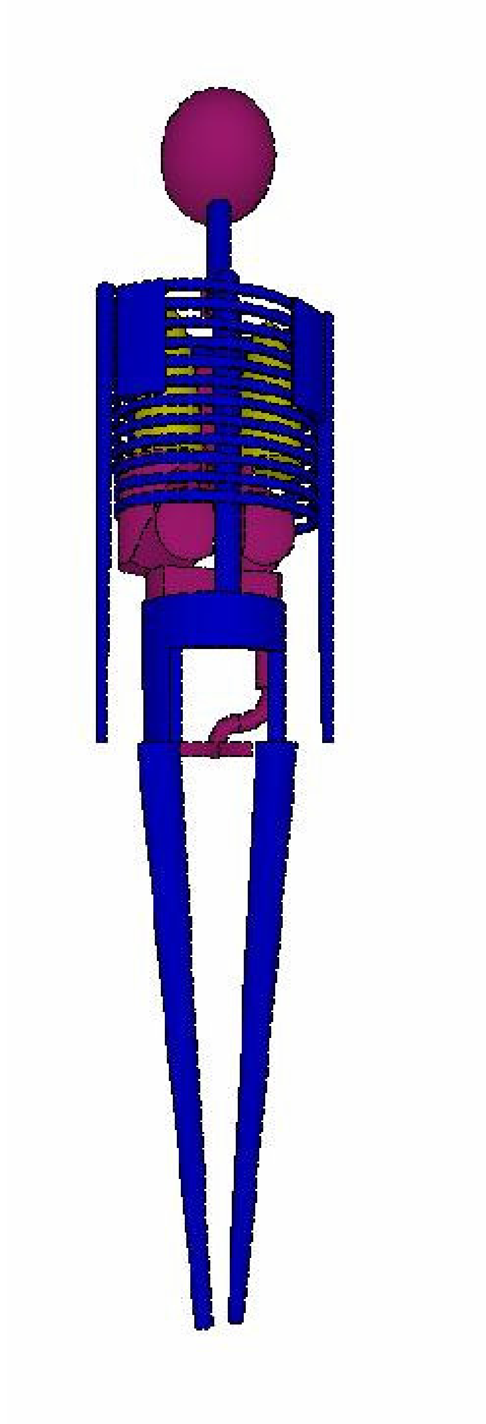

Figure 2. Example of an anthropomorphic phantom.

Table 1. List of organs used in phantom with respective volumes and masses.

Organ	Volume (cm^3)	Mass (g)
LEG BONES	1250.0	1750.0
ARM BONES	404.0	565.6
PELVIS	258.0	361.2
SPINE	411.0	575.4
SKULL & FACE	595.0	833.0
RIBS	295.0	413.0
CLAVICLES	23.2	32.5
SCAPULAE	85.7	120.0
ADRENALS	6.9	7.2
BRAIN	1310.0	1362.4
GALL BLADDER	44.0	45.8
ESOPHAGUS	18.7	19.4
STOMACH	209.8	218.2
SMALL INTESTINE	447.0	464.9
ASCENDING COLON	79.6	82.8
TRANSVERSE COLON	104.0	108.2
DESCENDING COLON	81.7	85.0
SIGMOID COLON	45.0	46.8
HEART	355.0	369.2
KIDNEYS	166.0	172.6
LIVER	853.0	887.1
LUNGS	1530.0	452.9
PANCREAS	28.9	30.1
SPLEEN	74.4	77.4
TESTICLES	1.8	1.9
THYMUS	30.2	31.4
THYROID	7.6	7.9
URINARY BLADDER	120.9	125.7
PENIS & SCROTUM	34.4	35.8
HEAD & NECK SKIN	127.0	132.1
TRUNK SKIN	385.0	400.4
PENIS & SCROTUM SKIN	4.1	4.2
LEG SKIN	363.0	377.5
LEGS	7317.0	7609.7

MONTE CARLO N-PARTICLE (MCNP) CODE

MCNP is a Monte Carlo program that was developed by Los Alamos National Laboratory. A Monte Carlo program uses random sampling algorithms that are repeated numerous times. In health physics applications, it can be used to track radiation events and dose to relevant areas. MCNP will simulate millions of sequential radiation events and track each particle history and its energy loss at given locations. The following sections will describe the input file in Appendix A.

Geometry

The geometry in MCNP is arranged into two major parts: surfaces and cells. Each surface is a two-dimensional plane with given parameters that are created for cell boundaries. These planes can have many shapes, including spheres, cylinders, and spheroids, a curved plane. An example of a cylindrical surface used for constructing the neck is shown in Figure 3:

```
27    cz     4.5000
```

Figure 3. Example of MCNP surface card structure.

The number 27 refers to the surface number. The surface type is given by ‘cz’, defining that the surface will be a cylinder parallel to the z-axis. The last number, 4.5, provides the radius of the cylinder. This surface was created as the outer boundary of the neck cell.

A cell is defined with a given density and atomic composition and uses Boolean operators to bound it between surfaces. The neck skin cell card is shown in Figure 4:

```
28    1 -1.04       28 -27 8 -12
```

Figure 4. Example of MCNP cell card structure.

The first number refers to the cell number, followed by the material number and the density. In this instance, material 1 refers to the atomic composition created for body tissue. The density of this cell is 1.04 g cm^{-1}. The last four numbers are the boundary surfaces that define the shape of the cell.

Source

The goal of this research was to uniformly place source particles over the skin. MCNP is not designed to track particles that originate on a surface other than planar or spherical surfaces. The shape of the body skin is very complex; therefore, a one millimeter thick volume of air was added exterior to the skin to define a source location.

The source term used in this research was the SDEF, or source definition card. This card contains the parameters that simply define a location for creation of a particle and the initial energy of the particle. The SDEF card used for ^{137}Cs is shown in Figure 5.

```
SDEF PAR=2 ERG=0.662 CEL=900 POS=0 0 0 AXS=0 0 1 RAD=D1 EXT=D2
      EFF=0.0001
SI1   0       14.15
SP1  -21      1
SI2  -66.15   74.15
SP2   0       1
```

Figure 5. Example of MCNP source definition card structure.

The first line of the SDEF card allows parameter adjustment for the source variables. The PAR and ERG variables change particle type and energy. In this case, a 0.662 MeV gamma will be created. In this research, the key gamma ray-energies for ^{60}Co, ^{137}Cs, and ^{131}I were used, shown in Table 2.

Table 2. Gamma-emitting radionuclides with respective energies.

Isotope	Energy (MeV)
^{60}Co	1.173, 1.332
^{137}Cs	0.662
^{131}I	0.080, 0.287, 0.364, 0.637, 0.723

Monoenergetic gamma rays were also considered at energies of 50 keV, 100 keV, 250 keV, 500 keV, 750 keV, 1 MeV, 1.25 MeV, 1.5 MeV, and 2 MeV.

The MCNP code does not allow a source to be created in a complex cell, such as the one millimeter of air surrounding the body. Instead, the RAD and EXT cards, used with the four lower lines of the example card, were used to create a sampling volume entirely enclosing the cell. If a point is sampled and found to be in the cell, it is accepted, and a radiation history is started at that location. If a point is sampled and it exists outside the cell, then it is rejected and a new point is sampled (X-5 Monte Carlo Team 2003).

Number of Radiation Histories Calculated (NPS)

The dose or fluence calculated using an MCNP program is determined on a 'per particle history' basis. This means that more particle histories do not increase calculated doses, but rather improve the statistics of the calculation. In the input deck used for this research, five million histories were simulated.

Tallies

The tally card is used to specify output information needed from the problem (X-5 Monte Carlo Team 2003). In this scenario, two types of tallies were used. The f6 tally, shown in Figure 6, provides energy deposited in a given cell. Each major organ cell was tallied for this problem.

```
f6:p        50      $LEG BONES
```

Figure 6. MCNP f6 tally list used in input deck.

The FMESH tally was also used in this problem. This tally provides a track length estimate of the particle fluence, averaged over the given mesh cell (X-5 Monte Carlo Team 2003). The tally counts particle fluence through a grid that the user defines. For this problem, a one centimeter thick planar tally was placed normal to each axis through the origin. The coronal, sagittal, and transverse planes correspond to the planes normal to the x-, y-, and z-axes, respectively. The purpose of these differentially thick planes was to obtain a rough estimate of the dose rates at points around the body. Figure 7 shows the setup of a FMESH tally:

```
fmesh24:p origin= -0.5 -175 -250
      imesh= 0.5 iints=1
      jmesh= 175 jints=349
      kmesh= 250 kints=499 out=jk
```

Figure 7. Example of MCNP FMESH tally structure.

The origin defines the lower most corner point of the mesh grid. The “imesh,” “jmesh,” and “kmesh” give the coordinates of the upper most point of the grid, exactly opposite the origin. The “ints” variable sets the number of divisions there are for each of the directions. The “out” variable specifies the plane in which the output will print.

DATA ANALYSIS

Each of the organ dose tallies was taken from the MCNP output file and read into Microsoft Excel. These data for the organs had units of MeV g^{-1} $history^{-1}$. The units were converted to J kg^{-1} $history^{-1}$ and multiplied by the radiation weighting factor (1 for gamma-rays). These data, with units of mSv $history^{-1}$, represent the equivalent dose, H_T, to each tissue.

The effective dose was calculated using the formula:

$$E = \sum_T w_T H_T \tag{1}$$

where E is the effective dose for the whole body, w_T is the tissue weighting factor for each tissue, and H_T is the equivalent dose to that tissue. The tissue weighting factor, w_T, gives the fraction of the total stochastic risk associated with the irradiation of a given tissue. This factor is intended to correlate with the overall detriment to an individual (Turner 1995). The list of tissues with their respective weighting factors is shown in Table 3. It should be noted that the breast tissue was omitted from the calculation since the phantom is male. It should also be noted that the "remainder" tissue was calculated as the weighted average of the remaining organs not classified by the previous categories.

Table 3. ICRP tissue weighting factors (IRCP 1991).

Organ Tissue	w_T
Gonads	0.20
Colon	0.12
Red Bone Marrow	0.12
Lung	0.12
Stomach	0.12
Breast	0.05
Bladder	0.05
Liver	0.05
Thyroid gland	0.05
Esophagus	0.05
Skin	0.01
Bone surface	0.01
Remainder	0.05

The effective dose to the body still retained its "per history" dependence at this point. This means that the effective dose of the body is directly proportional to the source activity on the skin. Rather than choose an arbitrary value for the skin activity, Microsoft Excel Solver was used to calculate the activity that would give an effective dose of 0.1 mSv, the legal limit for minors in the United States (NCRP 1992). This was repeated for each photon energy and/or radionuclide chosen. An activity per skin area was determined based on these values and used as the "standard activity" throughout the remainder of the data analysis. This standard activity was first used to calculate effective doses to the body for each photon source.

The FMESH tally data produced for ^{60}Co also retained its "per particle history" dependence and, therefore, was also multiplied by the standard activity. The FMESH tally output was read into a MATLAB matrix, representing particle fluence rate through each mesh division. This particle fluence rate was changed into exposure using the following formula (Attix 2004):

$$\dot{X} = \dot{\Psi} \cdot \left(\frac{\mu_{en}}{\rho}\right)_{air} \cdot \left(\frac{e}{w}\right)_{air} \qquad (2)$$

where $\dot{X}$ is the exposure rate, $\dot{\Psi}$ is the photon fluence rate, $(\mu_{en}/\rho)_{air}$ is the energy-dependent attenuation coefficient for air, *e* is the charge of an electron, and *w* is the amount of energy required to produced an ion pair in air.

This matrix was converted to isodose rate curves using the "contour" function, shown in Figure 8.

```
xy=xlsread('input.xls','xy')
v=[0.1 0.25 0.5 0.75 1 1.25]
contour(xy,v)
```

Figure 8. MATLAB code used to produce isodose contour figures.

A three-dimensional FMESH tally was calculated for the ^{60}Co scenario. The mesh output was read into a multi-dimensional array in MATLAB and plotted for qualitative representation using the “vol3d” package. This MATLAB add-on produced a semi-transparent three-dimensional image with a color spectrum dependent on respective exposure values. The code used to create the image from multidimensional array “M” is shown in Figure 9.

```
h = vol3d('cdata',M,'texture','2D');
view(3);
vol3d(h);
grid;
alphamap('rampup');
```

Figure 9. MATLAB code used to produce three-dimensional representation of exposure rates.

CHAPTER III

RESULTS

ORGAN DOSE TALLIES

For the trials using various gamma-ray energies, each organ tally was compiled and converted from MeV per gram to mSv, the equivalent dose for each organ. Table 4 shows the organs that were tallied with their associated doses. The equivalent doses for each organ in the table will result in an effective dose of 0.1 mSv and are unique solutions for this specific scenario.

Table 5 shows the weighted equivalent doses for each organ and the respective effective dose to the whole body. These values were calculated using Microsoft Excel Solver to find the activity on the skin corresponding with and effective dose of 0.1 mSv.

Figure 10 shows the activity required to reach the limit of 0.1 mSv. This shows that the highest activity per area on the skin was found to be 126 µCi/100 cm^2. Considering the nature of the emergency scenario, it would be conservative to make calculations based on events with higher activities on the skin. The nominal value chosen was approximately ten times larger than the maximum value required to reach the limit of exposure for a minor. This value of one mCi per one-hundred square centimeters was used for the remainder of the data analysis.

Table 4. Organ dose equivalents (mSv) to reach 0.1 mSv effective dose.

Organ	50keV	100keV	250keV	500keV	750keV	1MeV	1.25MeV	1.5MeV	2MeV
Leg Bones	0.13	0.11	0.08	0.07	0.07	0.07	0.07	0.07	0.07
Arm Bones	0.41	0.25	0.19	0.19	0.19	0.19	0.18	0.18	0.18
Pelvis	0.17	0.14	0.10	0.09	0.09	0.09	0.09	0.09	0.09
Spine	0.19	0.18	0.12	0.11	0.10	0.10	0.10	0.10	0.10
Skull & Face	0.36	0.23	0.17	0.16	0.16	0.16	0.16	0.16	0.16
Ribs	0.31	0.20	0.14	0.14	0.14	0.14	0.14	0.14	0.14
Clavicles	0.44	0.26	0.18	0.17	0.17	0.17	0.17	0.17	0.17
Scapulae	0.34	0.22	0.16	0.16	0.16	0.16	0.16	0.16	0.16
Adrenals	0.05	0.08	0.08	0.08	0.09	0.09	0.09	0.09	0.09
Brain	0.10	0.13	0.14	0.14	0.14	0.14	0.14	0.14	0.14
Gall Bladder	0.05	0.07	0.08	0.08	0.08	0.08	0.08	0.08	0.08
Esophagus	0.06	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09
Stomach	0.06	0.08	0.09	0.09	0.09	0.09	0.09	0.09	0.09
Small Intestine	0.05	0.07	0.08	0.08	0.08	0.08	0.08	0.08	0.08
Ascending Colon	0.06	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.09
Transverse Colon	0.05	0.07	0.08	0.08	0.08	0.08	0.08	0.08	0.08
Descending Colon	0.05	0.07	0.08	0.08	0.08	0.08	0.08	0.08	0.09
Sigmoid Colon	0.04	0.06	0.07	0.07	0.07	0.07	0.07	0.07	0.07
Heart	0.06	0.08	0.09	0.09	0.09	0.09	0.09	0.09	0.09
Kidneys	0.06	0.08	0.09	0.09	0.09	0.10	0.10	0.10	0.10
Liver	0.07	0.09	0.09	0.10	0.10	0.10	0.10	0.10	0.10
Lungs	0.09	0.10	0.11	0.11	0.11	0.11	0.11	0.11	0.11
Pancreas	0.05	0.07	0.07	0.08	0.08	0.08	0.08	0.08	0.08
Spleen	0.07	0.09	0.10	0.10	0.10	0.10	0.10	0.10	0.10
Testicles	0.05	0.06	0.06	0.07	0.07	0.07	0.07	0.07	0.07
Thymus	0.08	0.10	0.11	0.11	0.11	0.11	0.11	0.11	0.11
Thyroid	0.30	0.30	0.33	0.32	0.32	0.32	0.31	0.31	0.31
Urinary Bladder	0.05	0.07	0.07	0.07	0.07	0.07	0.07	0.08	0.08
Penis & Scrotum	0.04	0.05	0.06	0.06	0.06	0.07	0.07	0.07	0.07
Head & Neck Skin	0.23	0.23	0.29	0.29	0.29	0.29	0.28	0.28	0.27
Trunk Skin	0.19	0.20	0.24	0.25	0.24	0.24	0.24	0.24	0.24
Penis & Scrotum Skin	0.04	0.05	0.06	0.06	0.06	0.06	0.06	0.06	0.06
Leg Skin	0.17	0.17	0.21	0.21	0.21	0.21	0.21	0.21	0.20
Legs	0.08	0.08	0.10	0.10	0.10	0.10	0.10	0.10	0.10

Table 5. ICRP weighted equivalent organ doses (mSv) to reach 0.1 mSv effective dose.

Organ	50keV	100keV	250keV	500keV	750keV	1MeV	1.25MeV	1.5MeV	2MeV
Gonads	0.009	0.011	0.013	0.013	0.014	0.014	0.014	0.014	0.014
Colon	0.006	0.009	0.009	0.009	0.009	0.009	0.010	0.010	0.010
Red Bone Marrow	0.035	0.024	0.017	0.016	0.016	0.016	0.016	0.016	0.016
Lung	0.010	0.012	0.013	0.013	0.013	0.013	0.013	0.013	0.013
Stomach	0.008	0.010	0.011	0.011	0.011	0.011	0.011	0.011	0.011
Bladder	0.002	0.003	0.004	0.004	0.004	0.004	0.004	0.004	0.004
Liver	0.003	0.004	0.005	0.005	0.005	0.005	0.005	0.005	0.005
Thyroid gland	0.015	0.015	0.016	0.016	0.016	0.016	0.016	0.016	0.015
Esophagus	0.003	0.004	0.005	0.005	0.005	0.005	0.005	0.005	0.005
Skin	0.001	0.001	0.002	0.002	0.002	0.002	0.002	0.002	0.002
Bone surface	0.003	0.002	0.001	0.001	0.001	0.001	0.001	0.001	0.001
Remainder	0.003	0.004	0.004	0.005	0.005	0.005	0.005	0.005	0.005
Whole Body Dose	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1

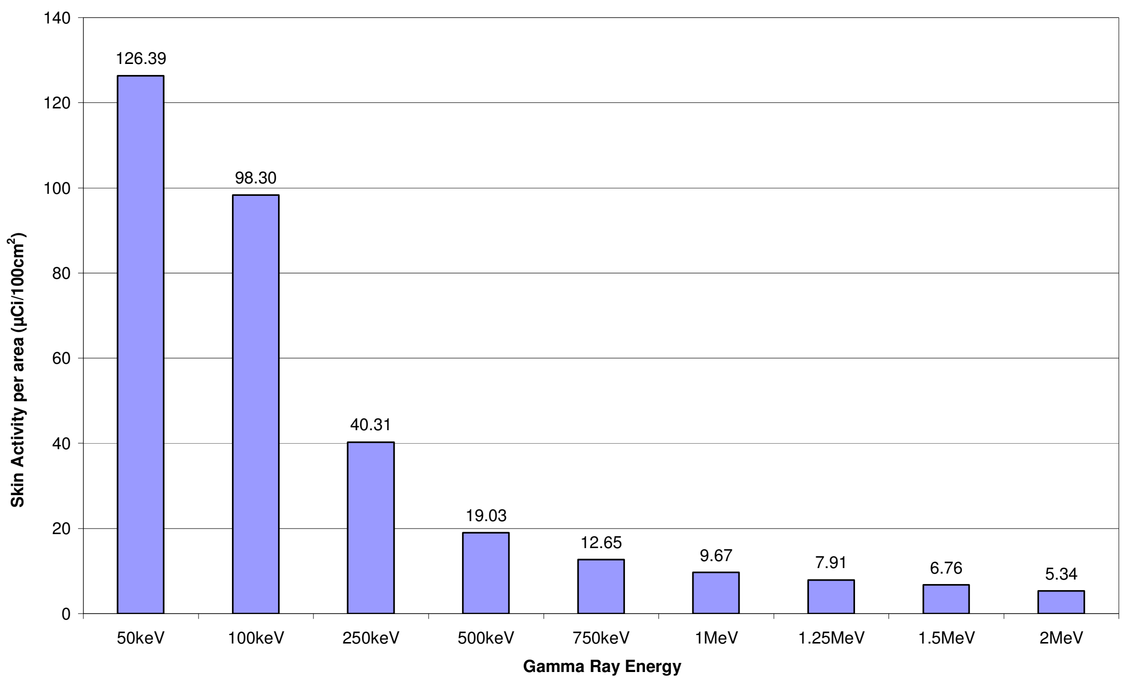

Figure 10. Activity per skin area to reach 0.1 mSv limit for 10-year-old male in 1 hour.

The organ doses were calculated using the “standard activity” on the skin and are shown in Table 6.

Table 6. Organ dose equivalents (mSv) from 1 mCi/100 cm^2 skin contamination for 1 hour.

Organ	50keV	100keV	250keV	500keV	750keV	1MeV	1.25MeV	1.5MeV	2MeV
Leg Bones	1.05	1.09	1.89	3.77	5.65	7.39	9.03	10.59	13.47
Arm Bones	3.25	2.55	4.80	9.87	14.71	19.17	23.27	27.07	34.05
Pelvis	1.34	1.47	2.38	4.60	6.81	8.92	10.93	12.80	16.35
Spine	1.49	1.79	2.92	5.62	8.27	10.80	13.16	15.38	19.54
Skull & Face	2.81	2.33	4.22	8.58	12.77	16.61	20.12	23.36	29.36
Ribs	2.49	2.02	3.55	7.23	10.79	14.11	17.23	20.11	25.41
Clavicles	3.51	2.68	4.57	9.15	13.59	17.66	21.41	24.83	31.26
Scapulae	2.70	2.22	4.08	8.39	12.48	16.30	19.82	23.14	29.20
Adrenals	0.41	0.78	2.07	4.42	6.78	9.05	11.23	12.90	16.32
Brain	0.81	1.30	3.56	7.58	11.36	14.83	18.03	20.99	26.37
Gall Bladder	0.39	0.72	1.91	4.01	6.08	8.03	9.87	11.62	14.97
Esophagus	0.48	0.88	2.34	4.91	7.38	9.60	11.79	13.85	17.65
Stomach	0.51	0.84	2.22	4.79	7.25	9.57	11.77	13.81	17.53
Small Intestine	0.39	0.72	1.88	4.01	6.08	8.10	9.94	11.70	15.07
Ascending Colon	0.45	0.78	2.02	4.30	6.50	8.58	10.56	12.40	15.99
Transverse Colon	0.42	0.75	1.94	4.13	6.28	8.29	10.22	12.05	15.51
Descending Colon	0.42	0.75	2.01	4.31	6.54	8.63	10.57	12.45	15.95
Sigmoid Colon	0.33	0.64	1.67	3.59	5.44	7.18	8.84	10.39	13.38
Heart	0.49	0.84	2.19	4.70	7.12	9.35	11.47	13.44	17.16
Kidneys	0.50	0.82	2.24	4.87	7.46	9.90	12.17	14.31	18.22
Liver	0.54	0.88	2.34	5.04	7.65	10.08	12.36	14.49	18.46
Lungs	0.69	1.03	2.70	5.74	8.64	11.30	13.76	16.05	20.28
Pancreas	0.38	0.73	1.86	3.99	6.03	7.90	9.80	11.51	14.77
Spleen	0.56	0.90	2.46	5.20	7.88	10.51	12.87	15.08	18.93
Testicles	0.37	0.57	1.59	3.53	5.36	7.01	8.70	10.19	12.89
Thymus	0.63	0.98	2.63	5.70	8.68	11.37	13.85	16.15	20.43
Thyroid	2.33	3.06	8.15	17.05	25.30	32.84	39.59	46.08	57.41
Urinary Bladder	0.38	0.67	1.78	3.84	5.81	7.70	9.43	11.20	14.38
Penis & Scrotum	0.36	0.54	1.50	3.36	5.09	6.76	8.31	9.80	12.57
Head & Neck Skin	1.83	2.39	7.14	15.34	22.83	29.57	35.65	41.22	51.24
Trunk Skin	1.53	1.99	5.98	12.93	19.34	25.17	30.46	35.30	44.08
Penis & Scrotum Skin	0.34	0.50	1.44	3.22	4.90	6.45	7.94	9.31	11.89
Leg Skin	1.36	1.72	5.19	11.22	16.74	21.72	26.22	30.35	37.79
Legs	0.59	0.83	2.39	5.19	7.84	10.30	12.57	14.69	18.57

The weighted equivalent organ doses and whole body doses were again calculated using Equation 1, shown in Table 7. As expected, the higher energies provided a higher dose to each organ and, therefore, a higher whole body dose.

Table 7. ICRP weighted equivalent organ doses and effective doses (mSv) from 1 mCi/100 cm^2 skin contamination for 1 hour.

Organ	50keV	100keV	250keV	500keV	750keV	1MeV	1.25MeV	1.5MeV	2MeV
Gonads	0.07	0.11	0.32	0.71	1.07	1.40	1.74	2.04	2.58
Colon	0.05	0.09	0.23	0.49	0.74	0.98	1.21	1.42	1.83
Red Bone Marrow	0.28	0.24	0.43	0.86	1.28	1.66	2.02	2.36	2.98
Lung	0.08	0.12	0.32	0.69	1.04	1.36	1.65	1.93	2.43
Stomach	0.06	0.10	0.27	0.57	0.87	1.15	1.41	1.66	2.10
Bladder	0.02	0.03	0.09	0.19	0.29	0.38	0.47	0.56	0.72
Liver	0.03	0.04	0.12	0.25	0.38	0.50	0.62	0.72	0.92
Thyroid gland	0.12	0.15	0.41	0.85	1.26	1.64	1.98	2.30	2.87
Esophagus	0.02	0.04	0.12	0.25	0.37	0.48	0.59	0.69	0.88
Skin	0.01	0.01	0.04	0.09	0.13	0.17	0.20	0.23	0.29
Bone surface	0.02	0.02	0.04	0.07	0.11	0.14	0.17	0.20	0.25
Remainder	0.02	0.04	0.11	0.24	0.36	0.48	0.59	0.69	0.87
Whole Body Dose	0.79	1.02	2.48	5.25	7.90	10.34	12.65	14.79	18.73

The effective doses were plotted against energy, as shown in Figure 11. This figure illustrates the activity to dose relationship. A scenario involving different skin activity can be calculated using simple linear relationships. For example, 2 mCi/ 100 cm^2 at a given energy would produce a whole body dose exactly double that of the data point specified. For energies between the intervals chosen, linear extrapolation would provide a very reasonable estimate.

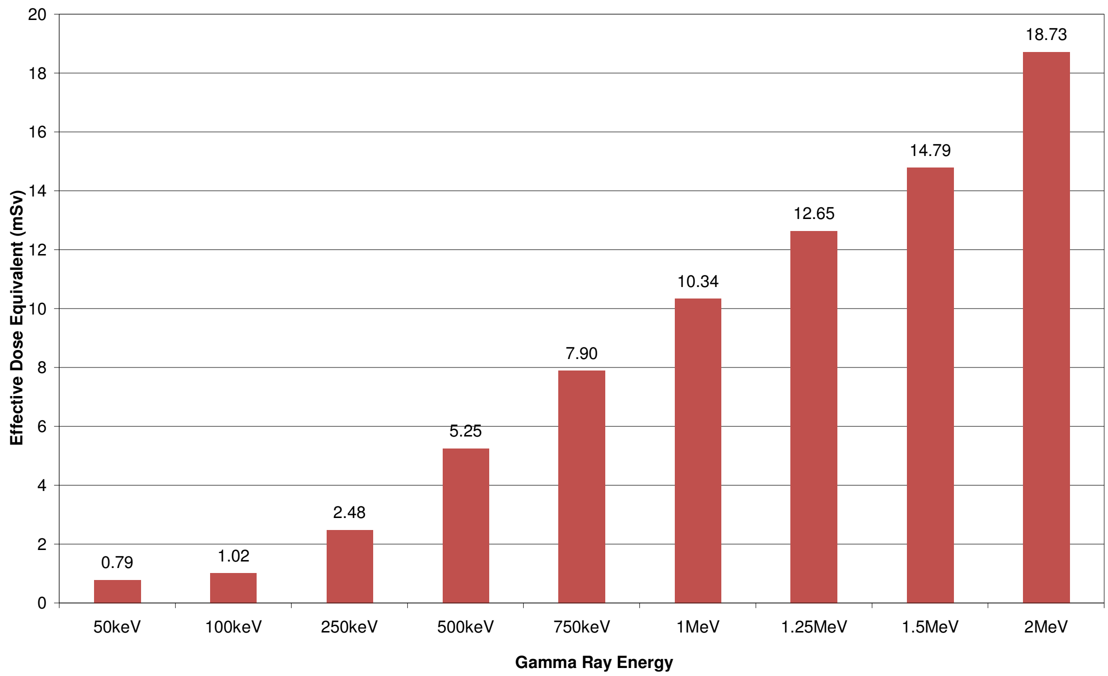

Figure 11. Effective dose for 10-year-old male from 1 mCi/100 cm^2 skin contamination.

For the ^{60}Co, ^{137}Cs, and ^{131}I simulations, each organ tally was converted from MeV per gram to mSv, the equivalent dose for each organ. Table 8 shows the organs that were tallied and their associated doses.

Table 8. Organ dose equivalents (mSv) from 1 mCi/100 cm^2 radionuclide skin contamination for 1 hour.

Organ	^{60}Co	^{137}Cs	^{131}I
Leg Bones	9.05	5.00	2.87
Arm Bones	23.31	13.06	7.42
Pelvis	10.91	6.03	3.50
Spine	13.20	7.34	4.33
Skull & Face	20.09	11.33	6.47
Ribs	17.13	9.56	5.42
Clavicles	21.56	12.09	7.04
Scapulae	19.75	11.09	6.29
Adrenals	10.97	5.99	3.28
Brain	17.92	10.07	5.62
Gall Bladder	9.88	5.35	2.92
Esophagus	11.98	6.58	3.68
Stomach	11.77	6.40	3.54
Small Intestine	9.96	5.35	2.98
Ascending Colon	10.71	5.76	3.21
Transverse Colon	10.28	5.54	3.06
Descending Colon	10.60	5.75	3.19
Sigmoid Colon	8.80	4.79	2.60
Heart	11.42	6.28	3.47
Kidneys	11.89	6.55	3.55
Liver	12.32	6.75	3.71
Lungs	13.78	7.64	4.26
Pancreas	10.01	5.33	2.95
Spleen	12.79	6.96	3.86
Testicles	8.78	4.59	2.45
Thymus	13.61	7.66	4.12
Thyroid	40.36	22.54	12.91
Urinary Bladder	9.41	5.11	2.77
Penis & Scrotum	8.35	4.49	2.41
Head & Neck Skin	35.85	20.29	11.46
Trunk Skin	30.46	17.16	9.58
Penis & Scrotum Skin	7.99	4.33	2.34
Leg Skin	26.20	14.86	8.31
Legs	12.58	6.93	3.84

The higher organ doses from the ^{60}Co are expected as its gamma energies are higher than those of ^{137}Cs and ^{131}I. The weighted equivalent dose for the organs was calculated using Equation 1 on page 13, shown in Table 9 along with the respective effective doses for the whole body. It can be seen that the whole body doses have a fairly linear relationship with their respective energies.

Table 9. ICRP weighted equivalent organ doses and effective doses (mSv) from 1 mCi/100 cm^2 radionuclide contamination for 1 hour.

Organ	^{60}Co	^{137}Cs	^{131}I
Gonads	1.76	0.92	0.49
Colon	1.21	0.66	0.36
Red Bone Marrow	2.03	1.13	0.65
Lung	1.65	0.92	0.51
Stomach	1.41	0.77	0.42
Bladder	0.47	0.26	0.14
Liver	0.62	0.34	0.19
Thyroid gland	2.02	1.13	0.65
Esophagus	0.60	0.33	0.18
Skin	0.25	0.14	0.08
Bone surface	0.17	0.09	0.05
Remainder	0.58	0.32	0.17
Whole Body Dose	12.76	6.99	3.90

MESH TALLIES

The mesh tally data was obtained for the three radionuclides: ^{60}C, ^{137}Cs, and ^{131}I. Data were used to produce contour lines on the three coordinate planes using MATLAB. The following four figures represent exposure contour curves for ^{60}Co. Figures for ^{137}Cs and ^{131}I are including in Appendix B. The coronal plane tally displays the anterior view as shown in Figure 12.

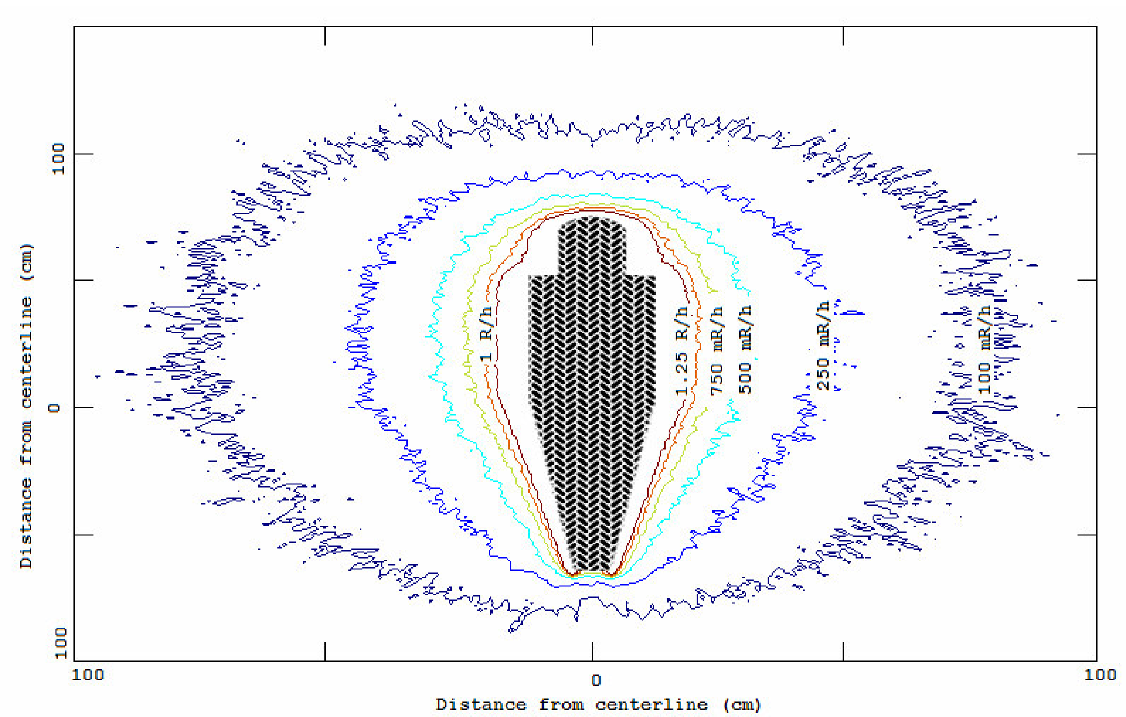

Figure 12. Anterior (frontal) view of exposure rate contour lines around body.

The contour lines are labeled in the figure and have units of R/h. These locations represent exposure rates for medical and emergency responders that would be near these points.

The same lines were calculated for the sagittal plane, shown as a right lateral view in Figure 13.

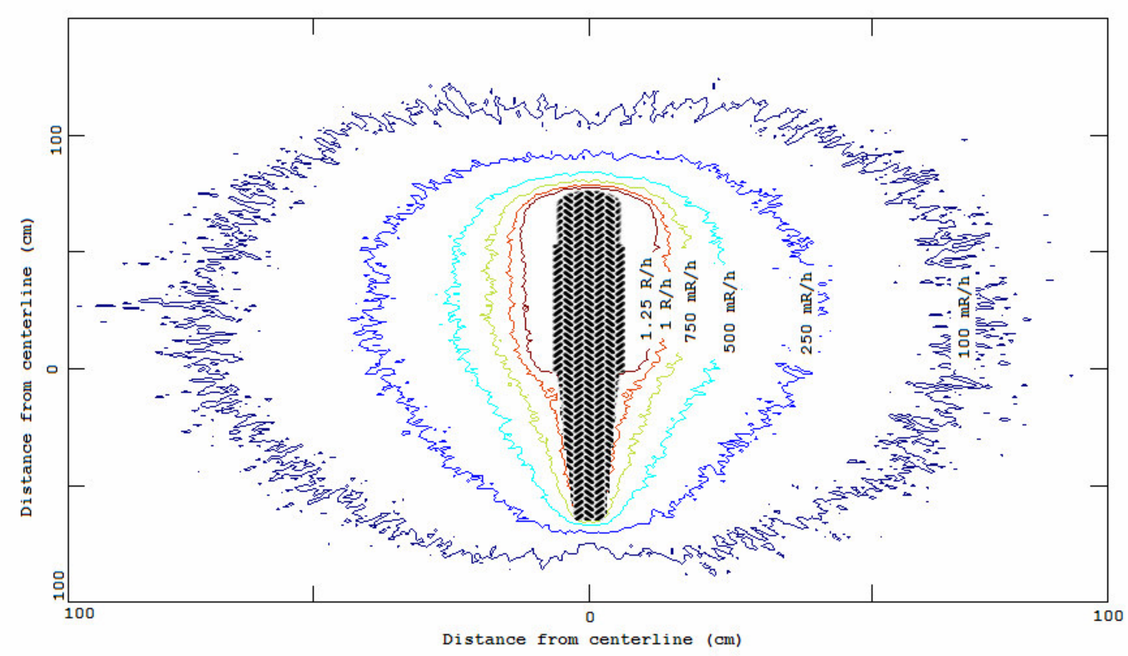

Figure 13. Lateral (side) view of exposure rate contour lines around body.

The transverse plane as viewed from above is shown in Figure 14.

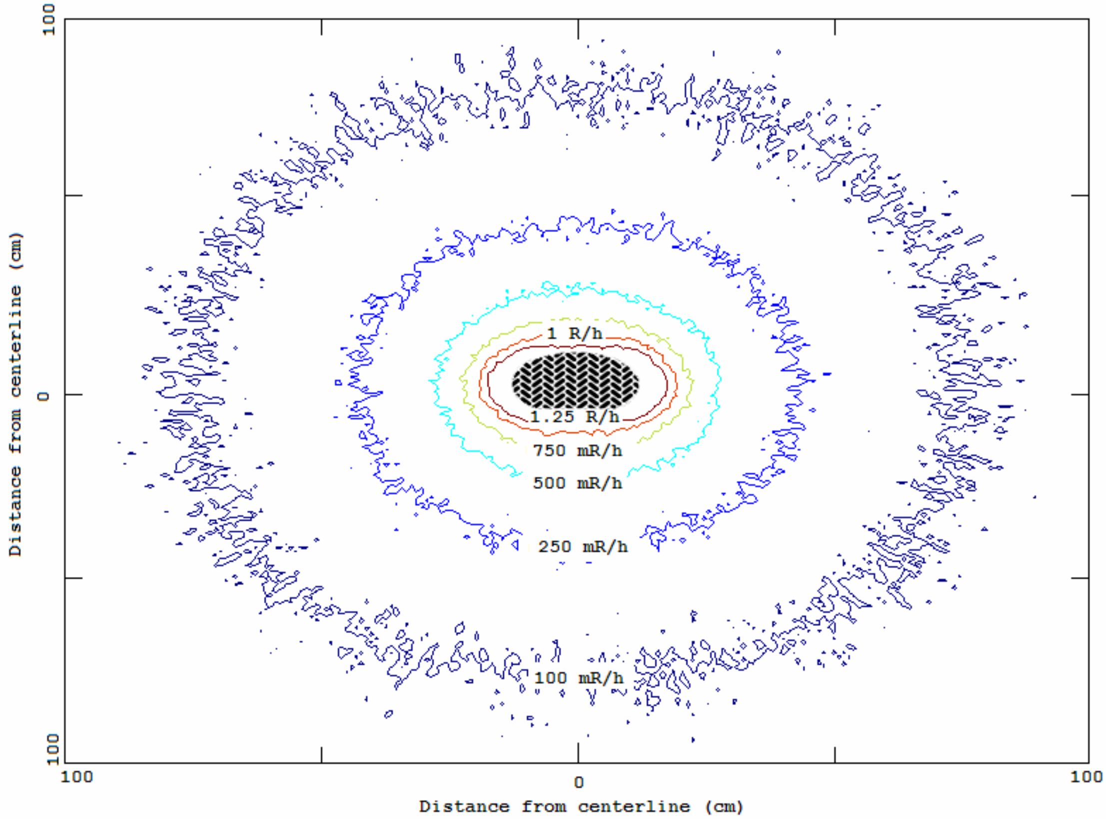

Figure 14. Dorsal (top) view of exposure rate contour lines around body.

A three-dimensional mesh tally was also compiled for ^{60}Co. It extended 75 cm to either side of the body, 50 cm to the anterior and posterior, and 125 cm dorsally and ventrally. It was compiled in MATLAB and plotted with a color scaling ratio correlating to the exposure rate. The resulting image is shown in Figure 15.

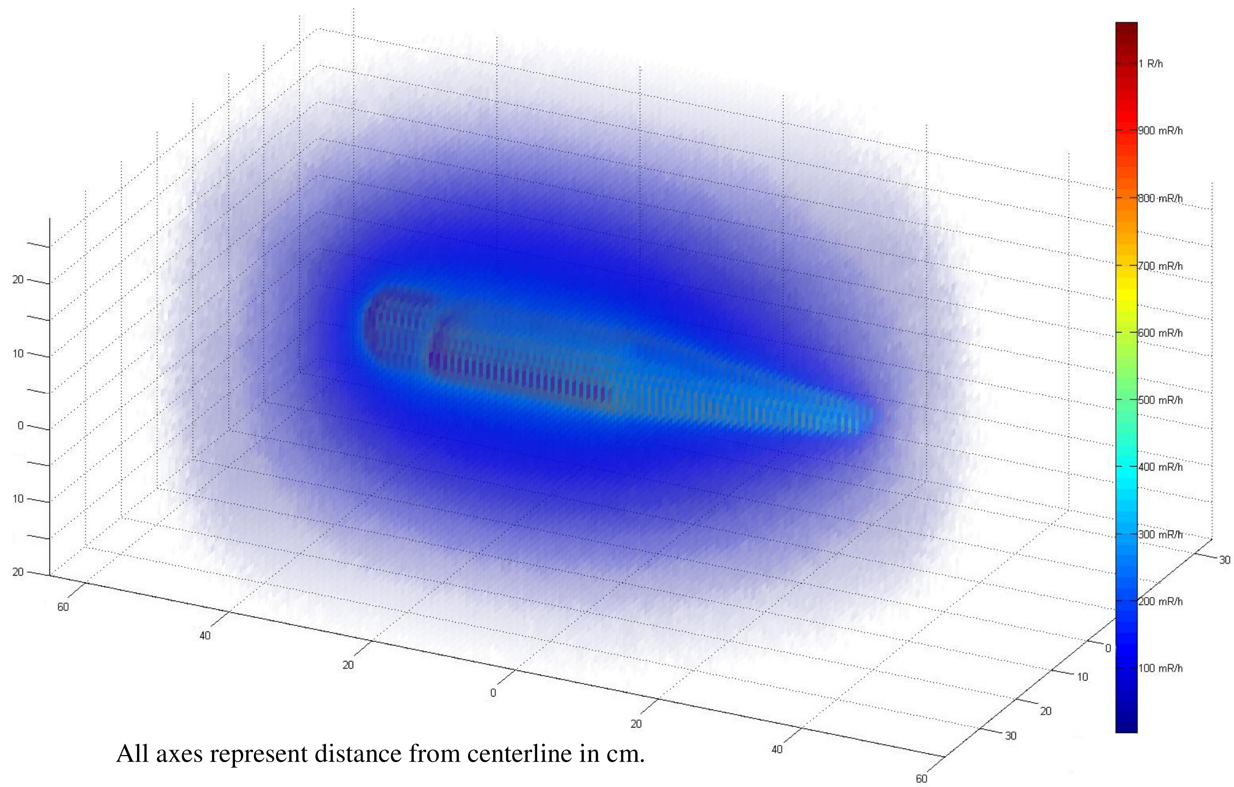

Figure 15. Three-dimensional representation of exposure rate levels around body.

CHAPTER IV

CONCLUSIONS

The organ doses responded as expected with respect to energy. High-energy gamma-rays have higher penetrability and, therefore, will irradiate more organs deeper in the body. The exposure rates given in the contour plots for ^{60}Co are also consistent with expected values. The concentric shapes around the body provide baseline exposure rates for medical responders that must work around contaminated individuals. The most advantageous position for medical personnel to work is directly above the head or directly below the feet. This is due to the geometrical position of the source and can be seen from the indented locations on the top and bottom of Figures 12 and 13.

The statistics in these calculations were well within reasonable MCNP expectations. The relative errors of the organ tissue doses were less than 1%. The FMESH tallies were higher in relative error, not exceeding 25%. This error is simply due to the thickness of the planes used. The one centimeter grid was thin relative to the direction of photon fluence. This thickness proved difficult for the track length statistics to converge in such a small region.

While the value of a standard activity used throughout the experiment was assumed, it does not represent a single data point. Linear scaling can be used to increase or decrease the value of the skin activity, increasing or decreasing the effective doses.

While these data provide solid results for the scenario, there are many assumptions that do not allow the scenario to exist in the real world. Uniform contamination on the skin is highly unlikely, especially when considering the clothing and hair that prevent much of the contamination from reaching the skin. It is also unlikely that a person involved in an emergency will have contamination on the skin but will not have ingested or inhaled any radioactive particles.

FUTURE WORK

Many of the problems associated with this model lie in the assumptions that were made. The "standard activity" used for calculations was based on the legal dose limits, chosen at a nominal value representative of an emergency scenario. A skin activity derived from air concentration would provide a baseline for this presumed data. The air concentration value would also allow inhalation and ingestion models to be used in conjunction with this model.

The assumption of uniform activity also presents many real world problems. While this is a dramatically conservative assumption, this could be remedied by sectioning areas of the skin into different regions. Each region would allow for independent calculations to be performed. In the event of the emergency, only selected areas of the skin could be chosen for dose calculations to obtain more accurate data.

The calculated values given in this research may differ significantly from data obtained using other phantoms. This phantom represents a standardized model of a 10-year-old male. While newer phantoms may be more realistic in their physical nature, they do not represent a standard to which an actual person can be compared.

One improvement that can be made to the model used is that for the bone dose. The dose calculated in MCNP for the bone was applied to the red bone marrow dose and bone surface dose. Red bone marrow, however, is not uniformly distributed throughout the bone. If included as a separate cell, this would provide a more accurate number to the red bone marrow dose and the effective dose as well. The red bone marrow dose could also be calculated using its mass ratio relative to the bone mass.

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APPENDIX A

SAMPLE MCNP INPUT CODE

```
Male Phantom at 10.0 Years - Uniform Co-60 Contamination on the Skin
c +++++++++++++++++++++++++++++++++++++++++
c
c    File Prepared by Body Builder
c    CopyRight 1996-1998, White Rock Science
c
c    This input file is for the use of
c    BodyBuilder License holder only.
c    Distribution is Prohibited.
c
c +++++++++++++++++++++++++++++++++++++++++
c
c ++++++++++++++++++++++++++++++++++++++++++++++
c           CELLS
c ++++++++++++++++++++++++++++++++++++++++++++++
c SkeletonVolume = 3321.900000, skel_vol = 3307.142857
c
c         LEG BONES
50      2 -1.40    -4 53 (-51:-52)
                 vol=  1250.00 imp:n,p,e = 1
c
c         ARM BONES
70     2 -1.40     4 -73 (-71:-72)
                 vol=   404.00 imp:n,p,e = 1
c
c         PELVIS
90     2 -1.40     91 -92 93 4 -101 (95:-94)
                 vol=   258.00 imp:n,p,e = 1
c
c         SPINE
100    2 -1.40   (-100 -103 101):(-100 -8 103):(-105 -102 8)
              vol=   411.00  imp:n,p,e = 1
c
c         SKULL & FACE
110    2 -1.40   (111 -110):(121 -120 122 -1 -123 110)
                 vol=   595.00 imp:n,p,e = 1
c
c         RIBS
130    2 -1.40    132 -131 ((134 -133):(136 -135):(138 -137):(74 -139):
                 (76 -75):(78 -77):(80 -79):(82 -81):(84 -83):
                 (86 -85):(88 -87):(98 -89))
                 vol=   295.00 imp:n,p,e = 1
c
c         CLAVICLES
140    2 -1.40    -140 ((141 -143):(-142 144))
                 vol=    23.20 imp:n,p,e = 1
c
c         SCAPULAE
150    2 -1.40     131 -156 154 -155 ((150 -152):(-151 153))
```

```
                 vol=    85.70 imp:n,p,e = 1
c
c         ADRENALS
160     1 -1.04     162 (-160:-161)
                  vol=     6.94 imp:n,p,e = 1
c
c         BRAIN
180     1 -1.04    -111
                 vol=  1310.00 imp:n,p,e = 1
c
c         GALL BLADDER
200   1 -1.04       (-202 -200):(202 -201 -203)
                 vol=    44.00 imp:n,p,e = 1
c
c         ESOPHAGUS
212   1 -1.04       (213 -212 322 -8 100) :
                    (-216 217 -218 210 350 100)
                 vol=   18.70 imp:n,p,e = 1
c           Air in Upper Esophagus
213   4 -0.001293   -213 322 -8
                              imp:n,p,e = 1
c
c         STOMACH
210   1 -1.04       -210
                 vol=   209.80 imp:n,p,e = 1
c
c         SMALL INTESTINE
220   1 -1.04       -91 221 -222 223 -7
C                exclude         Ascending Colon
                        (232:230:-223)
c                exclude         Transverse Colon
                        (240 :241 :-242 )
c                exclude         Descending Colon
                        (232:250:-223)
                  vol=   447.00 imp:n,p,e = 1
c
c         ASCENDING COLON
230   1 -1.04       -230 231 -232
                  vol=    79.60 imp:n,p,e = 1
c
c         TRANSVERSE COLON
240   1 -1.04       -240 -241 242
            vol=   104.00 imp:n,p,e = 1
c
c         DESCENDING COLON
250   1 -1.04       -250 251 -232
             vol=   81.70 imp:n,p,e = 1
c
c         SIGMOID COLON
280   1 -1.04       (-280 282 -251):(-281 -282 4)
             vol=   45.00 imp:n,p,e = 1
c
c         HEART
290     1 -1.04     (290((-291 -292):(291 -293))):
```

```
                   (-290((-291 -295):(291 -294)))
                 vol=   355.00 imp:n,p,e = 1
c
c         KIDNEYS
310     1 -1.04     (-310 312 -162):(-311 -313 -162)
                  vol=   166.00 imp:n,p,e = 1
c
c         LIVER
320     1 -1.04     -320 -321 7 -322 -132
                   vol=   853.00 imp:n,p,e = 1
c
c         LUNGS
330     3 -0.296   332 ((-331 (-335:336:334:-333)):
                        (-330 ( 339:338:337)))
                 vol=  1530.00 imp:n,p,e = 1
c
c         PANCREAS
350   1 -1.04       -350 351 (352:-312)
                 vol=    28.90 imp:n,p,e = 1
c
c         SPLEEN
360   1 -1.04       -360
                 vol=   74.40 imp:n,p,e = 1
c
c         TESTICLES
370   1 -1.04       -370:-371
             vol=    1.82 imp:n,p,e = 1
c
c         THYMUS
380     1 -1.04  -380
                vol=    30.20 imp:n,p,e = 1
c
c         THYROID
390     1 -1.04    -390 391 -392 -393 8
                 vol=     7.62 imp:n,p,e = 1
c
c         URINARY BLADDER
410   1 -1.04       -410
             vol=  120.90 imp:n,p,e = 1
c
c         PENIS & SCROTUM
40     1 -1.04       -1 -4 47 -45 49 -48 37 38
c                exclude         Testicles
                  370 371
             vol=   34.38 imp:n,p,e = 1
c
c         SKIN
c
c              Head & Neck Skin
22    1 -1.04       (-21 22 9):(-20 23 -9 12):(28 -27 8 -12)
             vol=  127.00 imp:n,p,e = 1
c            (Above Volume for Head + Neck Skin Combined
c
c           Trunk Skin
```

```
17    1 -1.04       (-8 18 20 -10)
                  : (4 -18 -10 11)
             vol=  385.00 imp:n,p,e = 1
c
c         Penis & Scrotum Skin
41     1 -1.04       -1 -4  41 -42 43 -44 31 32 #40
c                exclude         Testicles
                  370 371
             vol=    4.05 imp:n,p,e = 1
c        Legs Skin
34    1 -1.04      (-4 34 -31 36 32):(-31 33 -36 32)
             vol=  181.50 imp:n,p,e = 1
35    1 -1.04      (-4 35 -32 36 31):(-32 33 -36 31)
             vol=  181.50 imp:n,p,e = 1
c
c            HEAD
c
20    1 -1.04       ((-22 9):(-23 -9 12))
c                exclude         Skull & Brain
                       110
c                exclude         Face Bones
                       (-121:120:-122:1:123:-110)
c                exclude         Spine
                       (105:-8:102)
c                exclude         Thyroid
                       (390:-391:392:393:-8)
                 imp:n,p,e = 1
c
c            NECK
c
27    1 -1.04       -28 8 -12
c                exclude         Spine
                        105
c                exclude         Thyroid
                       (390:-391:392:393:-8)
                 imp:n,p,e = 1
c
c         OUTER TRUNK---ARMS & SCAPULAE
c
10    1 -1.04       4 131 -18 -11
c                exclude         Scapulae
                       (-131:156:-150:152:-154:155)
                       (-131:156:151:-153:-154:155)
c                exclude         Arm Bones
                       (-4:71:73) (-4:72:73)
                 imp:n,p,e = 1
c
c         UPPER TRUNK---ABOVE RIBS
c
11    1 -1.04   ((-18 -131 133) : (-8 18 -20 -10))
c                exclude         Spine
                      (105:102:-8)(100:8:-133)
c                exclude         Clavicles
                      (140:-141:143) (140:142:-144)
```

```
c                 exclude         Upper Lungs
                         (-133:330) (-133:331)
c                 exclude          Thymus
                         380
c                 exclude          Esophagus
                        #212 #213
                  imp:n,p,e = 1
c
c
c          UPPER RIB CAGE
c
12    1 -1.04       -131 132 79 -133
c                 exclude         Ribs 1-9
                   (131:-132:133:-134) (131:-132:135:-136) (131:-
132:137:-138)
                   (131:-132:139:-74) (131:-132:75:-76) (131:-132:77:-
78)
                  imp:n,p,e = 1
c
c
c          LOWER RIB CAGE
c
13    1 -1.04       -131 132 -79 98
c                 exclude         Ribs 10-12
                   (131:-132:85:-86) (131:-132:87:-88) (131:-132:89:-98)
                   (131:-132:79:-80) (131:-132:81:-82) (131:-132:83:-84)
                  imp:n,p,e = 1
c
c
c          HIGH CHEST ORGANS
c
14    1 -1.04       -132 -133 332
c                 exclude          Spine
                         (100:133:-332)
c                 exclude          Heart
                         #290
c                 exclude          Lungs
                         (330:133:-332:(-339 -338 -337))
                         (331:133:-332:(335 -336 -334 333))
c                 exclude          Thymus
                         380
c                 exclude          Esophagus
                        #212 #213
                  imp:n,p,e = 1
c
c          CHEST---LIVER LEVEL
c
15    1 -1.04       ((-132 -332 98):(-131 -98 7))
c                 exclude          Spine
                         (100:332:-7)
c                 exclude          Adrenals
                        (160:-162) (161:-162)
c                 exclude          Gall Bladder
                         (202:200) (-202:201:203)
```

```
c                exclude          Kidneys
                        (310:-312) (311:313)
c                exclude          Liver
                        #320
c                       (320:321:322:-7)
c                exclude         Pancreas
                       (350:-351:(-352 312))
c                exclude          Spleen
                        360
c                exclude          Esophagus
                       #212 #213
c                exclude         Stomach
                       210
                 imp:n,p,e = 1
c
c
c         LOWER TRUNK
c
16    1 -1.04       -131 4 -7
c                exclude           Spine
                        (100:-101:7)
c                exclude           Pelvis
                        #90
c                exclude           Small Intestine
                        (91:-221:222:-223:7)
c                exclude           Ascending Colon
                        (232:230:-231)
c                exclude           Descending Colon
                        (232:250:-251)
c                exclude           Sigmoid Colon
                        (280:-282:251) (281:282:-4)
c                exclude           Urinary Bladder
                        410
                 imp:n,p,e = 1
                 imp:n,p,e = 1
c
c        LEGS
c
30     1   -1.04 (-4 53 -35 52 ):(-4 53 -34 51 ):(-35 -53 36 ):(-34 -53
36 )
             vol=  7317.00 imp:n,p,e = 1
c
c         SURROUNDING AIR
600    4 -0.001293   -600
c            exclude         HEAD & NECK
                       (802:-9)  (803:9:-804)
c            exclude         TRUNK
                        (-4:805:804)
c            exclude         LEGS
                        (4:-33:(37 38))
c                exclude         GENITALIA
                    (1:4:-41:42:-43:44:-31:-32)
             imp:n,p,e = 1
c            air            OUTSIDE of NECK
```

```
601    4 -0.001293   -803 801 804 -12
             imp:n,p,e = 1
c
c
c        1MM AIR SURROUNDING SKIN USED FOR SOURCE
900   4  -0.001293 (21 -802 9):(20 -803 -9 12):  $head
             (27 -801 -12 8):                    $neck
             (8 -804 -10 801):                   $shoulder
             (4 -804 10 -805):                   $torso
             (-4 -37 31 33 ):(-4 -38 32 33) #41  $legs
             imp:n,p,e = 1
c
c
c
c         VOID
700   0               600
             imp:n,p,e = 0

c ++++++++++++++++++++++++++++++++++++++++++++++
c           SURFACES
c ++++++++++++++++++++++++++++++++++++++++++++++
c Planes used in several places
c
1     py 0
4     pz 0
332   pz    31.5700
7     pz    19.5900
8     pz    50.8000  $bottom of neck
9     pz    67.1800  $flat top of head
12    pz    55.5000  $top of neck
c
c
c Planes used for source air
801   cz     4.6000
$neck
802   sq  4264.4255  2691.8520  5387.7761 0 0 0 -248691.3171 0 0
67.232   $top of head
803   sq    92.3867    58.3177 0 0 0 0 -5391.476074 0 0 0
$side of head
804   pz    50.9000
$shoulder
805   sq    73.2531   199.8491 0 0 0 0 -14639.558645 0 0 0
$torso
c
c
c         BODY SURFACE
c
c            HEAD
21    sq  4039.2380  2537.7112  5117.2562 0 0 0 -229028.4313 0 0
67.180
22    sq  3837.3069  2397.4439  4877.9050 0 0 0 -211838.1446 0 0
67.180
20    sq    90.2500    56.7009 0 0 0 0 -5117.256225 0 0 0
23    sq    88.3600    55.2049 0 0 0 0 -4877.904964 0 0 0
```

```
c
c
c            NECK
27    cz      4.5000
28    cz      4.4000
c
c
c            TORSO
10    sq    72.2500   196.0000 0 0 0 0 -14161.000000 0 0 0
11    sq    70.5600   193.2100 0 0 0 0 -13632.897600 0 0 0
18    pz    50.7000
c
c            LEGS
c      left
31    gq 1 1 0 0 0  -0.1544   -14.0000 0 0 0
32    gq 1 1 0 0 0   0.1544    14.0000 0 0 0
33    pz  -66.100
34    gq 1 1 0 0 0  -0.1544   -13.9000 0 0 0
35    gq 1 1 0 0 0   0.1544    13.9000 0 0 0
36    pz  -66.000
37    gq 1 1 0 0 0  -0.1544   -14.1000 0 0 0
38    gq 1 1 0 0 0   0.1544    14.1000 0 0 0
c
c        PENIS & SCROTUM
41    pz     -1.7800
42    p  0 -12.95 -1  90.00
43    p   -12.95 0 1 -90.00
44    p    -12.95 0 -1  90.00
47    pz     -1.6800
45    p  0 -13.04 -1  90.00
49    p   -13.04 0 1 -90.00
48    p    -13.04 0 -1  90.00
c
c     SKELETON
c
c
c        LEG BONES
51    gq   1 1  0.005459 0 0  -0.154679   -13.900000
            0   0.963851      42.3854
52    gq   1 1  0.005459 0 0   0.154679    13.900000
            0   0.963851      42.3854
53    pz   -65.9000
c
c        ARM BONES ( left/right) )
71     gq   1.062812     0.194065 0 0 0     0.020590
             -28.217664 0    -0.283315   187.044744
72    gq   1.062812   0.194065 0 0 0    -0.020590
              28.217664 0    -0.283315     187.044744
73    pz      50.0700
c
c        PELVIS
91    sq    90.0601    61.6225 0 0 0 0 -5549.7285
       0    -3.1900 0
92    sq   101.6064    69.5556 0 0 0 0 -7067.2941 0    -2.5200 0
```

```
93    py    -2.5200
94    py     4.2000
95    pz    10.1600
c
c         SPINE
100      sq      4.4100     1.9321 0 0 0 0    -8.5206 0     4.6200 0
105      sq      4.4100     1.9321 0 0 0 0    -8.5206 0     0.9000 0
101      pz    15.9700
102      pz    60.8400
103      pz    25.4700
c
c     SKELETON
c
c
c             SKULL (head)
c
c
c             CRANIUM
110    sq  3365.2761  2072.1796  4316.0958 0 0 0
     -173488.0607 0 0    67.1800
111    sq   2311.8403  1362.4736  3047.5699 0 0 0
          -97976.0213 0 0    67.1800
c
c         FACIAL
120      sq     79.2100    48.0249 0 0 0 0 -3804.0523 0 0 0
121      sq     66.5856    38.3161 0 0 0 0 -2551.3005 0 0 0
c
122      pz    59.1100
123      pz    69.2300
c
c         RIBS
131      sq     67.7329   139.7124 0 0 0 0 -9463.1260 0 0 0
132      sq     61.4656   130.6449 0 0 0 0 -8030.1672 0 0 0
133      pz    48.8900
134     pz    47.8700
135     pz     46.8500
136     pz     45.8300
137     pz     44.8100
138     pz     43.7900
139     pz     42.7700
74      pz     41.7500
75      pz     40.7300
76      pz     39.7100
77      pz     38.6900
78      pz     37.6700
79      pz     36.6500
80      pz     35.6300
81      pz     34.6100
82      pz     33.5900
83      pz     32.5700
84      pz     31.5500
85      pz    30.5300
86      pz    29.5100
87      pz    28.4900
```

```
88      pz    27.4700
89      pz    26.4500
98     pz    25.4300
c
c         CLAVICLES
140     tz    0     4.9300    49.5300
           12.4000   0.598100   0.598100
141     p   6.258100 1 0      4.930
142     p   6.258100 -1 0     -4.930
143     p   0.657080 1 0      4.930
144     p   0.657080 -1 0     -4.930
c
c         SCAPULAE
156     sq    67.7329   174.2400 0 0 0 0 -11801.7805
           0 0 0
150   p      0.3000 1 0 0
151   p      0.3000 -1 0 0
152   p      0.9700 1 0 0
153   p      0.9700 -1 0 0
154   pz    36.9400
155   pz    48.8400
c
c         ADRENALS
160   1 sq     2.0042    18.0379     0.2082 0 0 0    -2.7436 0 0 0
161   2 sq     2.0042    18.0379     0.2082 0 0 0    -2.7436 0 0 0
162    pz    27.5800
c
c         GALL BLADDER
200  3 so     1.8740
201  3 gq 1 1 -0.05175625 0 0 0 0 0   0.852670  -3.511876
202  3 pz 0
203  3 pz     7.0700
c
c         ESOPAHGUS
212    sq     0.1296     0.6241 0  0 0 0    -0.0809 0     2.0400 0
213    sq     0.0121     0.2916 0  0 0 0    -0.0035 0     2.0400 0
216 6  cx     0.5200
217 6  px     0.0000
218 6  px     5.7500
c
c         STOMACH
210    sq   253.4273   332.8216    74.0219 0 0 0 -2498.6918
              5.5600    -3.5100    25.4000
c extent     2.4200     8.7000    -6.2500    -0.7700    19.5900
31.2100
c
c         SMALL INTESTINE
221    py    -4.0800
222    py     1.8500
223    pz    12.3400
c
c         ASCENDING COLON
230    sq     4.4100     3.0276 0 0 0 0   -13.3517    -5.9100    -
1.9800 0
```

```
231    pz    10.4900
232    pz    17.4200
c
c         TRANSVERSE COLON
240    sq  0   1.166400     4.4100 0 0 0    -5.1438 0    -1.9800
18.5100
241    px     7.3000
242    px    -7.3000
c
c
c         DESCENDING COLON
251     pz     6.3300
250    gq   3.204100   1.716100     0.069190 0     0.649921    -
0.313245
            -35.748001      -4.113998       0.968404    96.676774
c
c
c         SIGMOID COLON
282    px     2.0900
280    ty     2.0900 0     6.3300     4.1500     1.5000     0.9600
281    ty      2.090 0 0      2.180     1.5000     0.9600
c
c         HEART
c
290  4 px 0
291  4 pz 0
c
c         Left Ventricle
292   4 sq   461.4591  1360.1639   695.9888 0 0 0 -20900.8226 0 0 0
c        Right Ventricle
293   4 sq    90.7371   267.4500   695.9888 0 0 0 -4109.7444 0 0 0
c
c        Left Atrium
294   4 sq    90.7371   105.6558   274.9495 0 0 0 -1623.5491 0 0 0
c
c        Right Atrium
295   4 sq   461.4591   537.3309   274.9495 0 0 0 -8256.8422 0 0 0
c
c
c         KIDNEYS
310    sq    34.4017   213.2593    28.9466 0 0 0  -460.8320
              4.1700     5.0400    23.5900
311    sq    34.4017   213.2593    28.9466 0 0 0  -460.8320
             -4.1700     5.0400    23.5900
312    px     1.7400
313    px    -1.7400
c
c         LIVER
320    sq    46.6489   130.6449 0 0 0 0 -6094.4409 0 0 0
321     p       926.0       686.0      -652.1    -20353.5
322    pz    31.2100
c
c
c         LUNGS
```

```
330    sq      12.0442       4.4282       0.5792 0 0 0
                -175.7536     5.9100 0    31.5700
331   sq      12.0442       4.4282       0.5792 0 0 0
               -175.7536    -5.9100 0    31.5700
333    px    -4.1000
334    py     1.3000
335    pz    33.4000
336    pz    39.6000
337    px     5.9000
338    py     0.7500
339    pz    40.0000
c
c         PANCREAS
350 sq     3.9856   479.4042    86.1704 0 0 0  -405.7677
          -0.3800 0    26.8500
351    px    -0.3800
352    pz    26.8500
c
c         SPLEEN
360    sq    53.4069   111.7355    16.6660 0 0 0  -315.3622
               7.6500     2.5200    26.8500
c extent     5.2200    10.0800     0.8400     4.2000    22.5000
31.2000
c
c         TESTICLES
370    sq     0.2134440     0.155867     0.066822 0 0 0    -0.0471498
               0.4700    -6.1500    -0.8400
371    sq     0.2134440     0.155867     0.066822 0 0 0    -0.0471498
              -0.4700    -6.1500    -0.8400
c
c         THYMUS
380    sq    15.2100    52.0562     3.4225 0 0 0
             -52.0562 0    -6.1300    43.0000
c extent    -1.8500     1.8500    -7.1300    -5.1300    39.1000
46.9000
c
c             THYROID
390    c/z 0    -2.7500     1.6000
391    c/z 0    -2.7500     0.7300
392    py    -2.7500
393    pz    54.4300
c
c         URINARY BLADDER
410    sq    63.9232    90.1417   120.4375 0 0 0  -833.0538 0
               3.7800     5.8100
c extent    -3.6100     3.6100     0.7400     6.8200     3.1800
8.4400
c      Void
600    so 301
c
c     STATISTICS
c  Weight =    32.69 kg ( =    72.07 pounds)
c  Height =   139.97 cm ( =    55.11 inches)
```

```
c +++++++++++++++++++++++++++++++++++++++++++++
c
c         TRANSFORMATIONS
c +++++++++++++++++++++++++++++++++++++++++++++
c
c         ADREANALS
tr1        2.430      4.200    27.5800
        0.541708   0.840566 0
       -0.840566   0.541708 0
      0       0       1
tr2       -2.430      4.200    27.5800
        0.541708  -0.840566 0
        0.840566   0.541708 0
      0       0       1
c
c         GALL BLADDER
tr3       -1.690     -2.690     21.770
       -0.040000       0.985  -0.166100
        0.972200   0.000000   -0.234200
        0.230700   0.170900    0.957900
c
c         HEART
tr4       0.800     -1.700     36.600
       0.634500  -0.537000  -0.555900
      -0.424300   0.359100  -0.831200
       0.646000   0.763300       0.000
c
c         ESOPHAGUS
tr6       0.000      2.040     30.620
       0.678998  -0.677776  -0.282102
       0.706470   0.707743   0.000000
       0.199655  -0.199296       0.959
c
c +++++++++++++++++++++++++++++++++++++++++++++
c      MATERIALS
c      Compositions from ORNL Report TM-8381
c +++++++++++++++++++++++++++++++++++++++++++++
c      Adult Tissues (Density = 1.04 g/cc)
m1       1000  -0.10454
         6000  -0.22663
         7000  -0.02490
         8000  -0.63525
        11000  -0.00112
        12000  -0.00013
        14000  -0.00030
        15000  -0.00134
        16000  -0.00204
        17000  -0.00133
        19000  -0.00208
        20000  -0.00024
        26000  -0.00005
        30000  -0.00003
        37000  -0.00001
        40000  -0.00001
```

```
c
c       Skeleton (Density = 1.4 g/cc)
m2       1000  -0.07337
         6000  -0.25475
         7000  -0.03057
         8000  -0.47893
         9000  -0.00025
        11000  -0.00326
        12000  -0.00112
        14000  -0.00002
        15000  -0.05095
        16000  -0.00173
        17000  -0.00143
        19000  -0.00153
        20000  -0.10190
        26000  -0.00008
        30000  -0.00005
        37000  -0.00002
        38000  -0.00003
        82000  -0.00001
c
c       Lung (Density = 0.296 g/cc)
m3       1000  -0.10134
         6000  -0.10238
         7000  -0.02866
         8000  -0.75752
        11000  -0.00184
        12000  -0.00007
        14000  -0.00006
        15000  -0.00080
        16000  -0.00225
        17000  -0.00266
        19000  -0.00194
        20000  -0.00009
        26000  -0.00037
        30000  -0.00001
        37000  -0.00001
c
c      Air (Density = 0.001020 /cc)
m4       6000  -0.00012
         7000  -0.75527
         8000  -0.23178
        18000  -0.01283
c
c
mode p e
c
nps 5000000
c
c
SDEF PAR=2 ERG=D1 CEL=900 POS=0 0 0 AXS=0 0 1 RAD=D2 EXT=D3 EFF=0.0001
SI1 L 1.173  1.332
SP1 D 1      1
SI2   0      14.15
```

```
SP2  -21     1
SI3  -66.15  74.15
SP3   0      1
c
c
f6:p        50     $LEG BONES
f16:p       70     $ARM BONES
f26:p       90     $PELVIS
f36:p      100     $SPINE
f46:p      110     $SKULL & FACE
f56:p      130     $RIBS
f66:p      140     $CLAVICLES
f76:p      150     $SCAPULAE
f86:p      160     $ADRENALS
f96:p      180     $BRAIN
f106:p     200     $GALL BLADDER
f116:p     212     $ESOPHAGUS
f126:p     210     $STOMACH
f136:p     220     $SMALL INTESTINE
f146:p     230     $ASCENDING COLON
f156:p     240     $TRANSVERSE COLON
f166:p     250     $DESCENDING COLON
f176:p     280     $SIGMOID COLON
f186:p     290     $HEART
f196:p     310     $KIDNEYS
f206:p     320     $LIVER
f216:p     330     $LUNGS
f226:p     350     $PANCREAS
f236:p     360     $SPLEEN
f246:p     370     $TESTICLES
f256:p     380     $THYMUS
f266:p     390     $THYROID
f276:p     410     $URINARY BLADDER
f286:p      40     $PENIS & SCROTUM
f296:p      22     $HEAD & NECK SKIN
f306:p      17     $TRUNK SKIN
f316:p      41     $PENIS & SCROTUM SKIN
f326:p      34     $LEG SKIN
f336:p      35     $LEG SKIN
f346:p      30     $LEGS
c
c
fmesh4:p origin= -175 -175 -0.5
         imesh= 175 iints=349
         jmesh= 175 jints=349
         kmesh= 0.5 kints=1   out=ij
c
fmesh14:p origin= -175 -0.5 -250
         imesh= 175 iints=349
         jmesh= 0.5 jints=1
         kmesh= 250 kints=499 out=ik
c
fmesh24:p origin= -0.5 -175 -250
         imesh= 0.5 iints=1
```

```
          jmesh= 175 jints=349
          kmesh= 250 kints=499 out=jk
c
print
c
```

APPENDIX B

EXPOSURE RATE FIGURES FOR ^{137}CS AND ^{131}I

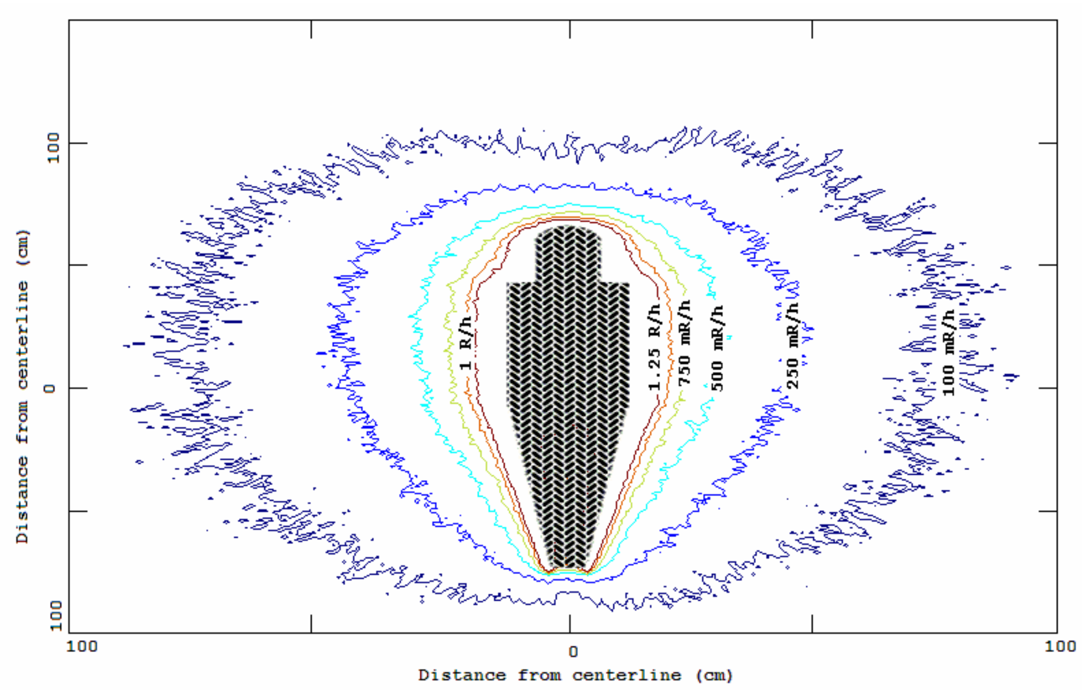

Figure B1. Anterior (frontal) view of exposure rate contour lines around body for ^{137}Cs.

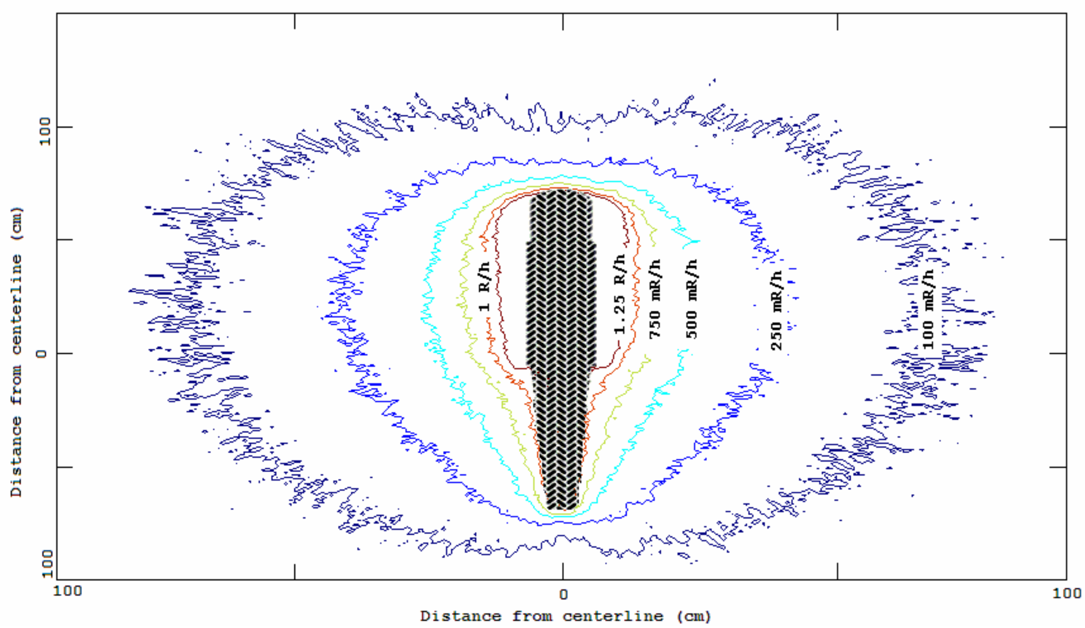

Figure B2. Lateral (side) view of exposure rate contour lines around body for ^{137}Cs.

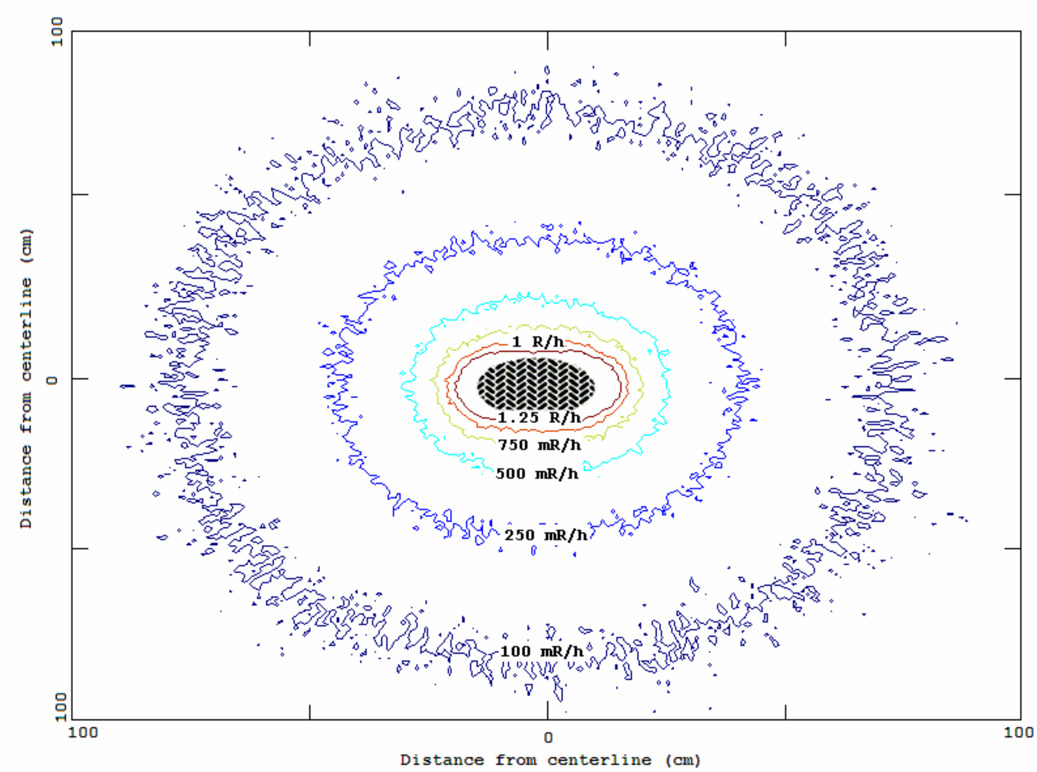

Figure B3. Dorsal (top) view of exposure rate contour lines around body for ^{137}Cs.

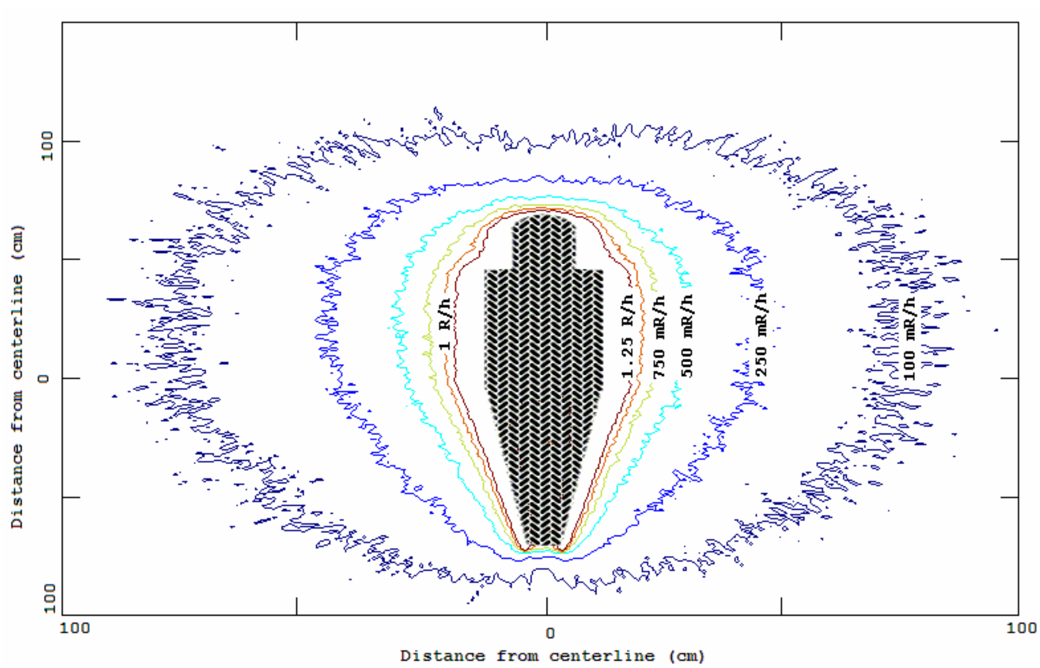

Figure B4. Anterior (frontal) view of exposure rate contour lines around body for ^{131}I.

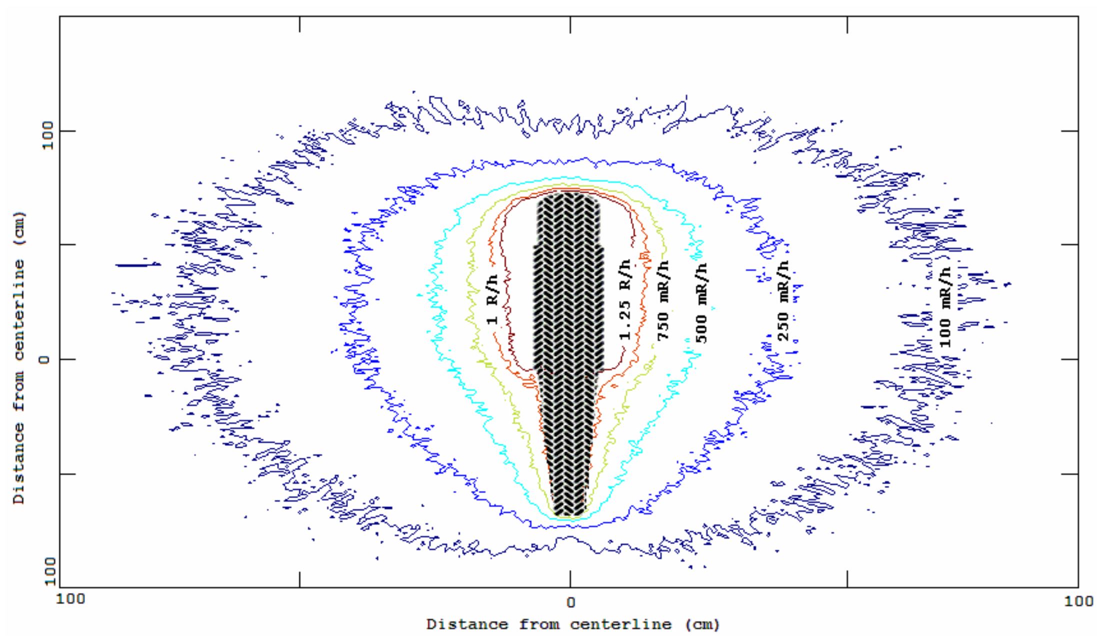

Figure B5. Lateral (side) view of exposure rate contour lines around body for ^{131}I.

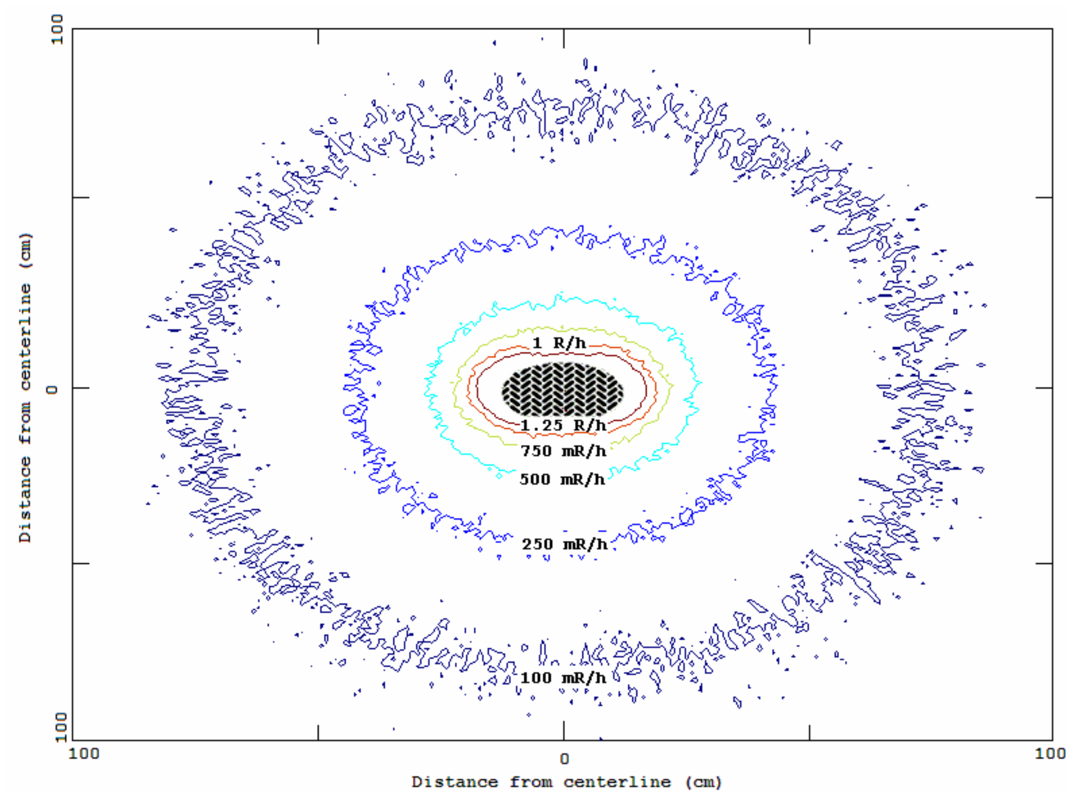

Figure B6. Dorsal (top) view of exposure rate contour lines around body for ^{131}I.

VITA

Name: Jeffrey Aaron Kowalczik

Address: Department of Nuclear Engineering
Texas A&M University
3133 TAMU
College Station, TX 77843-3133

Email Address: kowalczik@tamu.edu

Education: B.S., Radiological Health Engineering, Texas A&M University, 2006

M.S., Health Physics, Texas A&M University, 2008