ESTIMATING THE EXPOSURE TO FIRST RECEIVERS FROM A CONTAMINATED VICTIM OF A RADIOLOGICAL DISPERSAL DEVICE DETONATION

A Thesis

by

HOLLY ANNE PHILLIPS

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

August 2008

Major Subject: Health Physics

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Approved by:

Chair of Committee,	John W. Poston, Sr.
Committee Members,	John R. Ford
	Michael A. Walker
Head of Department,	Raymond J. Juzaitis

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ABSTRACT

Estimating the Exposure to First Receivers from a Contaminated Victim of a Radiological Dispersal Device Detonation. (August 2008)

Holly Anne Phillips, B.S., Purdue University

Chair of Advisory Committee: Dr. John W. Poston

The threat of a Radiological Dispersal Device (RDD) detonation arouses the concern of contaminated victims of all ages. The purpose of this study was to investigate the dose to a uniformly contaminated five-year old male. It also explores the exposure rates surrounding the victim to be used by first receivers to estimate their exposure from the victim.

The victim was modeled as an anthropomorphic phantom using the BodyBuilder program. A thin layer of source material was added to the surface of the phantom's skin to simulate whole-body contamination. The computer code MCNP5 was used to tally the doses to the individual organs of the phantom and create a mesh to generate contour exposure rate lines.

Using an activity of 37 GBq m^{-2}, the five-year-old victim received an effective dose 158.23 mSv in one hour. Contour lines were produced that showed the exposure rates around the victims ranging from 0.5 to 10 R/h. The contour exposure-rate contour lines were also generated after the removal of contaminated clothing. Removing the victim's clothing reduced the exposure rates by eighty percent.

DEDICATION

To my family, without whom the completion of this thesis would not have been possible.

Their encouragement and love have been my rock and inspiration.

ACKNOWLEDGEMENTS

It is my pleasure to thank my committee chair, Dr. John Poston, for his support and guidance. I am also grateful for the aid of my committee members, Dr. John Ford and Dr. Michael Walker. I am incredibly appreciative of the knowledge, anecdotes, and experience I have gained from working with my committee.

I would also like to thank the National Science Foundation and Kathy Polzer's class at A&M Consolidated Middle School for giving me two days to explore science with middle school students throughout the 2007-2008 school year. I am appreciative of the NSF GK-12 program for funding my work at the middle school, research, and coursework.

Many thanks go out to my friends, whose support has been unfailing. I owe the completion of this thesis to Jeff Kowalczic for his unending patience in answering questions regarding MCNP. I am also grateful for the lunch hours and meaningful conversations spent with Holly Elder and Zach Bailey. Katie Kline and Samita Pendse have offered life-long friendship, and their support during the difficult times was priceless. Hours of support on the phone with Rick DeWitt were invaluable.

Words cannot express my gratitude to my parents, Ron and Nancy Philips, whose spiritual, emotional, and intellectual gifts have guided me throughout the years. Finally, I want to express deep thanks to God for all of the blessings he has given me.

NOMENCLATURE

^{241}Am	americium-241
Bq	becquerel
^{252}Cf	californium-252
^{137}Cs	cesium-137
^{60}Co	cobalt-60
ICRP	International Commission on Radiological Protection
^{192}Ir	iridium-192
keV	kiloelectron volts
MeV	megaelectron volts
mSv	millisievert
MCNP	Monte-Carlo N-Particle Transport Code
NCRP	National Council of Radiation Protection and Measurements
^{238}Pu	plutonium-238
R	roentgen
RDD	radiological dispersal device
^{90}Sr	strontium-90

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1. INTRODUCTION

In recent years, devices that scatter a radiological material into the environment, known as Radiological Dispersal Devices (RDDs), have been recognized as a threat facing domestic security. Radiological disasters are an important problem facing emergency response personnel and offer unique challenges compared to natural disasters and other emergencies. Bystanders may show no immediate outward signs of contamination. Emergency workers arriving at the scene, termed first responders, not only face the obvious dangers from the disaster area such as fires and collapsing buildings but also the unseen danger of radiation. Situations involving explosions and mass casualties are rarely calm and orderly. In addition to causing injuries and unrest, an RDD could hinder emergency response efforts in aiding those wounded from the explosion. First responders worried about working safely in a contaminated environment could waste valuable time due to concern about the safety of the scene rather than tending to the injured victims (Ferguson et al 2003).

One characteristic of radiological events is that the injured persons themselves pose a danger to those with whom they come into contact. In the case of RDDs, there could be thousands of victims presenting themselves at hospitals and clinics to demand medical attention. The medical personnel attending these victims are termed first receivers.

This thesis follows the style of Health Physics.

The National Council of Radiation Protection and Measurements (NCRP) recommends transferring victims with critical injuries from the scene to hospitals even if they may be contaminated. Because medical personnel may be in the vicinity of a contaminated person for quite some time as they attend to the victim's injuries, it is quite possible that they may receive a radiation dose from the victim; however, fear of contamination should never take precedence over the treatment of life-threatening injuries. The NCRP has declared, "It must be noted emphatically that radioactive contamination (whether internal or external) is never immediately life threatening and therefore, a radiological assessment or decontamination should never take precedence over significant medical conditions" (NCRP 2001). Knowing more about the potential absorbed dose from external contamination would be a tool for the first receivers to estimate the risk from a contaminated victim.

The staff can limit doses received by keeping exposures as low as reasonably achievable (ALARA). The three principle components of ALARA are time, distance, and shielding. In the specific case of first receivers, ALARA can be followed by increasing the distance between the staff member and the source (in this case a contaminated patient) and minimizing the staff's time spent in the proximity of the victim. Shielding by lead aprons is generally not recommended because the dose can be limited by the first two ALARA components. The first receivers should follow universal precautions as usual but wear two pairs of gloves to avoid cross-contamination (Bushberg 2007). The NCRP advises responders and receivers concerned about external

contamination of the victim to remove his or her clothing. This can remove eighty to ninety percent of the contamination (NCRP 2005).

The main goal of this research is to computationally determine the dose received by first receivers from a contaminated victim. The NCRP states that "exposure rates from contaminated wounds rarely exceed a few mR/h…and emergency responders should be reassured that their exposures in this situation will very likely be insignificant or minimal" (NCRP 2005), but there have been few studies to determine the validity of this statement. In order to explore the exposures that the staff members might actually acquire from a universally contaminated victim, this research project will model the dose to first receivers from a five-year old male victim covered uniformly in whole-body external contamination. Since concern about the perceived dangers of radiation could expend valuable treatment time for those victims injured by the conventional explosion, understanding the potential exposure from the victim will determine how long the healthcare provider could safely care for the victim.

2. BACKGROUND

2.1. RDD THREAT

While they have not yet been employed in the United States, improvised nuclear devices such as RDDs have been increasingly sources of concern since the September 11 attacks in 2001. An RDD disperses radioactive material into the environment using conventional explosives. It is unlikely that the doses received by RDD victims would be fatal to many victims; generally, RDDs are thought to be weapons of mass "disruption" rather than destruction. The combination of chaos and fear of radiation could waste valuable time in the emergency response process and delay the treatment and removal of the injured parties. Additionally, the economic impact of an RDD explosion could be enormous, costing billions of dollars in decontamination, remediation, reconstruction and medical follow-ups.

The source material for an RDD could come from several areas, including nuclear power plant waste or commercial radioactive sources. When considering a commercial source as the radiological material in an RDD, candidate sources that pose a high security risk share several major characteristics. These commercial radioactive sources are portable, dispersible, and highly radioactive. A 2003 study by the Center for Nonproliferation Studies found that tens of thousands of the world's sources share the characteristics of a likely candidate. Considering the millions of sources used globally, this number represents only a fraction of the available sources, but is still high enough to be a significant threat. These high risk sources generally contain large amounts of

radioactivity, upwards of 100 GBq. The study found seven radionuclides to be the greatest threat: ^{241}Am, ^{252}Cf, ^{238}Pu, ^{137}Cs, ^{60}Co, ^{192}Ir, and ^{90}Sr. The others could deliver both internal and external doses to their victims. This report considers ^{60}Co as the source in an RDD (Ferguson et al 2003).

2.2. Cobalt-60 SOURCES

Cobalt is a gray-blue metal that is typically solid. It was isolated in 1735 by Swedish scientist George Brandt. The radioisotope ^{60}Co does not occur naturally. It was not manufactured until the 1930s, when scientists Glenn Seaborg and John Livingood discovered it at the University of California-Berkeley. It is now produced for commercial use by linear accelerators or nuclear reactors. It has a half-life of 5.27 years and decays by beta and gamma decay to stable nickel (U.S. Environmental Protection Agency 2000) as shown in Fig. 1.

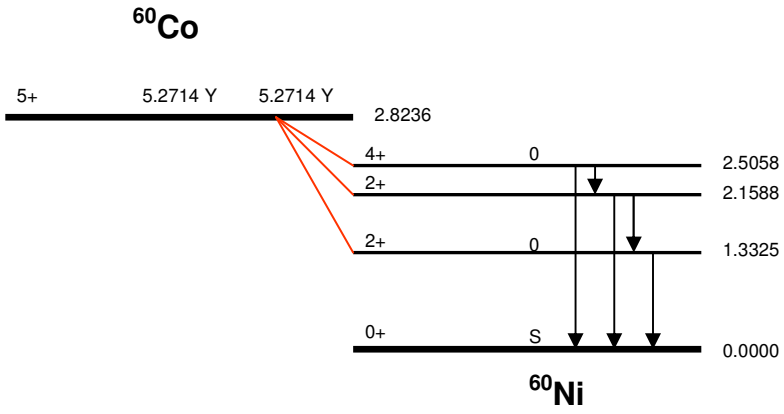

Fig. 1. Decay scheme of ^{60}Co (Adapted from Table of Nuclides, 2000).

The principal radiological concern with ^{60}Co is its two strong gamma rays of energies 1.17 MeV and 1.33 MeV. Co-60 also releases beta particles and the average beta energy is 0.096 MeV (Rad Toolbox). Table 1 displays the average energies and intensities of the radiation released by ^{60}Co as it decays to ^{60}Ni.

Table 1. Decay information of ^{60}Co (Rad Toolbox)

Radiation Type	**Intensity (per 100 particles)**	**Energy**
γ-ray	99.86	1.17
	99.99	1.33
β-Particle	99.9	0.096 (average)

Large radiological sources used to sterilize medical supplies or food products are usually located in regional facilities that are plentiful and vulnerable to be pilfered by terrorists. Most of the 190 industrial irradiators employ ^{60}Co as the gamma-source of choice. These sources usually have an activity ranging from 3.7×10^6 GBq to 1.85×10^8 GBq. Research irradiators are also plentiful and vary in activity from 7.4×10^4 to 3.7×10^6 GBq. Research institutions face funding issues and are generally unlikely to employ thorough security procedures. Medical institutions utilize ^{60}Co for teletherapy and gamma knife procedures. There are approximately 2350 ^{60}Co teletherapy units and dozens of gamma knives worldwide, having activities up to 5.55×10^5 GBq (Van Tuyle and Mullen 2003). Each of these sources is a potential candidate for the radiological material in an RDD.

The availability of high-risk sources such as ^{60}Co is increasing. Current US regulations allow unrestricted export of most sources to locations around the world

excluding Cuba, Iran, Iraq, Libya, North Korea, and Sudan with no scrutiny of the end-user of the source. This means that the sources can be transmitted to states that could in turn pass them on to terrorists and rogue states. Additionally, the U.S. must increase its efforts to verify the end-user of its licensed domestic sources (Ferguson et al 2003).

2.3. PROBLEM SUMMARY

This project will computationally model the dose received by a five-year-old male victim covered in whole-body external contamination of the radionuclide ^{60}Co. It will also examine the dose received by first receivers at different distances from the victim. Finally, it will determine the dose to healthcare workers when the victim's clothing has been removed such that the source is only on his head and face. Having an estimate of the potential dose from the victim will determine how long healthcare providers could safely care for their patients.

3. MATERIALS AND METHODS

One point to be considered before beginning the study was determining how contaminated the victim might be. Tests performed at Sandia National Laboratories explored the maximum levels of contamination per surface area that a victim of an RDD would be expected to survive. Using these data, the injured party was set to have an activity ranging from 3.7 to 37 GBq m^{-2}, the upper contamination level that a victim of an RDD with source strength on the order of 10^6 GBq would be expected to survive (Smith et al 2005).

3.1. MCNP

Monte Carlo N-Particle Transport Code (MCNP) is a software package that can be used to simulate neutron, photon, or electron transport. The method of solving mathematical problems by means of random sampling has existed since 1772; however, the mathematical method was not named until the Manhattan Project during World War II. From World War II to the present, Monte Carlo methods have developed along with computers. Calculations that would have taken several tedious days to complete by hand can now be done in minutes or hours by computers. The MCNP code was developed by the Monte Carlo Group, now known as the Diagnostic Applications Group, (Group X-5) in the Applied Physics Division (X Division) at the Los Alamos National Laboratory. The simulation can track billions of particles and photons individually and estimate

criticality, particle fluence, and absorbed dose. This project used MCNP5, released in 2003. MCNP5 is a collection of over 400 subroutines written in Fortran and C.

The MCNP input file contains three blocks that create the model of interest. The first section is referred to as the cell card. MCNP employs a three-dimensional Cartesian coordinate system, and each space is referred to as a cell. No gaps are allowed in the geometry. Cells are the regions used to tally the item of interest, such as energy deposition. The second section is termed the surface card. Surfaces are used to define the cells of interest. MCNP surfaces can be two-dimensional planes or basic three-dimensional shapes such as spheres and cylinders. The third section is called the data card. The data card contains the specifications about details other than geometry. This includes the definition of materials, the type and number of particles, radiation sources, tally specifications and other details for the assessment of the source. When the input has been entered, the code is ready to be executed to perform calculations (X-5 Monte Carlo Team 2003).

To make a source in MCNP, the source must be entirely enclosed inside a volume, typically a sphere or a cylinder. Random numbers are generated by the computer to select points inside the enclosed volume. If the selected point is within the source cell, then a particle is generated and tracked until it has dissipated its energy or is lost. The enclosed volume should be minimized so that it is slightly larger than the source while completely surrounding the source volume in order to increase the efficiency of the point selection and random number generation process. The simulation is terminated when all particle histories are completed.

3.2 BODYBUILDER

To create an input file for MCNP that represented the five-year-old male victim, the BodyBuilder computer program by White Rock Science† was used to create an anthropomorphic phantom, a mathematical representation of the human body. Phantoms are important to radiation research in order to simulate doses delivered to the whole body or specific organs. BodyBuilder allows a user to easily design a phantom without writing a complicated MCNP input file. This input, as demonstrated by Fig. 2, consists of a single person surrounded by a sphere of air:

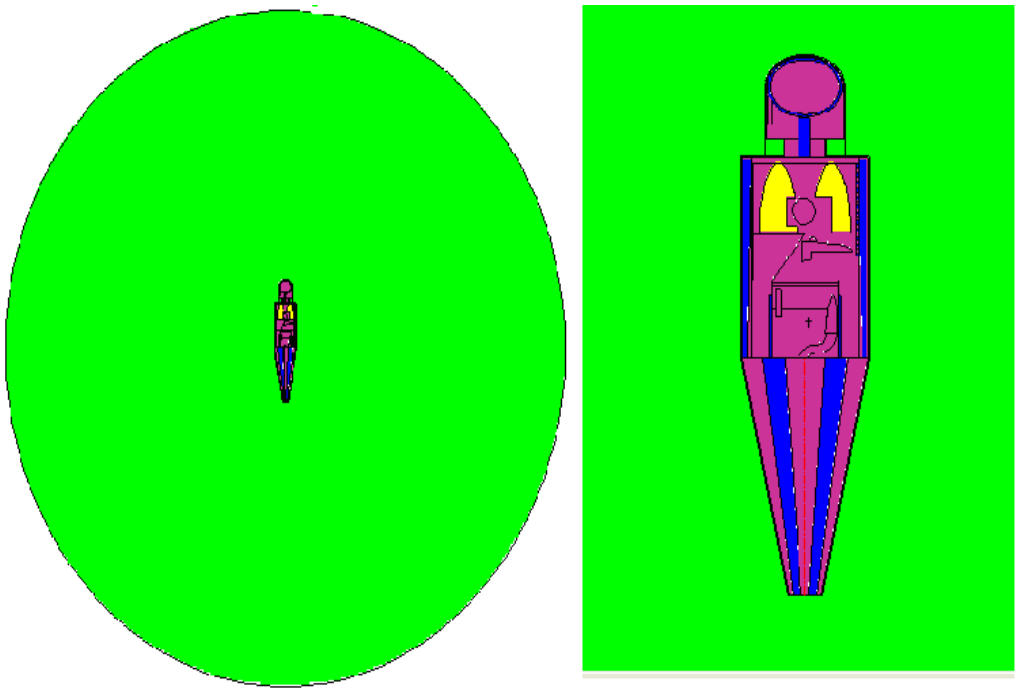

Fig. 2. 2D view of 5-year-old male phantom.

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

The BodyBuilder phantoms were built according to the work done by Cristy and Eckerman at Oak Ridge National Laboratory. Cristy and Eckerman generated descriptions of phantoms ranging in age from newborn, 1, 5, 10, and 15 years, and adult (Cristy and Eckerman 1987). Phantoms created by BodyBuilder can be male or female and range in age from newborn to adult. Additionally, the code can be used to create pregnant female phantoms. The BodyBuilder code produces the phantoms of varying ages by interpolating between the Cristy and Eckerman models, although the adult phantom is slightly larger than Reference Man. Table 2 describes the densities of the materials used to create the organs, tissues, and air of the phantom:

Table 2. List of materials used by BodyBuilder (Van Riper, 1998)

Material Description	**Density (g cm^{-3})**
Adult Soft Tissue	1.04
Skeleton	1.4
Lungs	0.296
Air	0.001020

Figure 3 shows the BodyBuilder user interface. Each organ displayed in Table 3 was checked, meaning it was included in the initial code and tallied for photon and electron doses from ^{60}Co. To place radioactive contamination on the surface of the phantom skin, a thin layer needed to be added that completely surrounded the phantom skin.

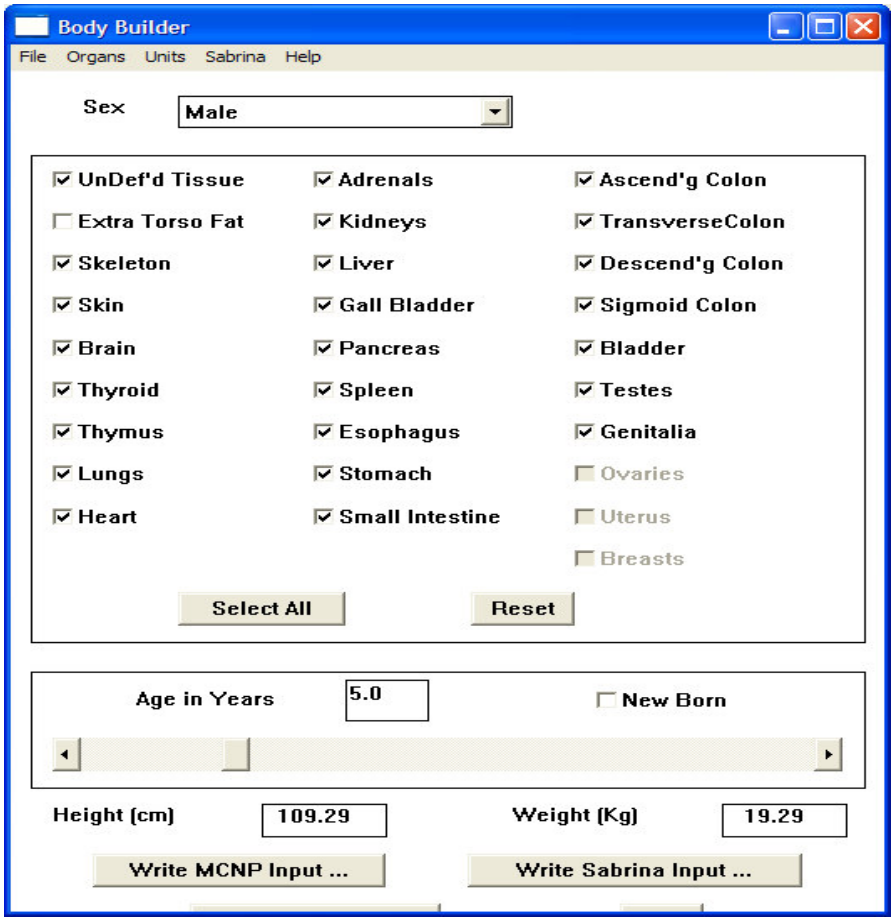

Fig 3. BodyBuilder user interface for creating MCNP input files.

Table 3. List of the organs and their respective masses used in the male phantom

Organ	Mass (g)
LEG BONES	854.00
ARM BONES	334.60
PELVIS	211.40
SPINE	340.20
SKULL & FACE	634.20
RIBS	243.60
CLAVICLES	19.18
SCAPULAE	70.56
ADRENALS	5.27
BRAIN	1258.40
GALL BLADDER	23.40
ESOPHAGUS	11.54
STOMACH	124.18
SMALL INTESTINE	275.60
ASCENDING COLON	48.88
TRANSVERSE COLON	64.27
DESCENDING COLON	50.34
SIGMOID COLON	27.78
HEART	227.03
KIDNEYS	115.44
LIVER	584.48
LUNGS	290.08
PANCREAS	23.61
SPLEEN	48.26
TESTICLES	1.63
THYMUS	29.64
THYROID	3.45
URINARY BLADDER	79.25
PENIS & SCROTUM	22.50
HEAD & NECK SKIN	132.08
TRUNK SKIN	247.52
PENIS & SCROTUM SKIN	2.75
LEG SKIN	101.40
LEG SKIN	101.40
LEGS	3718.00

3.3. PROCEDURE

A five-year-old male phantom was created using BodyBuilder with the characteristics shown in Table 4. On the phantom, a thin cell approximately 2 mm thick was created on the outside of the skin parallel to the skin surface. A ^{60}Co source was then uniformly distributed throughout the volume of the cell surrounding the skin in the source definition card to simulate surface contamination from an RDD. The phantom with skin contamination was then input into MCNP. Separate simulations were performed to tally the doses from gamma and beta-radiations.

Table 4. Characteristics of the RDD victim

Age (years)	5
Height (cm)	109.29
Weight (kg)	19.29

A pulse-height tally (*F8 tally) was taken of the significant organs in the phantom. Pulse-height tallies given with an asterisk convert the pulse height tallies to energy deposition pulses in a detector to give the energy deposited in each tally cell by the source particle and its secondary particle in the units of MeV. Tally type eight can track the energy from photons or electrons in each cell. This is ideal for a nuclide such as ^{60}Co that emits both gamma and beta-radiation.

After completing the tallies, the dose to each cell was calculated. The tally results were divided by the mass of the cell in kg and converted to give the absorbed dose $D_{T,R}$ in Gy (J kg^{-1}). Absorbed dose is the amount of energy imparted by ionizing radiation averaged over a mass of material. The stochastic effects of radiation depend

not only on the absorbed dose but also on the type of radiation interacting with the tissue and the type of tissue being irradiated. To account for this, the absorbed dose must be doubly weighted to find the equivalent dose H and effective dose.

The absorbed dose must be adjusted by a radiation weighting factor w_R to account for the rate of energy deposition in tissue (LET). This gives the equivalent dose in Sv. The weighting factors set by the ICRP are displayed in Table 5. Photons and electrons, the radiations emitted by ^{60}Co, have radiation weighting factors of unity, so using Eq. 1 the absorbed dose is equal to the equivalent dose for ^{60}Co:

$$H_T = \sum_R D_{T,R} w_R \tag{1}$$

where:

H_T = equivalent organ dose (Sv)

$D_{T,R}$ = absorbed dose (Gy), and

w_R = radiation weighting factor.

Table 5. Radiation weighting factors (w_R) from ICRP-60

Particle Type	**Radiation Weighting Factors (w_R)**
Photons	1
Electrons/muons	1
Protons (not recoil protons)	2
Alpha particles, fission fragments, and heavy nuclei	20
Neutrons	A function of neutron energy

When using BodyBuilder, a number of individual cells make up the organs or tissues defined by ICRP-60. Additionally, the remainder is composed of a number of organs, defined as the "adrenals, brain, upper large intestine, small intestine, kidney, muscle, pancreas, spleen, thymus and uterus" (ICRP 1991). In those cases, a special method was used to find the equivalent dose contributed by those cells to the organ. The equivalent dose of a cell *i* must be weighted using the sum of the product of the equivalent dose in the cell by its respective mass. This is done for each cell comprising the organ and divided by the total mass of the organ as demonstrated in Eq. 2:

$$H_T = \sum_T \frac{m_i H_i}{m_T} \tag{2}$$

where:

H_T = equivalent organ dose (Sv)

H_i = equivalent dose of cell *i* (Sv)

m_i = mass of cell *i* (kg), and

m_T = mass of organ (kg).

Once the total equivalent dose to each organ was found, the equivalent dose to each organ was weighted by the tissue weighting factors in Table 6 to give the effective dose *E*.

Table 6. Tissue weighting factors (w_T) from ICRP-60 (ICRP 1991)

Organ or Tissue	w_T
Gonads	0.2
Red Bone Marrow	0.12
Colon	0.12
Lung	0.12
Stomach	0.12
Bladder	0.05
Breasts	0.05
Liver	0.05
Oesophagus	0.05
Thyroid	0.04
Skin	0.01
Bone Surfaces	0.01
Remainder	0.05

The effective dose is a quantity that accounts for the notion that some tissues are more sensitive to the stochastic effects of radiation than others and will contribute more to the total damage to the body from those stochastic effects. Effective dose is, therefore, the weighted sum of the equivalent doses to each organ and a tissue weighting factor w_T. The tissue weighting factors are values set by the ICRP corresponding to the contribution of each tissue towards whole body damage from the stochastic effects of radiation. In this study, the dose to breast tissue was omitted because the victim was male. The effective dose to the body was calculated using Eq. 3 by summing the product of the tissue weighting factors and the equivalent dose of that tissue (ICRP 1991):

$$E = \sum_T w_T H_T \tag{3}$$

where:

E = effective dose (Sv)

w_T = tissue weighting factor, and

H_T = equivalent dose (Sv).

To find the equivalent dose per disintegration, the equivalent dose in sieverts per event must be multiplied by the intensity of each particle. The equivalent dose rate to each organ was found by multiplying the equivalent dose per disintegration, the surface area of the victim, and the contamination level (in this case 37 GBq m^{-2}). Summing the product of the equivalent dose rates and the tissue weighting factors gave the effective dose rate in Sv s^{-1}. Simple unit manipulation was applied to give mSv h^{-1}.

To examine the exposure to the first receivers in the operating room, an FMESH tally, or superimposed mesh tally, was also taken. FMESH tallies give a track length estimate of the particle fluence. This tallies the particle fluence through a user-defined grid (X-5 2003). The grid outlined in this scenario contained a one centimeter thick planar tally normal to the x-, y- , and z- axes through the origin. The FMESH tally was used to estimate the radiation exposure to the first receivers at varying distances from the victim. The FMESH output is given for each particle history during the MCNP calculation, meaning it is also proportional to the source activity on the victim's skin. To account for this, the tally data was multiplied by 37 GBq, similarly to the *F8 tally data. The FMESH data was then entered into a MATLAB matrix. To convert the particle fluence rate into an exposure rate, Eq. 4 was employed (Attix 2004):

$$\dot{X}(E) = \dot{\Psi}\left(\frac{\mu_{en}}{\rho}\right)_{air}\left(\frac{e}{w}\right)_{air} \quad (4)$$

where:

$\dot{X}(E)$ = exposure rate (C kg^{-1} s^{-1})

$\dot{\Psi}$ = photon energy fluence rate (J cm^{-2} s^{-1})

$\left(\frac{\mu_{en}}{\rho}\right)_{air}$ = energy dependent attenuation coefficient in air (cm^2 kg^{-1})

e = charge of an electron (C J^{-1}), and

w = energy required to produce an ion pair in air.

The result of Eq. 4 was converted to give the exposure in R h^{-1}. The contour function in MATLAB was used to generate isodose curves that showed the exposure at varying distances from the victim.

The FMESH tally was also used for a second scenario, which was set up such that the victim's contamination was located only on his head and neck. This arrangement was designed to simulate a victim whose contaminated clothing had been removed. The victim was assumed to be fully clothed, so that removing his clothing would remove all of the source material below the neck. As BodyBuilder does not model hands and feet, these were not considered as source locations. Similarly to the first FMESH data, the second scenario converted the MCNP tally data using Eq. 4. and the contour function in MATLAB.

4. RESULTS

4.1. DOSE TO VICTIM

The dose imparted to the victim covered in whole-body ^{60}Co contamination was tallied using the energies of the ^{60}Co beta particles and gamma-rays. The absorbed dose calculations referenced in Section 3 give the equivalent dose results displayed in Table 7. Using an activity of 37 GBq m^{-2}, the effective dose could be converted into a dose rate using the surface area of the victim. The victim's surface area was determined to be 0.78 m^2 using the reference value from ICRP-89 (ICRP 2002).

Table 7. Equivalent dose rates to the organs of the five year-old victim in mSv/hr from 37 GBq m^{-2} of ^{60}Co skin contamination

Organs/Tissues	**H_T (mSv h^{-1})**
Gonads	107.55
Red Bone Marrow	143.31
Colon	149.24
Lung	187.22
Stomach	175.41
Bladder	130.02
Liver	183.22
Oesophagus	164.98
Thyroid	335.28
Skin	1187.54
Bone Surfaces	143.31
Remainder	89.58

The tissue weighting factors from Table 6 were multiplied by the equivalent doses to the organs from Table 7 and summed to give the effective dose. The effective dose to the victim at contamination levels ranging from 3.7 GBq m^{-2} to 37 GBq m^{-2} were tabulated and are displayed in Table 8. The maximum dose the victim would expect to receive was 158.23 mSv h^{-1}. The dose he would receive in one hour would be a factor of over 150 times the ICRP recommended limit to the public of 1 mSv per year (ICRP 1991). The dose from beta-radiation accounted for less than 8% of the total contamination.

Table 8. Effective dose rates to the five year-old victim (mSv h^{-1})

Surface Contamination Level	**Dose Rate from γ-rays (mSv h^{-1})**	**Dose Rate from β-rays (mSv h^{-1})**	**Effective Dose Rate (mSv h^{-1})**
3.7 GBq m^{-2}	14.57	1.25	15.82
15 GBq m^{-2}	59.06	5.09	64.15
37 GBq m^{-2}	145.69	12.55	158.23

4.2. EXPOSURE TO FIRST RECEIVERS

Using a surface contamination level on the victim of 37 GBq m^{-2}, the ^{60}Co gamma rays were tracked using an FMESH tally. The beta particles were ignored, as it was assumed that any of these low-energy particles that reached the medical workers would be stopped by the worker's scrubs, gloves, and mask. Figures 4– 6 show the exposure rate curves produced from the FMESH data using MATLAB. The colorbar legend provides a key to match the color of the contour lines to find the exposure rate per hour (R h^{-1}). The contour exposure rate lines depicted in Figs. 4-6 are shown at

0.5, 1, 2, 3, 4, 5 and 10 R h^{-1}. These lines estimate a medical worker's exposure from the victim. Figure 4 reveals the exposure rates seen from the coronal plane, which is oriented so that the victim is front-facing. A medical worker standing approximately 20 cm from the mid-torso of the victim would receive an exposure of approximately 5 R h^{-1}.

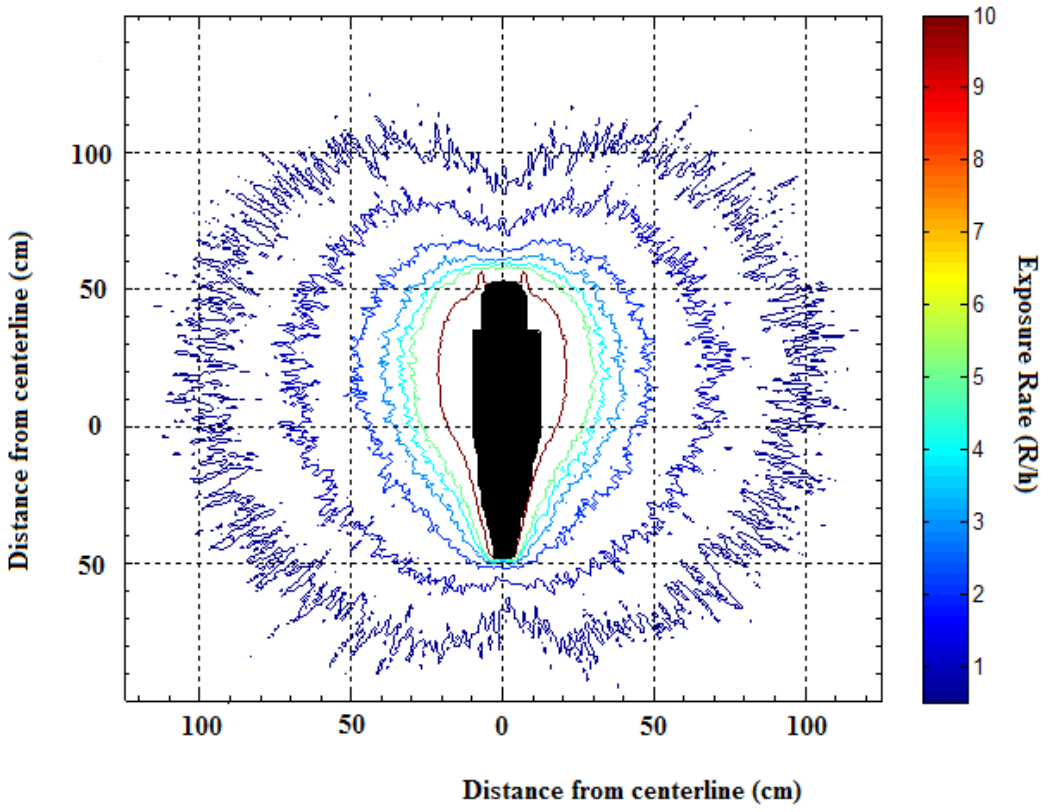

Fig. 4. Front view of the exposure rate lines surrounding the victim.

The same lines can be seen from the sagittal plane, as shown in Figure 5. This shows the side view of the victim.

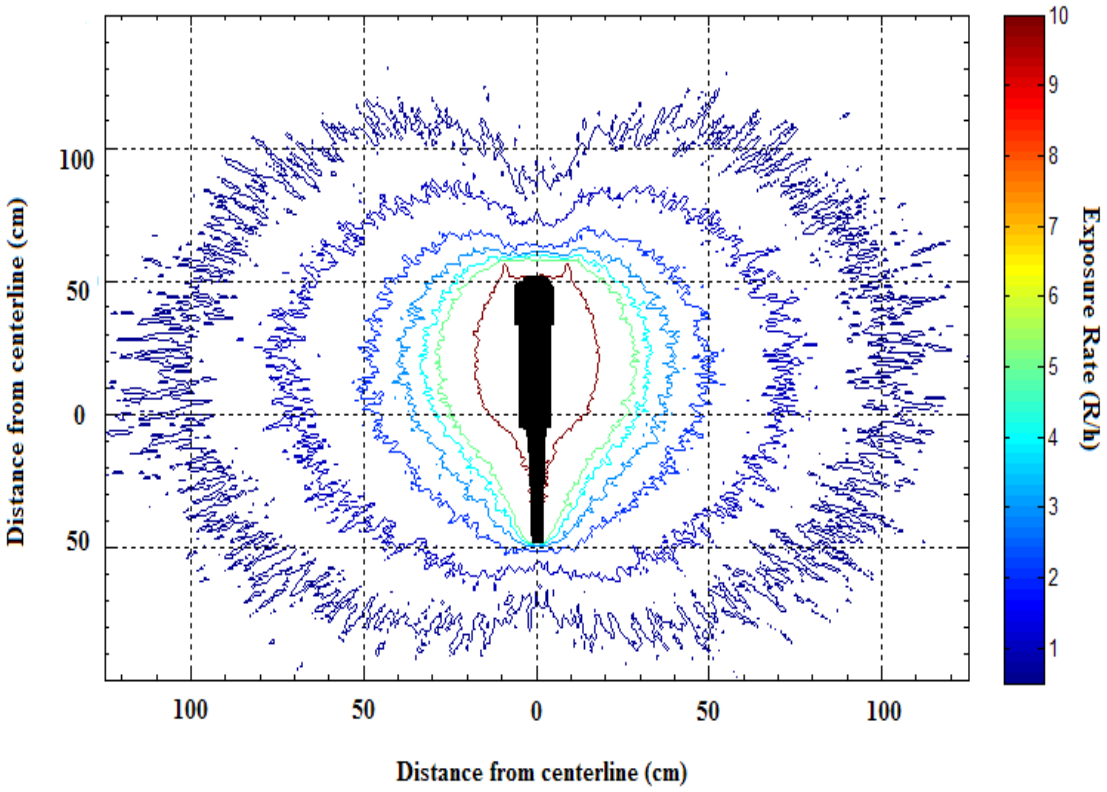

Fig. 5. Lateral view of the exposure rate lines surrounding the victim.

Figure 6 shows a view of the victim cut through a transverse plane. This illustrates a dorsal view of the exposure rate lines.

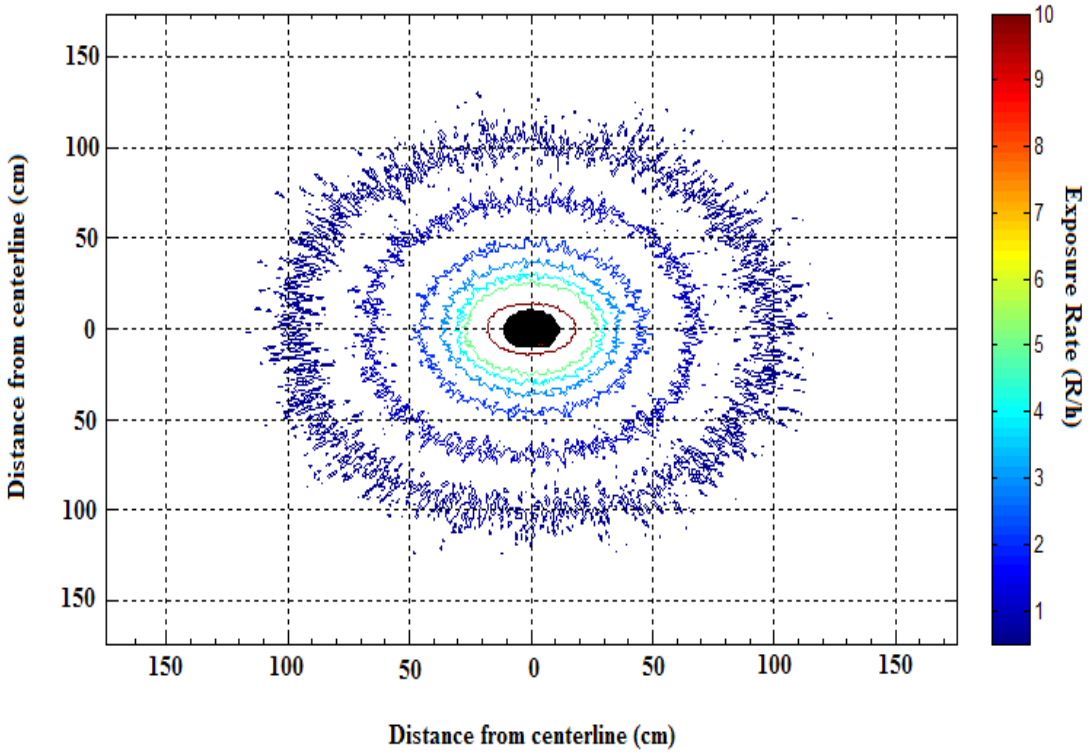

Figure 6. Top view of the exposure rate lines surrounding the victim.

4.3. EXPOSURE TO FIRST RECEIVERS WITH THE VICTIM'S CLOTHING REMOVED

As when the victim was covered in whole-body contamination, the ^{60}Co gamma rays were tracked using an FMESH tally and the dose from beta particles was assumed to be negligible. The approximate surface area of the head of a five year old male is 13% of his total surface area, or 0.1014 m^2. The surface contamination levels for the victim remained at 37 GBq m^{-2}. Figures 7-9 show the contour lines of the exposures around the victim. The colorbar legend provides a key to match the color of the contour

lines to find the exposure rate per hour (R h^{-1}). Figures 7 and 8 feature contour exposure rate lines at 0.25, 0.5, 1, 2.5, 5 and 10 R h^{-1}. Figure 7 shows a coronal section of the victim and the exposure rate lines surrounding him. Emergency personnel standing approximately 20 cm from the mid-torso of the victim would be subjected to an exposure of approximately 1 R h^{-1}.

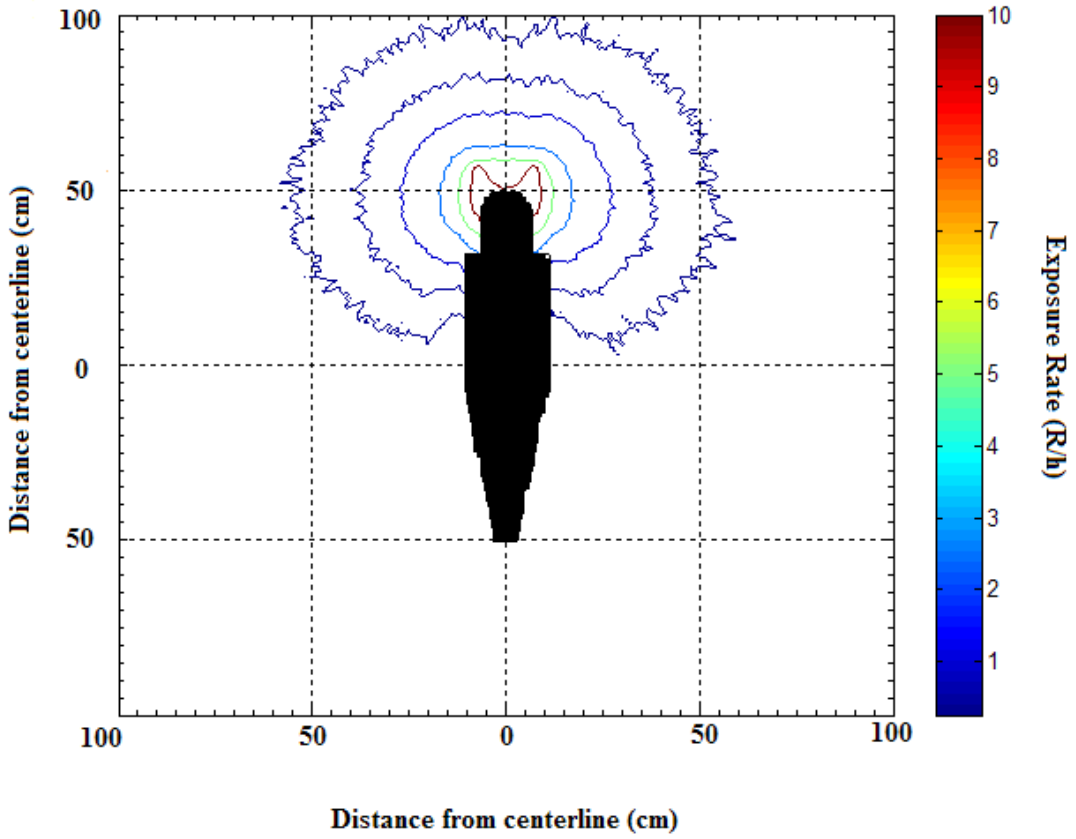

Fig. 7. Front view of the exposure rate lines surrounding the victim with source on the head and neck only.

A sagittal section cut of the victim is exhibited in Fig. 8. This shows the side view of the victim.

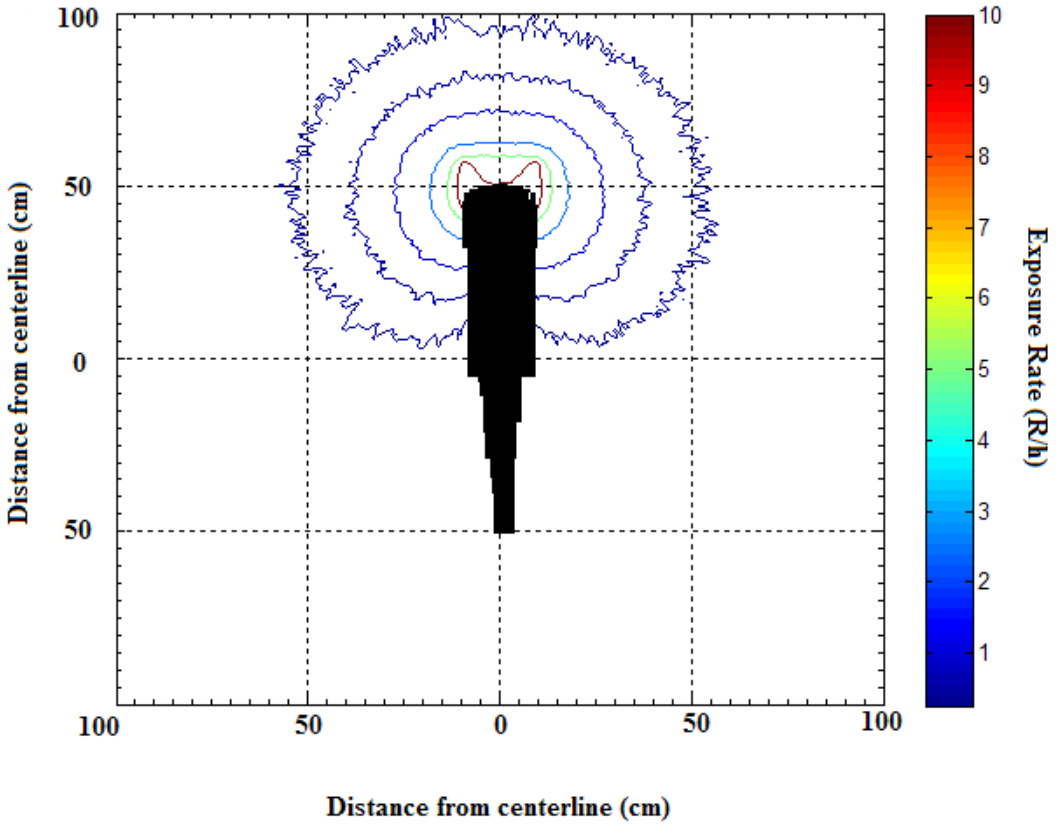

Fig. 8. Lateral view of the exposure rate lines surrounding the victim with source on the head and neck only.

Figure 9 show the view of the victim cut through the transverse plane. The contour exposure rate lines in Fig. 9 are drawn at 0.05, 0.1, 0.15, 0.2 and 0.25 R h^{-1}.

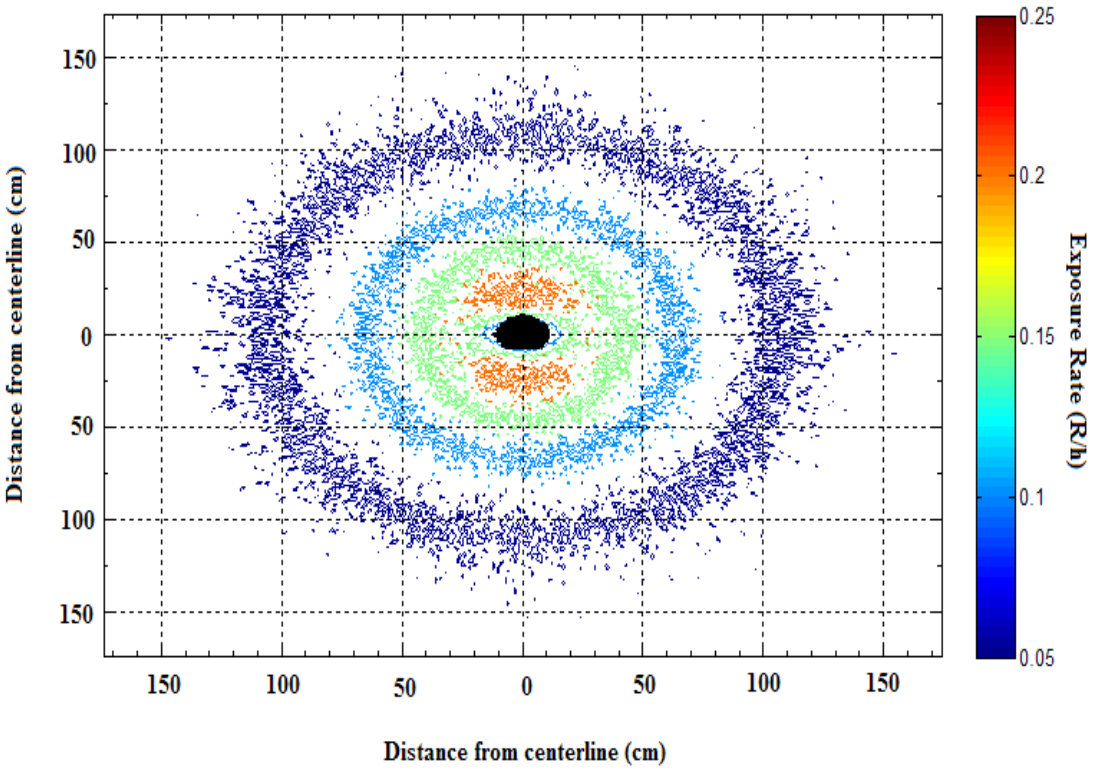

Fig. 9. Top view of the exposure rate lines surrounding the victim with source on the head and neck only.

5. CONCLUSIONS

5.1. CONCLUSIONS

At a contamination level of 37 GBq m^{-2}, the effective dose to the five-year-old victim in one hour of 158 mSv h^{-1} greatly exceeds the ICRP's recommended dose limit of 1 mSv per annum. The equivalent dose received by the gonads would exceed the 150 mSv threshold for temporary sterility of an adult male in less than 1.5 hours (ICRP 1991). As expected, the skin on which the source material lay received the highest individual organ dose. The dose from beta-radiation accounted for less than 10% of the total dose due to the highly penetrable gamma-rays emitted by ^{60}Co because these gamma-rays were able to reach the internal organs deep within the body.

The contour exposure-rate lines can be used by first receivers as estimations of the doses they would receive while working with a contaminated victim. The exposure rate depictions in Figs. 4.1 and 4.2 showed that it would be advantageous for medical personnel to work from the top of the head or the bottom of the feet, as the contour exposure rate lines are indented in these locations. The exposures calculated could be scaled linearly to account for varying contamination activities per surface area covered.

The simulation involving the removal of the victim's clothing greatly reduced the exposure to first receivers. With universal contamination, the estimated exposure rate 20 cm from the victim's torso was 5 R h^{-1}. The scenario involving contamination on the head and neck only reduced the estimated exposure rate in the same location to 1 R h^{-1}, an eighty percent reduction in exposure rate. This coincides with the NCRP's claim that

removing clothing from a victim can eliminate eighty to ninety percent of the contamination (NCRP 2005),.

5.2. FUTURE WORK

This project could be extended to include the other radionuclides considered to be candidates for use in dirty bombs such as ^{241}Am, ^{252}Cf, ^{238}Pu, ^{137}Cs, ^{192}Ir, and ^{90}Sr. Phantoms of other ages and genders could be built to examine the effect of height and weight variation. Rather than using an FMESH tally, a second phantom could be placed next to the phantom victim to perform a direct tally of the energy from the victim's contamination. Phantoms containing extra adipose tissue could be studied to observe the shielding and scattering effect that the adipose tissue could have on the dose to workers.

It is extremely unlikely that a victim would be covered in whole-body external contamination without incurring an internal exposure via ingestion, inhalation, or absorption. The procedure in this study could be combined with an internal dosimetry study to determine the dose to a victim of both internal and external exposure.

When examining the effects of the removal of clothing, many more details could be studied. Clothing material, such as denim and cotton, could be added to the victim to consider the shielding of beta particles and their effect on the victim's dose. In the present study, the victim was assumed to be completely clothed below the neck; however, seasonal and geographical factors would impact the amount of clothing a victim might actually be wearing. For instance, a victim in Houston during the summer might be exposing much of her arms, legs, and torso; removing her clothing would

provide much less dose reduction than removing the clothing of the same victim during an attack in New York City in the winter.

BodyBuilder and other phantom-generating software are limited by the complexity of the anatomical geometry they employ. As phantoms become more realistic, these simulations will be able to provide more accurate results. The scenario removing the contaminated clothing from the victim could be improved by including hands and feet as source locations.

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APPENDIX A

MCNP INPUT CODE FOR WHOLE-BODY ^{60}CO CONTAMINATION

```
Male Phantom at 5.0 Years with Uniform Whole Body Co-60 Contamination
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 = 1934.100000, skel_vol = 1935.714286
c
c       LEG BONES
50     2 -1.40    -4 53 (-51:-52)
             vol=   610.00 imp:n,p,e = 1
c
c       ARM BONES
70     2 -1.40     4 -73 (-71:-72)
             vol=   239.00 imp:n,p,e = 1
c
c       PELVIS
90     2 -1.40     91 -92 93 4 -101 (95:-94)
             vol=   151.00 imp:n,p,e = 1
c
c       SPINE
100    2 -1.40   (-100 -103 101):(-100 -8 103):(-105 -102 8)
          vol=   243.00  imp:n,p,e = 1
c
c       SKULL & FACE
110    2 -1.40   (111 -110):(121 -120 122 -1 -123 110)
             vol=   453.00 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=   174.00 imp:n,p,e = 1
c
c       CLAVICLES
140    2 -1.40    -140 ((141 -143):(-142 144))
             vol=    13.70 imp:n,p,e = 1
c
c       SCAPULAE
```

```
150    2 -1.40     131 -156 154 -155 ((150 -152):(-151 153))
             vol=    50.40 imp:n,p,e = 1
c
c        ADRENALS
160    1 -1.04     162 (-160:-161)
              vol=     5.07 imp:n,p,e = 1
c
c        BRAIN
180    1 -1.04    -111
             vol=  1210.00 imp:n,p,e = 1
c
c        GALL BLADDER
200   1 -1.04       (-202 -200):(202 -201 -203)
             vol=    22.50 imp:n,p,e = 1
c
c        ESOPHAGUS
212   1 -1.04       (213 -212 322 -8 100) :
                (-216 217 -218 210 350 100)
             vol=   11.10 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=   119.40 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=   265.00 imp:n,p,e = 1
c
c        ASCENDING COLON
230   1 -1.04       -230 231 -232
             vol=    47.00 imp:n,p,e = 1
c
c        TRANSVERSE COLON
240   1 -1.04       -240 -241 242
          vol=    61.80 imp:n,p,e = 1
c
c        DESCENDING COLON
250   1 -1.04       -250 251 -232
           vol=   48.40 imp:n,p,e = 1
c
c        SIGMOID COLON
280   1 -1.04       (-280 282 -251):(-281 -282 4)
           vol=   26.71 imp:n,p,e = 1
c
```

```
c        HEART
290      1 -1.04     (290((-291 -292):(291 -293))):
                       (-290((-291 -295):(291 -294)))
                   vol=   218.30 imp:n,p,e = 1
c
c        KIDNEYS
310      1 -1.04     (-310 312 -162):(-311 -313 -162)
                    vol=   111.00 imp:n,p,e = 1
c
c        LIVER
320      1 -1.04     -320 -321 7 -322 -132
                    vol=   562.00 imp:n,p,e = 1
c
c        LUNGS
330      3 -0.296   332 ((-331 (-335:336:334:-333)):
                          (-330 ( 339:338:337)))
                   vol=   980.00 imp:n,p,e = 1
c
c        PANCREAS
350    1 -1.04       -350 351 (352:-312)
                   vol=    22.70 imp:n,p,e = 1
c
c        SPLEEN
360    1 -1.04       -360
                   vol=   46.40 imp:n,p,e = 1
c
c        TESTICLES
370    1 -1.04       -370:-371
                 vol=    1.57 imp:n,p,e = 1
c
c        THYMUS
380      1 -1.04  -380
                   vol=    28.50 imp:n,p,e = 1
c
c        THYROID
390      1 -1.04    -390 391 -392 -393 8
                    vol=     3.32 imp:n,p,e = 1
c
c        URINARY BLADDER
410    1 -1.04       -410
                 vol=   76.20 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=   21.63 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=  238.00 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=    2.64 imp:n,p,e = 1
c       Legs Skin
34    1 -1.04      (-4 34 -31 36 32):(-31 33 -36 32)
           vol=   97.50 imp:n,p,e = 1
35    1 -1.04      (-4 35 -32 36 31):(-32 33 -36 31)
           vol=   97.50 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=  3575.00 imp:n,p,e = 1
c
c       SURROUNDING AIR
600    4 -0.001293   -600
c          exclude        HEAD & NECK
                   (802:-3)  (803:3:-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        THIN LAYER SURROUNDING SKIN FOR SOURCE
900   4  -0.001293 (21 -802 3):(20 -803 -9 12):(9 -3 -803 21):  $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        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    25.3500
7     pz    15.7400
8     pz    40.8000
9     pz    54.8000
3     pz    55.9
12    pz    44.1000
c
c
c Planes used for air outside of source
801   cz    3.99       $neck
802   sq    3480.1155  2173.1148  4426.9296 0 0 0 -182974.0376 0 0
           55.038   $top of head
803   sq    84.1990    52.5770 0 0 0 0 -4426.929645 0 0 0   $side of head
804   pz    40.90000   $shoulder
805   sq    58.9978   138.9098 0 0 0 0 -8195.366945 0 0 0   $torso
c
c        BODY SURFACE
c
c           HEAD
21    sq  3421.7820  2135.1793  4354.7857 0 0 0 -178372.0216 0 0
          54.800
22    sq  3261.0381  2024.1271  4163.6692 0 0 0 -165781.0693 0 0
          54.800
20    sq    83.5396    52.1284 0 0 0 0 -4354.785685 0 0 0
23    sq    81.9025    50.8369 0 0 0 0 -4163.669202 0 0 0
c
```

```
c
c          NECK
27   cz    3.8900
28   cz    3.8000
c
c
c          TORSO
10   sq    57.6081   133.1716 0 0 0 0 -7671.762850 0 0 0
11   sq    56.2500   131.1025 0 0 0 0 -7374.515625 0 0 0
18   pz    40.7100
c
c          LEGS
c    left
31   gq 1 1 0 0 0  -0.1762   -11.5400 0 0 0
32   gq 1 1 0 0 0   0.1762    11.5400 0 0 0
33   pz  -48.090
34   gq 1 1 0 0 0  -0.1762   -11.4500 0 0 0
35   gq 1 1 0 0 0   0.1762    11.4500 0 0 0
36   pz  -48.000
37   gq 1 1 0 0 0  -0.1762   -11.6300 0 0 0
38   gq 1 1 0 0 0   0.1762    11.6300 0 0 0
c
c       PENIS & SCROTUM
41   pz    -1.6900
42   p  0 -11.35 -1  65.00
43   p   -11.35 0 1 -65.00
44   p    -11.35 0 -1  65.00
47   pz    -1.6000
45   p  0 -11.44 -1  65.00
49   p   -11.44 0 1 -65.00
48   p    -11.44 0 -1  65.00
c
c    SKELETON
c
c
c       LEG BONES
51   gq   1 1  0.007100 0 0  -0.176485   -11.450000
          0   0.905391      28.7606
52   gq   1 1  0.007100 0 0   0.176485    11.450000
          0   0.905391      28.7606
53   pz   -47.9100
c
c       ARM BONES ( left/right) )
71    gq   1.562500     0.242665 0 0 0     0.031079
          -34.156250 0    -0.352126   186.413906
72   gq   1.562500   0.242665 0 0 0    -0.031079
          34.156250 0    -0.352126     186.413906
73   pz     40.2200
c
c       PELVIS
91   sq    71.9104    41.8609 0 0 0 0 -3010.2341
     0    -2.8500 0
92   sq    81.0000    47.1969 0 0 0 0 -3822.9489 0    -2.2500 0
```

```
93    py    -2.2500
94    py     3.7500
95    pz     8.1600
c
c        SPINE
100      sq      3.5344     1.3225 0 0 0 0    -4.6742 0     4.1300 0
105      sq      3.5344     1.3225 0 0 0 0    -4.6742 0     0.6900 0
101      pz     12.8200
102      pz     48.7200
103      pz     20.4600
c
c     SKELETON
c
c
c            SKULL (head)
c
c
c            CRANIUM
110    sq  2875.7050  1759.9703  3703.6962 0 0 0
    -136912.3139 0 0    54.8000
111    sq   2078.9223  1224.7760  2742.4493 0 0 0
        -83563.5277 0 0    54.8000
c
c        FACIAL
120      sq     73.9600    44.6224 0 0 0 0 -3300.2727 0 0 0
121      sq     64.3204    37.2100 0 0 0 0 -2393.3621 0 0 0
c
122      pz     47.4000
123      pz     56.6700
c
c        RIBS
131      sq     54.0225    94.6729 0 0 0 0 -5114.4667 0 0 0
132      sq     49.1401    88.1721 0 0 0 0 -4332.7858 0 0 0
133      pz     39.1600
134      pz     38.3500
135      pz     37.5400
136      pz     36.7300
137      pz     35.9200
138      pz     35.1100
139      pz     34.3000
74       pz     33.4900
75       pz     32.6800
76       pz     31.8700
77       pz     31.0600
78       pz     30.2500
79       pz     29.4400
80       pz     28.6300
81       pz     27.8200
82       pz     27.0100
83       pz     26.2000
84       pz     25.3900
85       pz     24.5800
86       pz     23.7700
```

```
87     pz    22.9600
88     pz    22.1500
89     pz    21.3400
98     pz    20.5300
c
c        CLAVICLES
140    tz    0     3.1400    39.7800
         9.8000   0.449100   0.449100
141    p   5.997700 1 0      3.140
142    p   5.997700 -1 0     -3.140
143    p   0.563910 1 0      3.140
144    p   0.563910 -1 0     -3.140
c
c        SCAPULAE
156    sq    54.0225   118.3744 0 0 0 0 -6394.8810
         0 0 0
150   p      0.3300 1 0 0
151   p      0.3300 -1 0 0
152   p      1.0500 1 0 0
153   p      1.0500 -1 0 0
154   pz    29.6700
155   pz    39.2300
c
c        ADRENALS
160   1 sq     1.1673    10.6955     0.1717 0 0 0    -1.4642 0 0 0
161   2 sq     1.1673    10.6955     0.1717 0 0 0    -1.4642 0 0 0
162    pz    22.1400
c
c        GALL BLADDER
200  3 so     1.4990
201  3 gq 1 1 -0.05175625 0 0 0 0 0   0.682045  -2.247001
202  3 pz 0
203  3 pz     5.6600
c
c        ESOPAHGUS
212    sq     0.1024     0.4225 0  0 0 0    -0.0433 0     1.6900 0
213    sq     0.0100     0.1849 0  0 0 0    -0.0018 0     1.6900 0
216 6  cx     0.4400
217 6  px     0.0000
218 6  px     4.8400
c
c        STOMACH
210    sq   125.0819   141.2057    37.4544 0 0 0  -813.3448
           4.5800    -3.1500    20.4000
c extent     2.0300     7.1300    -5.5500    -0.7500    15.7400    25.0600
c
c        SMALL INTESTINE
221    py    -3.6500
222    py     1.6500
223    pz     9.9100
c
c        ASCENDING COLON
230    sq     3.5344     2.0449 0 0 0 0    -7.2275    -4.8700    -1.7700 0
```

```
231    pz     8.4200
232    pz    13.9900
c
c        TRANSVERSE COLON
240    sq  0   0.796900     3.5744 0 0 0    -2.6752 0    -1.7700    14.8600
241    px     6.0100
242    px    -6.0100
c
c
c        DESCENDING COLON
251     pz     5.0800
250    gq   2.560000   1.166400     0.058085 0     0.490909    -0.256632
         -23.545717      -2.493818       0.655399    52.487693
c
c
c        SIGMOID COLON
282    px     1.7200
280    ty     1.7200 0     5.0800     3.3300     1.2100     0.8800
281    ty      1.720 0 0      1.750     1.2100     0.8800
c
c        HEART
c
290  4 px 0
291  4 pz 0
c
c        Left Ventricle
292   4 sq   240.8021   710.4997   362.8111 0 0 0 -7878.6600 0 0 0
c       Right Ventricle
293   4 sq    47.0569   138.8438   362.8111 0 0 0 -1539.6250 0 0 0
c
c       Left Atrium
294   4 sq    47.0569    54.6919   142.9149 0 0 0  -606.4735 0 0 0
c
c       Right Atrium
295   4 sq   240.8021   279.8728   142.9149 0 0 0 -3103.4818 0 0 0
c
c
c        KIDNEYS
310    sq    20.0704   104.8576    20.0704 0 0 0  -205.5209
           3.4400     4.5000    18.9400
311    sq    20.0704   104.8576    20.0704 0 0 0  -205.5209
          -3.4400     4.5000    18.9400
312    px     1.3100
313    px    -1.3100
c
c        LIVER
320    sq    39.6900    88.1721 0 0 0 0 -3499.5506 0 0 0
321     p       509.7       407.7      -330.9     -8293.2
322    pz    25.0600
c
c
c        LUNGS
330    sq       6.2037       2.3566       0.3817 0 0 0
```

```
            -74.6984     4.8700 0    25.3500
331   sq       6.2037      2.3566      0.3817 0 0 0
           -74.6984    -4.8700 0    25.3500
333    px    -3.5000
334    py     1.0000
335    pz    26.9000
336    pz    32.3000
337    px     5.0000
338    py     0.5000
339    pz    32.6000
c
c        PANCREAS
350 sq     2.9860   309.3096    67.9635 0 0 0  -250.5408
        -0.5700 0    21.5700
351    px    -0.5700
352    pz    21.5700
c
c        SPLEEN
360    sq    28.1409    53.2039    10.0921 0 0 0  -122.9223
          6.4000     2.2500    21.5700
c extent     4.3100     8.4900     0.7300     3.7700    18.0800    25.0600
c
c        TESTICLES
370    sq     0.1730560     0.129600     0.054756 0 0 0    -0.0350438
          0.4500    -4.9800    -0.8000
371    sq     0.1730560     0.129600     0.054756 0 0 0    -0.0350438
          -0.4500    -4.9800    -0.8000
c
c        THYMUS
380    sq    13.5056    41.9256     3.7733 0 0 0
         -46.2230 0    -5.4800    35.0000
c extent    -1.8500     1.8500    -6.5300    -4.4300    31.5000    38.5000
c
c           THYROID
390    c/z 0    -2.5400     1.2100
391    c/z 0    -2.5400     0.5500
392    py    -2.5400
393    pz    43.5600
c
c        URINARY BLADDER
410    sq    35.7987    43.1176    70.9099 0 0 0  -330.8371 0
          -3.3800     4.6600
c extent    -3.0400     3.0400    -6.1500    -0.6100     2.5000     6.8200
c      Void
600    so 301
c
c     STATISTICS
c  Weight =    19.28 kg ( =    42.51 pounds)
c  Height =   109.29 cm ( =    43.03 inches)

c ++++++++++++++++++++++++++++++++++++++++++++++++
c
c        TRANSFORMATIONS
```

```
c ++++++++++++++++++++++++++++++++++++++++++++++++
c
c        ADREANALS
tr1        2.000      3.750    22.1400
       0.510543   0.859852 0
      -0.859852   0.510543 0
     0       0       1
tr2       -2.000      3.750    22.1400
       0.510543  -0.859852 0
       0.859852   0.510543 0
     0       0       1
c
c        GALL BLADDER
tr3       -0.590     -2.400     17.490
      -0.029100       0.988  -0.149000
       0.981400   0.000000   -0.192100
       0.189800   0.151800    0.970000
c
c        HEART
tr4        0.770     -1.700     29.600
      0.623700  -0.572100  -0.532700
     -0.392600   0.360100  -0.846300
      0.676000   0.736900       0.000
c
c        ESOPHAGUS
tr6        0.000      1.690     24.530
      0.663545  -0.701214  -0.260782
      0.726347   0.687328   0.000000
      0.179243  -0.189418       0.965
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 ++++++++++++++++++++++++++++++++++++++++++++++++
c   User Supplied Cards
c ++++++++++++++++++++++++++++++++++++++++++++++++
c
c
mode p e
c
nps 10000000
c
c
c Source Definition
```

```
sdef erg=d1 rad=d2 pos=0 0 0 axs=0 0 1 ext=d3 par=2 cel=900 eff=0.0001
si1 l 1.17 1.33    $Cobalt-60
sp1 0.9986 0.9998
si2 0 12
sp2 -21 1
si3 -54 56
sp3 0 1
c
c
*F8:P,E        50    $LEG BONES
*F18:P,E       70    $ARM BONES
*F28:P,E       90    $PELVIS
*F38:P,E      100    $SPINE
*F48:P,E      110    $SKULL & FACE
*F58:P,E      130    $RIBS
*F68:P,E      140    $CLAVICLES
*F78:P,E      150    $SCAPULAE
*F88:P,E      160    $ADRENALS
*F98:P,E      180    $BRAIN
*F108:P,E     200    $GALL BLADDER
*F118:P,E     212    $ESOPHAGUS
*F128:P,E     210    $STOMACH
*F138:P,E     220    $SMALL INTESTINE
*F148:P,E     230    $ASCENDING COLON
*F158:P,E     240    $TRANSVERSE COLON
*F168:P,E     250    $DESCENDING COLON
*F178:P,E     280    $SIGMOID COLON
*F188:P,E     290    $HEART
*F198:P,E     310    $KIDNEYS
*F208:P,E     320    $LIVER
*F218:P,E     330    $LUNGS
*F228:P,E     350    $PANCREAS
*F238:P,E     360    $SPLEEN
*F248:P,E     370    $TESTICLES
*F258:P,E     380    $THYMUS
*F268:P,E     390    $THYROID
*F278:P,E     410    $URINARY BLADDER
*F288:P,E      40    $PENIS & SCROTUM
*F298:P,E      22    $HEAD & NECK SKIN
*F308:P,E      17    $TRUNK SKIN
*F318:P,E      41    $PENIS & SCROTUM SKIN
*F328:P,E      34    $LEG SKIN
*F338:P,E      35    $LEG SKIN
*F348:P,E      30    $LEGS
E8 0 30i 2.5
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
```

VITA

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