AN ABSTRACT OF THE THESIS OF

Mario Enrique Gomez Fernandez for the degree of Master of Science in Radiation Health Physics presented on March 8, 2016.

Title: Creation and Application of Voxelized Dosimetric Models: An Evaluation of Elemental Sensitivity in Dose Conversion Factors in *Apis Mellifera*

Abstract approved:

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Over the past decade the International Commission on Radiological Protection has developed a comprehensive approach to environmental protection that includes the use of Reference Animals and Plants (RAPs) to assess radiological impacts on the environment. For the purposes of calculating radiation dose, the RAPs are approximated as simple shapes that contain homogeneous tissue densities and radionuclide distributions. The objective of these models is to generate energy deposition data of radionuclides within the organism. As the uncertainties in environmental dose effects are larger than uncertainties in the radiation dose calculations, some have argued against more realistic dose calculation methodologies. However, owing to the complexity of organism morphology, internal structures and density, and biological aging, all of which can affect the calculated dose rates, a homogeneous model may be too simplistic. The purpose of this study is to examine the benefits of a voxelized phantom versus simple shapes for small organism dose

modeling, i.e. a honeybee. Both techniques typically use Monte Carlo methods to calculate absorbed dose. However, voxelized modeling, a reverse engineering method, uses a three-dimensional replica of an organism. Consequently, additional information can be included, such as measured tissue composition and density, for a more comprehensive study on absorbed fractions and dose distributions in different structures. This multi-stage procedure couples imaging modalities, imaging processing software, and Monte Carlo N-Particle (MCNP) code to generate a detailed phantom. Ultimately, these additional features increase dosimetric accuracy and reduce uncertainty in non-human biota (NHB) dose-effects studies by providing a more robust data generator of radionuclide sources for environmental impact analysis.

Creation and Application of Voxelized Dosimetric Models: An Evaluation of Elemental Sensitivity in Dose Conversion Factors in *Apis Mellifera*

by
Mario Enrique Gomez Fernandez

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APPROVED:

Major Professor, representing Radiation Health Physics

Head of the School of Nuclear Science and Engineering

Dean of the Graduate School

I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Mario Enrique Gomez Fernandez, Author

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I would like to dedicate this thesis to my aunt Alicia Mariela Fernández Arbizú, whose energy has always been by my side encouraging me to do my very best, and my family and friend in Guatemala. My motivation has always come from my deepest love of my parents, Mario Enrique Gómez Ayala and Patricia Elena Fernández Arbizú, my sister, Luz Angelina Gómez Fernández and my wiliness to represent the best of my being.

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1. Chapter 1: Introduction

1.1. Motivation

This study was motivated by ongoing discussions in radiological protection regarding non-human biota dose calculations. Further details of this work are presented in later sections. Presently, one of the main arguments in non-human biota radiation protection is the use of advanced and detailed models for dose calculations. The current approach is to assume that the organism is a spherical object made out of water. However, this approach presents some issues. To explain this work in a mathematical matter, one can look at the Dose Conversion Factor (DCF) equation:

$$DCF = C \times \sum_{i} \bar{E} \times AF(\bar{E}, S \rightarrow T) \times BR \times Y \qquad \text{Equation 1}$$

Where:

- Summed over all i radiation
- $\bar{E}$ is the average energy emission
- $AF(\bar{E}, S \rightarrow T)$ is the absorbed fraction of energy $\bar{E}$ for a particular source-to-target
- BR is the Branching Ratio
- Y is the yield for decay
- C is the activity concentration

Typically radionuclides have given values for the following three variables $\bar{E}, BR, Y$, yet, the absorption fraction (AF) and activity concentration (C) do change and are dependent on other variables, such as size, densities, elemental composition, energy, location within the organism, among others. With this in mind, this study focuses primarily on the absorption fraction parameter with the following three objectives:

1. Create a voxel phantom model of a honeybee
2. Perform an organic elemental analysis of various honeybee organs
3. Evaluate the sensitivity of DCFs based on the elemental composition of the organism by comparing it with the standard four-component human tissue composition.

1.2. International Commission on Radiological Protection

In 1928, an international commission, called the International X-Ray and Radium Protection Committee (IXRPC) was formed to make recommendations with regard to radiation protection on the human kind and to study the issues and control of radiation exposure (Nuclear Energy Agency 2011; Burnham 2011). After the Second World War, Lauriston Taylor, one of the two former member of the IXRPC who survived the war, was invited to revive and revise the commission which was given the name: International Commission on Radiological Protection (ICRP). Again, the main objective of the commission was to protect the human race in general, while still allowing the beneficial activities involving the use of ionizing radiation. The commission intended to provide recommendations for national, regional and international agencies by providing guidance on the fundamental principles on radiological protection. Nonetheless, governmental authorities still needed to develop their own structures of legislation, regulation, authorizations, licenses, codes of practice and guidance material (Sowby 1978).

The ICRP has made four major recommendations regarding the concepts of dose intake, dose-response relations in human species, and limits since it was established. The first recommendation made in 1959, in publication 2, provides a methodology to calculate dose for internal dosimetry purposes. It defines the concepts of Maximum Permissible Concentration (MPC) for air and water and the Maximum Permissible Body Burden (MPBB) (ICRP 2 1959). Recommendations made in 1977, in publication 26, identify the system of dose limitations and define the terms stochastic and non-stochastic (Sowby 1978). A stochastic effect is one where the probability of an effect occurring is dose dependent; in contrast, a non-stochastic effect is one where the severity of the effect is dose dependent. By introducing this terminology, the commission concludes that *"The principal objective of radiation protection is the achievement and maintenance of appropriately safe conditions for activities involving human exposure, the level of safety required for the protection of all human individuals is thought likely to protect other species, although not necessarily individual members of those species. The Commission therefore believes that if man is adequately protected then other living things are also likely to be sufficiently protected."* (ICRP 26 1977)

In the third major recommendations made in 1990, in publication 60, there was a review of the non-stochastic term and it was renamed the "deterministic" term for the calculation of the effects in organs and tissues and estimates were given for the threshold of these effects (ICRP 60 1991). Finally in recommendations made in 2007, in publication 103, there was an update on the radiation and tissue weighting factors in the quantities of equivalent and effective dose, based on the latest available scientific information of the biology and physics of radiation exposure (Obed et al. 2015).

In contrast to the development of the human radiation protection recommendation, there are no internationally agreed criteria or policies that address protection of the environment from ionizing radiation (although there are criteria under consideration in the International Atomic Energy Agency (reference). In addition, it was stated in publication 60 that the concerns of the commission were primarily to the human race and the transfer of radionuclides through the environment as it directly affects the radiological protection of the man. Furthermore, in the recommendations from 2007, publication 108, the commission proposed the creation of a framework for environmental protection and expressed the difficulty of determining or demonstrating whether or not the environment is adequately protected from potential radiation impacts under different circumstances (ICRP 108 2008). The framework includes the development of a similar framework used for the "Reference Man" using reference animals and plants (RAPS) in order to establish a basis for the protection of the environment.

1.3. ICRP's Environmental Protection Approach

There are three exposure situations that one should consider when discussing radiation protection (reference). Planned exposure, where known concentrations of radionuclides are released. This should require an environmental impact assessment before the execution of the plan. Existing exposure, where radionuclides are already present in the medium. Emergency exposures, which are unexpected and require could require immediate action. The framework developed for the protection of the general public has taken decades, and has resulted in a sophisticated protection plan that uses reference voxel phantoms to determine dose limits, dose constraints, and reference levels that are applied by each country and its regulatory body. The human system uses the "Reference Man", an idealized male or female with anatomical and physiological characteristics defined by the ICRP (Valentin 2002), as the reference point. In contrast to the Reference Man, there is no simple or single universal definition of environmental protection, as there exists many different species from the different ecosystems that vary from country to country. Figure **1-1** and Figure **1-2** show the conceptual relationships between the deterministic and the numerical calculation radiation reference levels for planned, emergency and natural exposure situation.

In Figure **1-1**, a complete methodology can be observed, as there are points of references to begin with. On the other hand, Figure **1-2** lacks those points of reference, and a "Derived Consideration Reference Levels" is considered instead. From ICRP Publication 108:

"*A derived consideration reference level (DCRL) can therefore be considered as a band of dose rate within which there is likely to be some chance of deleterious effects of ionizing radiation occurring to individuals of that type of Reference Animal or Plant, derived from a knowledge of defined expected biological effects from that type* *of organism that, when considered together with other relevant information, can be used as a point of reference to optimize the level of effort expected on environmental protection, dependent upon the overall management objective and the exposure situation*" (ICRP 108 2008).

Thus, DCRL's are not dose limits, but rather dose levels at which further investigation might be considered. Ultimately, the RAPs framework's objective is to create points of reference relating exposure to dose, and dose to dose effects to prevent or reduce the frequency of effects that cause early mortality or reproductive impediments and preserve a healthy natural habitat.

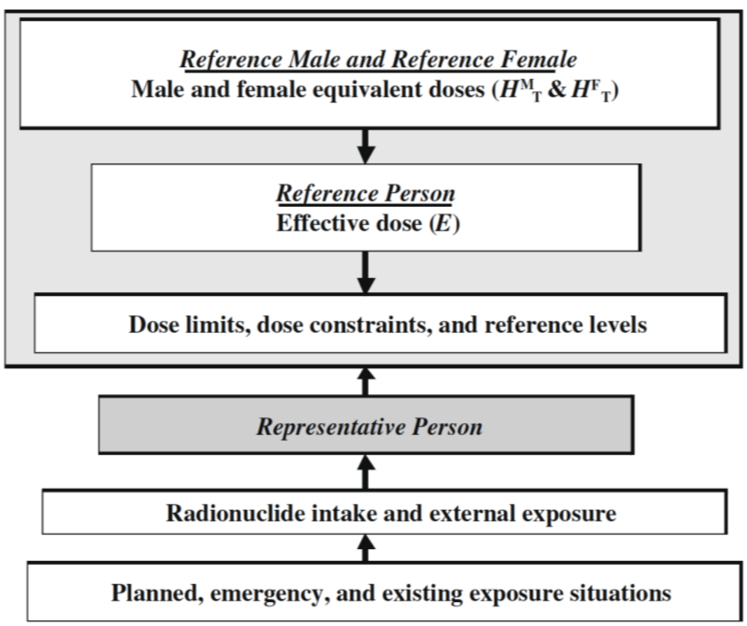

Figure 1-1 Radiation protection framework for the general public protection (Pentreath 2009).

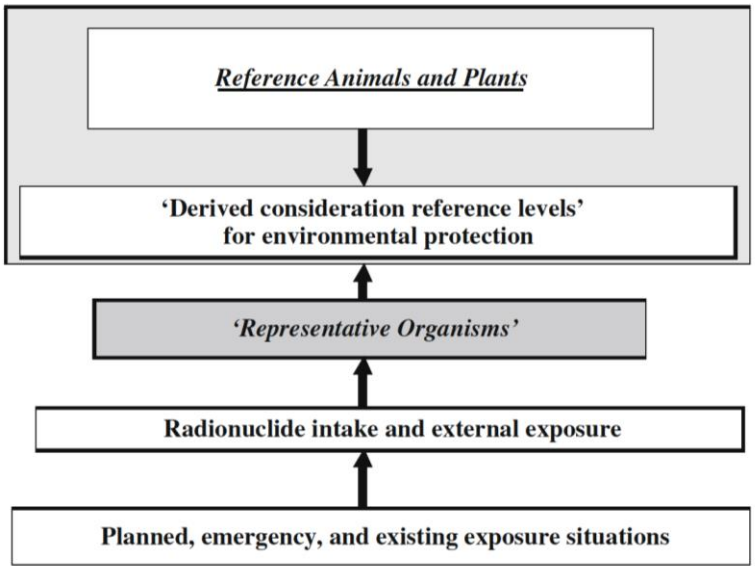

Figure 1-2 Radiation protection framework for non-human biota protection (Pentreath 2009).

1.3.1. Selection criteria

Though there is no possibility of providing a comprehensive biological background to all of the reference types chosen, the selected organisms are typical of the terrestrial, freshwater, and marine environments. The selection of each of the RAPs was decided based the following criteria (ICRP 108 2008):

- Amount of radiobiological information
- Amenable to future research
- Typical representative fauna or flora of particular ecosystems
- Likely to be exposed to radiation
- Different life histories
- Model using relatively simple geometries
- Have public or political resonance

The intense selection criteria narrowed the possible representative organisms and only few species are suitable with such criteria; as a result, the following twelve animal and plants were chosen as in ICRP 108:

Table 1-1: Selected Reference Animals and Plants

Animal	Environment
Deer	Terrestrial/Large Mammals
Rat	Terrestrial/Small Mammals
Duck	Terrestrial/Aquatic/Birds
Frog	Terrestrial/Aquatic/Amphibian
Trout	Aquatic/Freshwater Fish
Flatfish	Aquatic/Marine Fish
Bee	Terrestrial/Insect
Crab	Aquatic/Large Marine Crustaceans
Earthworm	Terrestrial/Annelids
Plants	Environment
Pine Tree	Terrestrial/Conifers
Wild Grass	Terrestrial/Grasses
Brown Seaweed	Aquatic/Algae

1.4. The Homogenous Model

Many different approaches have been used to estimate the doses received by animals and plants from both internal and external sources (Beaugelin-Seiller et al. 2006; Ulanovsky & Pröhl 2006; Blaylock et al. 1993; Copplestone et al. 2001; Department of Energy 2002; Higley et al. 2003); nonetheless, it is very challenging to find the appropriate methodology to apply due to the vast difference in biological anatomy and physiology in the animal and plant kingdom and the variation on biokinetics of radionuclide concentration on tissues. To address these issues, simplifications have been considered such as, the use of simple shapes to model a whole organism. This assumption seemed to be appropriate and useful for dose calculation for the RAPs (see Figure **1-3**) as it can provide a comparative method for the exploration of the dose contribution of different radionuclides. The figure represents the current model being used for internal dosimetry estimations with different dimensions for each of the RAPs shown in Table **1-2**. It is important to notice that not all the RAPs contain internal organs and they are only modeled as solid shapes with a uniformly distributed source within them.

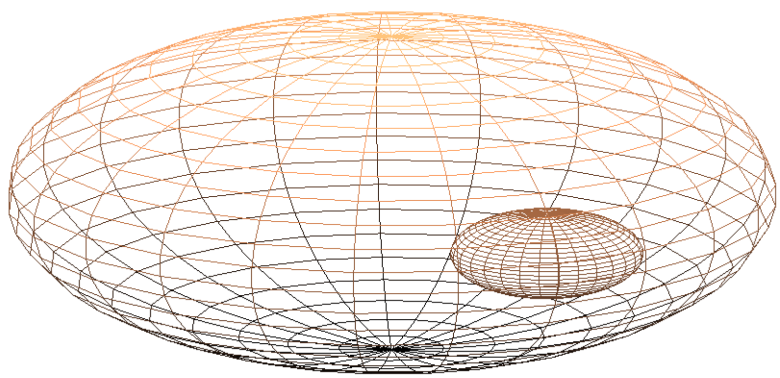

Figure 1-3 Current ICRP geometric model of the RAPs with inner ellipsoid representing an internal structure

Table 1-2: ICRP homogeneous model's parameters

Animal*	Shape*	Dimensions (cm)*	Volume (cm^3)	Organs Identified*
Deer	Ellipsoid	130x60x60	1960354	Liver Testes
Rat	Ellipsoid	20x6x5	2513	None
Duck	Ellipsoid	30x10x8	10053	None
Frog	Ellipsoid	8x3x2.5	251	None
Trout	Ellipsoid	50x8x6	10053	None
Flatfish	Ellipsoid	40x25x2.5	10472	None
Bee	Ellipsoid	2x0.75x0.75	4.7	None
Crab	Ellipsoid	20x12x6	6032	None
Earthworm	Ellipsoid	10X1x1	42	None
Pine Tree	Ellipsoid	1000x30x30	3769911	None
Wild Grass	Ellipsoid	5x1x1	21	None
Brown Seaweed	Ellipsoid	50x50x0.5	5236	None

*(ICRP 108 2008)

1.4.1. Dose Calculation

From the dose calculation perspective, estimating doses to non-human biota presents a challenging case because it is impossible to cover all radiation exposure conditions, as there is an enormous variability of organism's characteristics and their natural habitats. The models have to be based on selected typical assumptions for energies, contaminated media, and organism sizes that are to be used for detailed consideration (ICRP 108 2008), The following assumptions are then considered:

- DCFs are calculated for beta and gamma emitters. Alpha emitters are considered to have AF of 1 due to their short range
- Nuclide-specific dose-rate conversion values are derived as a function of habitat, target size, and exposure route
- In all models, radiation transport is simulated for mono-energetic in the range of 0.01–5 MeV. Data for other energy values in this range are obtained by interpolation
- For the calculations of DCFs for targets living in the soil, uniformly contaminated volume sources are assumed. In some models, the thickness of the volume source is assumed to be infinite; in other models, values for thickness are assumed to be 10, 20, or 50 cm

1.5. Voxel Phantoms Concept

The use of advance radiation transport codes based on Monte Carlo methods using numerical solutions for particle simulations provide several advantages, such as:

- Ability to use various materials differing in composition and density
- Use of complex geometries as sources and targets

- Radiation transport physics and self-shielding can be modified
- High confidence and low uncertainty outcomes

Due to the ability of handling complex geometries, the concept of a phantom model or digital model is to represent a body region of interest (Zaidi & Xu 2007) seems useful. These are constructed with a series of image slices formatted in pixels with a given thickness forming a volume pixel unit or voxel unit. Figure **1-4** exemplifies Figure **1-3** with the representation of an internal structure as a voxel object. Hence, the use of medical imaging ensures the conservation of the external shape and the anatomical realism of the internal organs. In addition, the use of this method can allow for further study in the interaction of particles through different medium within an organism such as: organ, an organ system, or the whole body.

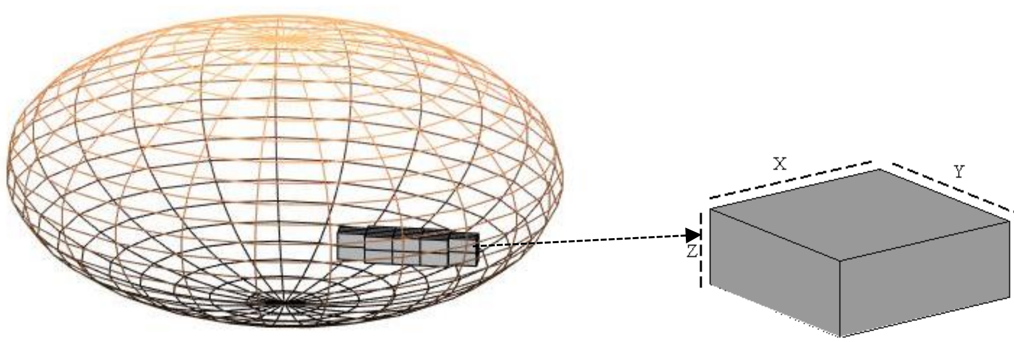

Figure 1-4 Representation of a voxel object within a sphere (Higley et al. 2015)

The introduction of the phantom models has provided a significant improvement over the current homogenous model. The advantages mentioned earlier in this section has led to a more sophisticated method to assess the protection of non-human species. Figure **1-5** show of examples of different voxels.

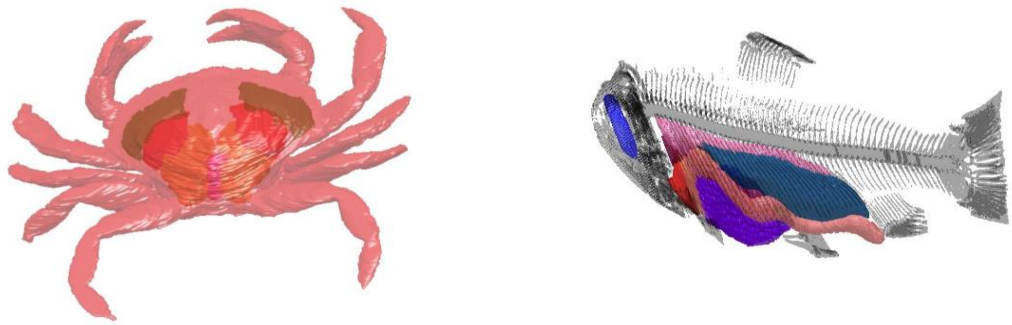

Figure 1-5 Voxel phantoms of a the Reference Crab and the Reference Trout (Caffrey 2012; Hess 2014).

The use of different imaging modalities facilitated the conservation of the organism internal structures as well as their natural shape. With realistic shapes and the use of Monte Carlo methods to has proven to be valuable approach for the basis of estimating doses to other species other than humans because it can allow for further research limited by the use of simple shapes. Table 1-3 shown the model dimensions for some of the selected reference animals that have been develop (Caffrey 2012; Stabin et al. 2006; Kinase 2008).

Table 1-3: Parameter of various organs on voxel-based models*

Animal	Imaging modality	Whole body volume (cm^3)	Organs identified	Volumes (cm^3)	Mass (g)
Crab	CT	328.34	Gills	68.32	68.32
			Gonads	21.36	22.21
			Heart	2.17	2.26
			Hepatopacreas	29.79	29.79
Flatfish	MRI	961.11	Brain	0.63	0.70
			Liver	2.05	2.16
			Gills	2.30	2.30
			Stomach	1.45	1.45
Trout	CT	651.19	Brain	0.57	0.59
			Esophagus	13.75	14.37
			Eyes	1.94	2.07
			Heart	1.78	1.84
Frog	CT	235.54	Brain	0.10	0.11
			Heart	0.20	0.21
			Kidneys	0.21	0.22
			Intestine	0.28	0.29

* (Higley et al. 2015)

2. Chapter 2: Materials, Software and Instrumentation

This chapter is intended to provide an introduction on the different instrumentation and software used in this project. As per objectives 1 and 2 on Section 1.1 the development of voxel phantom models requires different steps, which includes the acquisition of the organisms, tissue analysis, voxel rendering, data analysis and manipulation.

2.1. COSTECH Elemental Combustion Systems

The elemental Combustion System 4010, shown in Figure **2-1**, was designed as an advanced analytical platform for CHNS-O elemental analysis and Nitrogen/Protein determination by using flash combustion, chromatographic separation, and multi detector techniques (Costech n.d.). This instrument consists of three different modules as specified by the manufacturer

1) Sampling, combustion, and pneumatics,
2) Detection system for measuring the combustion products
3) The proprietary Elemental Analysis Systems software package for data acquisition and report generation.

Figure 2-1 Elemental Combustion System 4010

Modern gas chromatography uses instruments to measure one of more of the physical properties of the oxidation products such as their gaseous pressure, their light adsorption, or their thermal and electrical conductivity (Pella 1990).The basic steps to perform elemental analysis using a gas chromatogram is as follow:

1) Sample quantification/weighting
2) Combusting (oxidizing)
3) Separation of gases
4) Thermal conductivity detection
5) Post processing as analog-digital-sample composition

The first step is the most laborious of all, as the quantity of each of the samples needs to be small enough for the chromatographic method to be successful. Then, the samples are placed in a tin boat and folded to avoid contamination of the samples from the surrounding environment.

The second through the fourth steps are carried out by the combustion system. The sample is dropped into the combustion reactor, which heats up to1100 ^{o}C, and the sample is broken down into its elemental components in the form of oxide gasses N_2, CO_2, H_2O, and SO_2. After the sample is combusted, it passed through a reduction chamber up to 800 ^oC where the gasses are separated in the gas chromatographic column at up to 110 ^oC and detected by the gasses thermal conductivity.

2.2. Micro Balance

For the purpose of weighting small samples, a high accuracy microbalance SE2 manufactured by Sartorius was used for the first step of the elemental analysis. This instrument has a maximum weight capacity of 2.1 grams and a readability of 0.1μg throughout the weighting range.

Figure 2-2 Sartorious SE2 microbalance

2.3. Elemental Analyzer Data

Once data is collected and analyzed, Equation is then used to determine the number of samples that are required to have a good estimated of the elemental composition in a specific tissue with a low standard error:

$$SE_{\bar{x}} = \frac{\sigma}{\sqrt{n}} \qquad \text{Equation 2}$$

Where, there must be at least two samples, as standard errors cannot be determined when only one sample is given. In this study the first test consisted of 5 samples from

7 different tissues, see Figure **2-3**. It was then determined that more samples were required as the standard error was still decreasing. Thus, 7 more samples were added for a total of 12 samples; see Figure **2-4**. At this stage most of the elements in the tissue had plateau, however, N and O were still decreasing as more samples were added. Consequently, an additional 5 samples were added for a total of 17 samples. It can be observed in Figure **2-5** that most of the elements have reached a plateau and no further analysis is required.

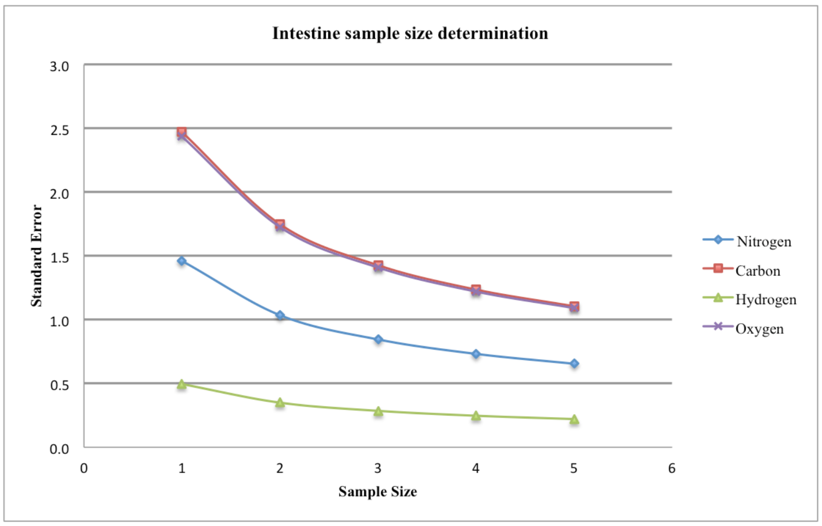

Figure 2-3: Intestine standard error plot of 5 samples

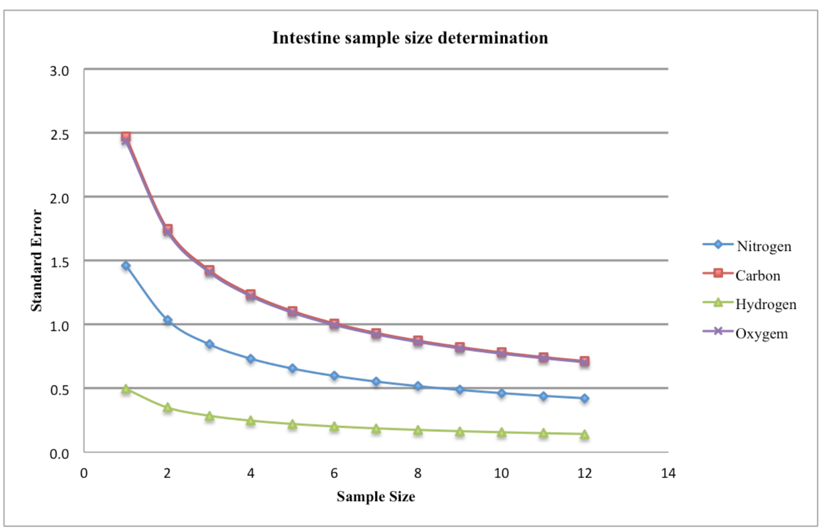

Figure 2-4: Intestine standard error plot of 12 samples

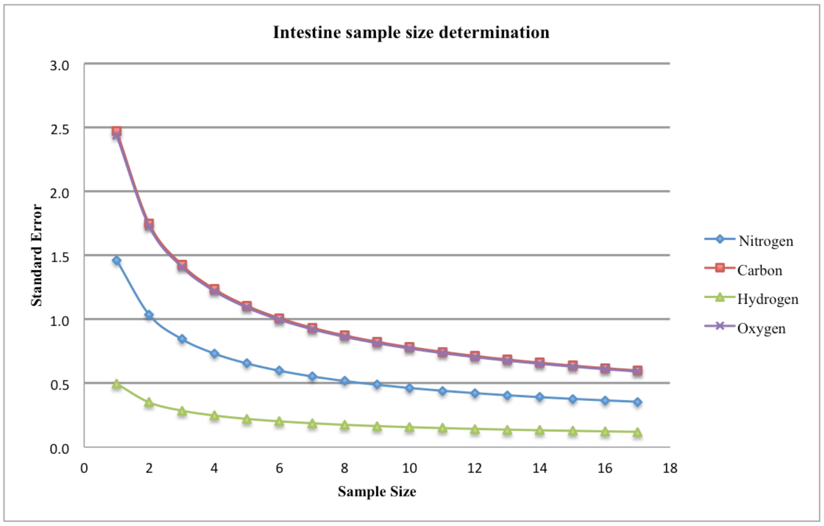

Figure 2-5: Intestine standard error plot of 17 samples

The standard error graphs of each tissue are shown in Appendix G.

2.4. MCNP

MCNP5 is a general purpose Monte-Carlo N-Particle code written in ANSI-Standard FORTRAN 90 that is capable of solving the transport equation in 3 dimensions for many particles types such as neutrons, photons, and electrons or coupled electron/photon/neutron (X-5 Monte Carlo Team 2008a). The code can be used within an energy regime of 10^{-11} to 20 MeV for all radionuclides, for neutrons, 1 KeV to 100 GeV for photons and 1 KeV to 1 GeV for electrons (X-5 Monte Carlo Team 2008a). The user creates an input file that contains the following information:

- Geometry specification
- Description of materials and selection of cross-section evaluation
- Location and characteristics of the source
- Type of tally desired

- Other options including variance reduction techniques used to improve efficiency

The code uses a statistical sampling process on the selection of random numbers that describe the statistical life of each particle; that includes scattering (coherent or incoherent), fission, leakage, absorption interaction, and other particle-material interaction that may occur (X-5 Monte Carlo Team 2008a); thus, it can take quite some time for the code to run Moreover, the code has built-in cross section libraries for different particles, allowing the user to specify the elemental composition and densities of the object. Consequently, it can be used in radiation protection and dosimetry, radiation shielding, criticality problems and more.

The general form on a readable input file can be represented as follow

Message Block
Blank Line Delimiter
One line Problem Title Card
Cell Card
-
-
Blank Line Delimiter
Surface Cards
-
-
Blank Line Delimiter
Data Cards
-
-
Blank Line Terminator

The cell and surface card specify the problem and the problem's geometry in a 3-dimensional Cartesian coordinate system. MCNP has many types of built-in surfaces that are typically used to define an object, such as planes, cylinders, and spheres. The geometry for the model presented in this project are lattice structures. Each lattice is made hexahedra, i.e. voxel or cubic with six faces. Each lattice structure is then filled with materials. The data card provides additional information about the problem, such as material specification, cross section specification, particle types, energies, tallies, sources and more.

The general code used for this research is presented in Appendix H. The input deck defines the problem by defining a spherical volume, where particles are giving an importance (IMP=1), i.e., their trajectory will be traced. Particles that do not travel within this boundary are then killed (IMP=0). The geometry is the output of Lattice tool and the 3D Doctor boundary model, which in MCNP is defined by lattices that make up universes. Universes represent each of the organs in the input deck. Again, each of the universes is given an importance of one to trace the particles of interest. For the purpose of this study the PAR option was used for photons (PAR=2) and electrons (PAR=3), a long with the ERG option that represents the initial energy of each of the particles. The elemental analysis results have also been included in the materials definition, which can be easily changed if more data becomes available. The source location in defined by the Source Information card as (Source <Lattice Unit<Cell Containing the Lattice), for instance, (1<996<997) defines the source in the antenna. Lastly a total of 2 million histories were run for electron and 10 million histories were run for photons.

2.5. 3D-Doctor

3-D Doctor is an image processing software for medical imaging, modelling, and visualization applications developed by Able Software Corp. It specializes in processing, rendering, modelling, visualization and quantitative analysis of images from MRI, CT, PET, and other industrial uses (Able Software Corp. 2012). Additionally, the software is capable of exporting ASCII text files readable by the Lattice Tool software.

2.6. Lattice Tool

Lattice Tool or Voxelizer is software developed using Microsoft VisualBasic.NET by The Human Monitoring Laboratory, now part of Health Canada's National Internal Radiation Assessment Section. This program essentially creates a virtual phantom from either computer tomography (CT) or magnetic resonance images obtained from hospitals or medical centers. The main idea is to extract the boundaries from Digital Imaging and Communication in Medicine (DICOM) format that define any identified and contoured structure within the image stacks. Each of the objects are identified and the names stored such that each object will form a unique universe in the lattice structure. The boundary file is then converted into lattice that is readable by the MCNP code. The program uses the boundary file (".bnd') as the input file and creates a temporary ".vxl" file that is subsequently used to create the MCNP lattice structure (Kramer et al. 2010). However, it is important to know the limitation of the MCNP version that is being used, i.e. 50 million voxels for MCNP5. When exceeding the limit, Voxelizer can adjust the arrays by using a compression factor or array reduction that will combine several voxels into one (Kramer et al. 2010). Additionally, if a compression factor is applied, there will be a reduction of resolution of the final lattice.

2.7. MATLAB

Matrix Laboratory or MATLAB® is a high-level language and interactive environment for numerical computation, visualization, and programming (Mathworks 2015). MATLAB® makes use of highly respected algorithms or the user can build up its own set of functions for a particular application; hence, making it a powerful tool for writing moderate-size programs that solve problems involving the manipulation of numbers, which makes it possible to write a powerful program in a few lines for a range of different applications, e.g. image processing. For the purpose of simplifying the calculation process, a customized script has been developed using the MATLAB code. The script is aimed to help anyone working with voxel modeling by reading the MCNP output files, extract the desired results, organizing them in a table, plot and preform the DCF calculations. However, the script presented here needs to be generalized as it has been created for this specific voxel phantom. It consists of a number of different functions, where each of the functions is used for a specific task, e.g. read the MCNP output file. The following functions can be found in the APPENDIX I and modified to a different model:

1. Data_extractor.m

   Data_extractor is the main script that calls the information from the different functions. Each of the different section can be run individually for debugging purposes.

2. Organs.m

   Organs contain the name and masses of the different objects that were segmented. This data is used during the DCF calculation, the organization of the results and the graphs as it is automatically selected based on the source location. This file must me modified for different voxel models.

3. ElectronData and PhotonData

   These functions are responsible to get the information from the MCNP output file as long as the folder's path is correctly provided. It will read the contents in the folder and open each of the files in it using the OpenFiles function, and store its identification number in a vector (it refer to it to get the information out of each file). Then it will use DataExtractor to get the desired information and format as a table.

4. DataExtractor.m

   DataExtractor will provide two different matrices. The first are the raw results form the MCNP files found using the find_val. The second one will include only the absorbed fraction whose relative error that is less than 10% and stored in the format shown in TABLE.

5. find_val.m

   find_val will read the text file and look for the string 'total', once found, it will grab the characters in column 18 through 28 (energy), and column 30 through 35 (error) and store in the following format.

6. DCFcal.m

   DCFcal uses the interpolated data, masses, and sources information to calculate the DCF for each or the particles emitted.

7. DCFadd.m

   DCFadd simply sums the results of DCFcal.m

8. Graph.m

   Graph is a simple plot function that will look into the structures (matrices) from the DataExtractor. It will use the names Organs function, type of source and location from Photon_Data or Electron_Data, and locate the energy row that corresponds to each of the organs and create an absorbed fraction plot as shown in APPENDIX A and APPENDIX B

9. InterData.m

   InteData used the source function to read each of the sources information to be used for the interpolation process.

10. OpenFiles.m

    OpenFiles opens each of the files contain in the folder and gives them an identification number, e.g. 20 that can be used to open that specific file.

11. Sources.m

    Sources include the energy, yield, and branching ratio of the radionuclides that were used in this project.

3. Chapter 3: *Apis Mellifera* Anatomy

This chapter is intended to demonstrate the complexity of the honeybee anatomy, and the limitation and rationale of the selected source-to-targets. For complete and detailed information about the honeybee anatomy see "The Anatomy of the Honey Bee" by Robert Snodgrass. In this study, the source-to-target terms refers to an organ or tissue where particles are being emitted from to the organ or tissue where particles deposit energy. There are 4 different types of configuration when it comes to source to target configurations: source and target being the same, source is inside the target, source and target are distance apart, and target inside the source. Figure **3-1** shows an illustration of each source-to-target configuration.

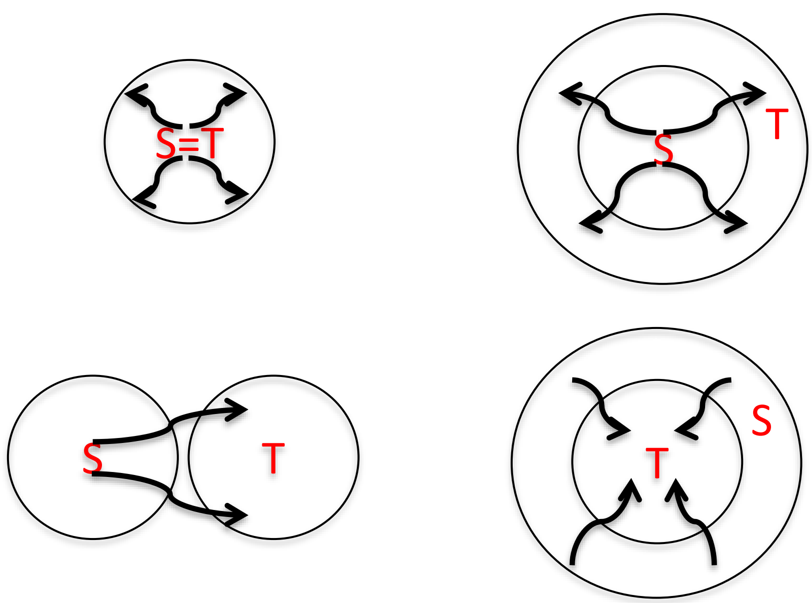

Figure 3-1: Source to target configurations

3.1. Apis Mellifera Biology

There are many different types of bees around the world, many of them being non-social social bees, i.e. they do not produce honey or colonies. However, the most common species is the western bee or *Apis Mellifera*. This a social species that exhibit a “colony defense” behavior (Stone 2005). As a colony-forming species, they have three members – Drone, Queen, and Worker – that have specific task assigned to them. Drones are male bees whose function in mainly to mate with the young queens once they flight out the colony to form their own. Once they mate, they die because their reproductive organs are located at the end of their abdomen, which breaks off. Their larger size and their eyes can distinguish them from the workers. Queens are the largest members in a hive, whose primary function is to lay eggs. There is only one queen per hive, which means that once a queen reaches maturity, she will fly away and form her own colony or she will kill the current dominant queen (Stone 2005). Lastly, perhaps the most encountered by humans are the worker bees. They are unfertile females whose primary job is to maintain the hive, which includes nursing young bees, cleaning and repairing, and defending the hive.

3.2. Honeybee Anatomy

Honeybees, like any other insect, have segmented exoskeleton that helps them protect their organs form the environment. The body of the honeybee can be divided into three different sections – the head, the thorax, and the abdomen – each containing a number of organs within them.

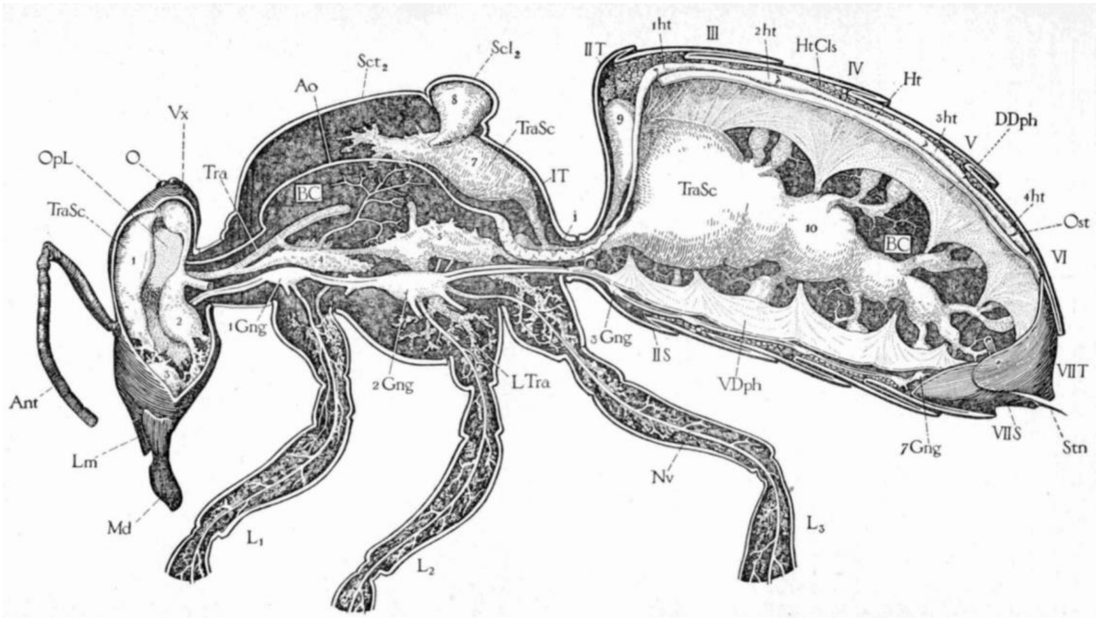

FIG. 1.—Longitudinal, median, vertical section of entire body of worker, showing nervous system (*OpL–7Gng*), tracheal system (*TraSc, 1–10*), dorsal and ventral diaphragms of abdomen (*DDph* and *VDph*), and dorsal vessel consisting of heart (*Ht*) and aorta (*Ao*).

Figure 3-2: Anatomy of a worker bee (Snodgrass 1910)

The head houses the visual – eyes–, olfactory – antenna– and gustatory – mouth– sensing organs in a honeybee, which all connect to the brain. The thorax carries both the legs and wings of the insect and it contains large muscles that allow movement in ground and air. The abdomen houses mainly the digestive tract, shown in Figure **3-3,** and the reproductive system. These systems are highly complex and consist of different organs in each of the honeybee sections. For the purpose for this research, the digestive tract can be divided into three main different parts: crop (honey stomach), midgut or bee stomach (ventriculus), and rectum, which are capable of expanding and storing food and waste, and retain it in those organs for up to two months (Stone 2005). Therefore, these four organs have been selected as source organs because of their expandability and their material retention.

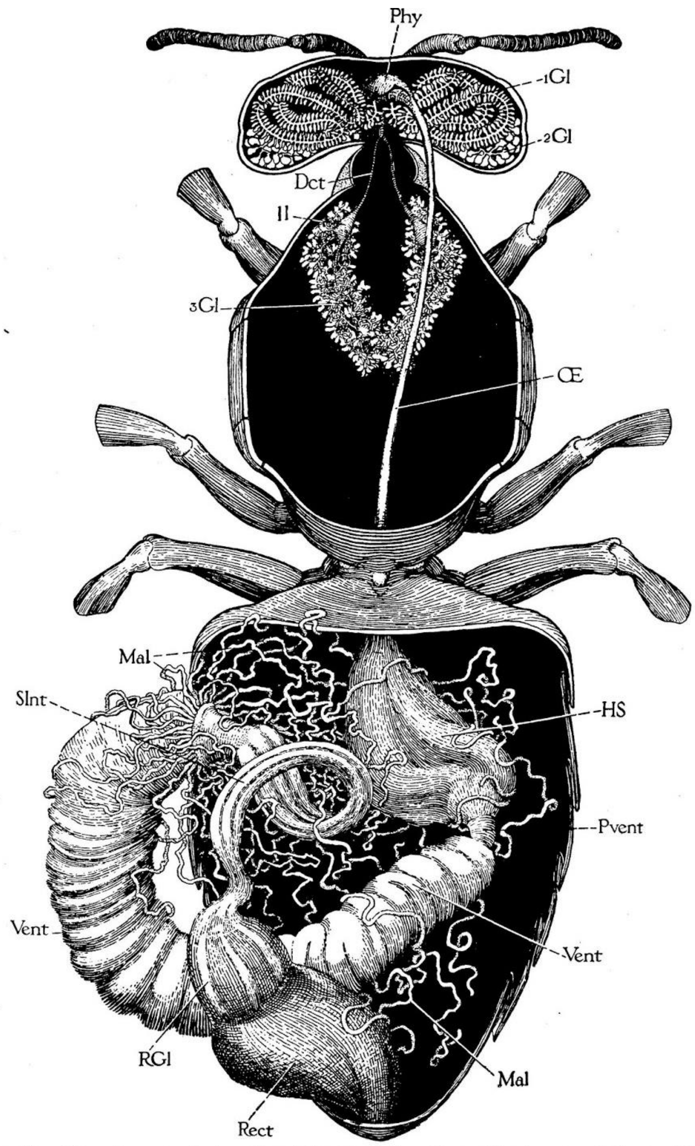

FIG. 42.—Alimentary canal of worker (*Phy–Rect*), together with pharyngeal glands (*1Gl*), and salivary glands of head (*2Gl*) and of thorax (*3Gl*), as seen by cutting body open from above and pulling the ventriculus (*Vent*) out to left.

Figure 3-3: Honeybee digestive tract from The Anatomy of the Honeybee (Snodgrass 1910)

3.3. Imaging limitations

As presented in the previous section, the anatomy of honeybees is quite complex and it is compacted in a small body. For this study the use of micro-Computerized Tomography (μCT) has made the imaging and identification of some of the internals structures possible; however, not many of them can be identified as the resolution, yet very good, is not sufficient to fully differentiate all organs.

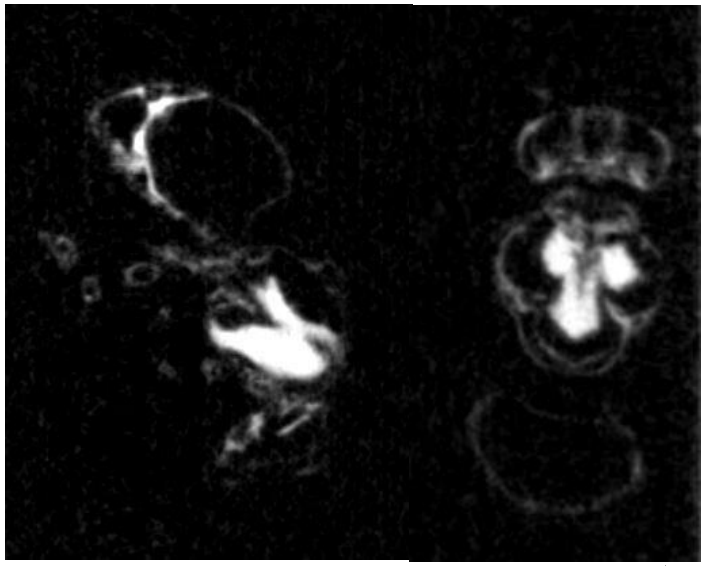

Figure 3-4: Honeybee CT scanner top and side views[1]

Figure **3-4** Shows an example of one of the 512 images from both top and side views. Clearly, when compared to the general anatomy of the honeybee, it falls short in the level of detail captured, which is can be complicated for the creation of a voxel phantom model. The most notable organ in the image are the leg and wing muscles on the thorax section; therefore, they were selected as the thoracic source for this model shown in Figure **3-5**. The digestive tract, shown in Error! Reference source not found. was chosen to be reconstructed because "*the alimentary canal is the most important organ it possesses and the entire system suffers if there is a deficiency in the food supply*" (Snodgrass 1910). It can be also understood that it enables the proper functionality of the other systems. Lastly, the brain has also been reconstructed and selected as a source location as it the information-processing unit in the honeybee, a reconstruction is shown in Figure 3-7**.** The final model is shown in Figure **4-2**.

[1] Scans have been provided by Oregon Health and Science University's Small Animal Research and Imaging Core (SARIC).

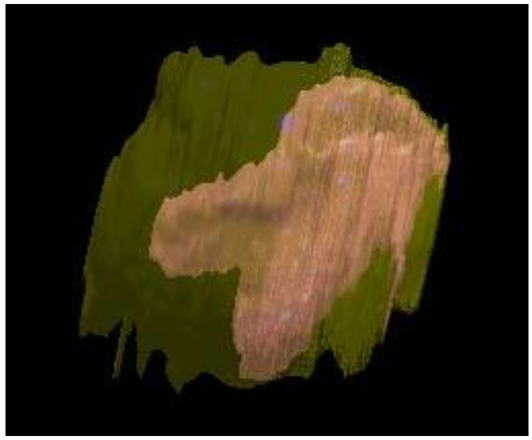

Figure 3-5: Honey bee voxel thorax

Figure 3-6: Honey bee voxel head

Figure 3-7: Reconstructed digestive tract model

4. Chapter 4: Creation and Application of Voxelized Dosimetric Models: An Evaluation of Dose Conversion Factor in *Apis Mellifera*

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4.1. Abstract

Over the past decade the International Commission on Radiological Protection has developed a comprehensive approach to environmental protection that includes the use of Reference Animals and Plants (RAPs) to assess radiological impacts on the environment. For the purposes of calculating radiation dose, the RAPs are approximated as simple shapes that contain homogeneous distributions of radionuclides. Yet, most organisms have complex morphologies, internal structures, and densities; therefore, dose rates calculated via a homogenous model could be questioned to be unnecessarily conservative and simplified. In this study a voxel phantom model was constructed and seven different tissue compositions were measured using organic elemental methods, with the objective of comparing dose conversion factors between the measured values and the standard tissue properties currently used in the RAPs, i.e. ICRU four component human tissue. The dose conversion factors were calculated using absorbed fractions for discrete photon energies ranging from 0.01 MeV to 4.0 MeV, and discrete electron energies ranging from 0.1 MeV to 4.0 MeV generated by the general Monte Carlo N-Particle transport code, for the following radionuclides: ^{137}Cs, ^{90}Sr, ^{90}Y, ^{60}Co, ^{131}I, ^{36}Cl, ^{226}Ra. Conclusively, the use of the voxel phantom has shown that the dose conversion factors do differ when applying the correct tissue composition and could have an impact by up to ±10% in the dose conversion factors calculations. Finally, a validation of these methods is suggested if they are to be used in the regulatory domain; nonetheless, they have shown to address some uncertainties by providing further detail in assessment of environmental protection of both large and small

organisms.

Keywords: Voxel phantom, Organic Elemental Analysis, 3D modeling, Reference Animals and Plants, Environmental protection

4.2. Introduction

During the last two decades, there has been an increase in concern regarding the radiological protection of the environment from society's perspective, expressing that explicit protection from harmful effects of ionizing radiation should also be provided for non-human species and ecosystems. Though there is no simple or single universal definition of 'environmental protection', and the concept differs from country to country, in 2008 the International Commission of Radiation protection (ICRP) developed a comprehensive approach that includes the use of Reference Animals and Plants (RAPs) for the assessment of dose to non-human species (ICRP, 2007). A RAP is a hypothetical entity, with the assumed basic biological characteristics of a particular type of animal or plant, with the objective of creating a framework in which one can examine and explore these relationships in an internally consistent manner, and provide a basis for advice on decision-making(ICRP 108 2008).

ICRP's current approach for dosimetry calculations relies on the principle called "uniform isotropic model" defined by Loevinger and Berman as "an organism assumed to be in an infinite homogeneous medium, with activity uniformly distributed throughout its body, with the densities of the medium and the organism's body being the same" (ICRP 106 2007). Additionally, it uses simple geometrical shapes, e.g. ellipsoid, along with a general radiation transport code for the evaluation of absorbed fractions for photons and electrons of energy ranges between 0.01 to 5 MeV, then leading to the calculation of Dose Conversion Factors based on the results obtained. The introduction of a voxel phantom or digital models has been around and applied to human internal dosimetry for a few decades, as it was the Commission's primary task, demonstrating improved accuracy and efficiency (Zaidi & Xu 2007). This technique is derived from the reverse engineering principle, which is an examination, identification and representation of an object or software without changing the original one (Chikofsky & Cross 1990). Prior to the advances in technology, computer hardware and medical imaging, the use of this method was limited to entities with access to high-performance computing. Today, computational performance has exponentially improved and voxel-base model application has become a "state of the art" technique for anatomical modeling (Zankl et al. 2007).

Currently in the area of environmental protection, many have been focused on creating voxel phantoms because of their multiple additional features that can be studied, including life stages and densities (Caffrey et al. 2015), degree of conservatism (Ruedig et al. 2015), and morphologies (Stabin et al. 2006; Padilla et al. 2008; Kinase 2008; Hess 2014; Caffrey 2012). In addition to the development of screening approaches based on the ICRP RAPs concept (Beresford et al. 2008). These efforts exemplify the importance of the development of a unified environmental radiation protection approach that is conservative enough for its use as a robust guiding tool. Although new approaches seems to provide more details, a recent study showed that even after experiencing unfortunate events, e.g. Chernobyl, our knowledge about biological effects due to nuclear accidents is still "poor" (Møller & Mousseau 2011). Clearly, the more data is generated from the RAPs framework, the more research opportunities arise to explore new applications or issues in current techniques, as it is the case of for this research paper.

4.3. Materials and methods

4.3.1. *Apis Mellifera* Voxel phantom

A honeybee from the Honeybee Laboratory at Oregon State University was acquired and was imaged using a Quantum FX μCT scanner at Oregon Health and Science University's Small Animals Research and Imaging Core (SARIC) group capable of acquiring full 360^o 3D data using a 127μm pixel X-ray flat panel detector (Caliper Life Sciences 2010). Resulting in a total of 512 columns × 512 rows × 201 planes data matrix.

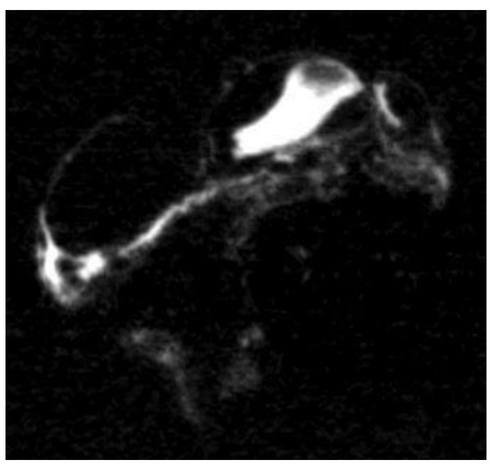

Figure 4-1 CT image from a top view angle

Each of the 201 planes was manually contoured to create the 3D model using the software tool 3D Doctor (Able Software Corp. 2012). It can be perceived that not all the organs were capture in the CT image and most of the biggest organs were reversed engineered, as shown in Figure **4-1**. The brain, fats, eyes and wing muscles were easily identified; however, the Gastro Intestinal Track (GIT) and heart were recreated using a general honeybee anatomy reference book (Snodgrass 1910), this includes the Crop, Rectum and Intestine in the model, with the final 3D model shown in Figure **4-2**. The contoured information was then exported in to a boundary (.bnd) file, to be used by a software tool known as Lattice Tool. Lattice Tool or Voxelizer is a tool created by Human Monitoring Laboratories, it uses the boundary file to create a temporary ".vxl" file that subsequently used to create a Monte Carlo lattice structure. Once converted in to a Monte Carlo readable file, the material's information was then included for simulations in the general transport code Monte Carlo N-Particle Extended (MCNPX) (X-5 Monte Carlo Team 2008a)

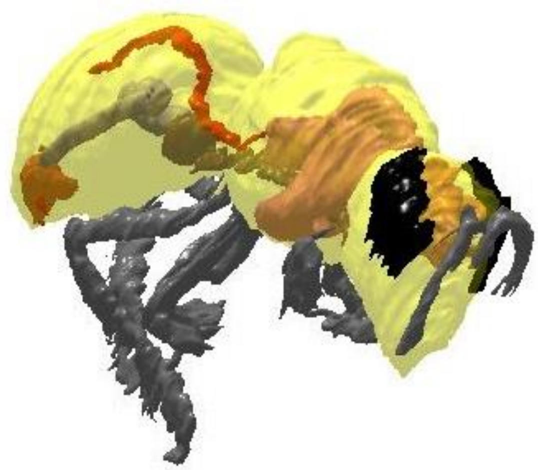

Figure 4-2 Honeybee voxel phantom 3D model

4.3.2. Sampling

In this study an elemental analysis was carefully carried out in seven honeybee organ structures: exoskeleton, muscles, legs, crop, rectum, venom sac and stinger intestine. This organs where selected due to the simplicity of their collection via dissection and their size within the specimen. To determine the sample size needed, a precision method was used using the standard error:

$$SE_{\bar{x}} = \frac{\sigma}{\sqrt{n}} \qquad \text{Equation 3}$$

The standard error measures the variability through repeated samples and it decrease as a function of the sample size; thus, using the measured data, the number of samples required can be estimated by plotting Equation for each of the different tissues.

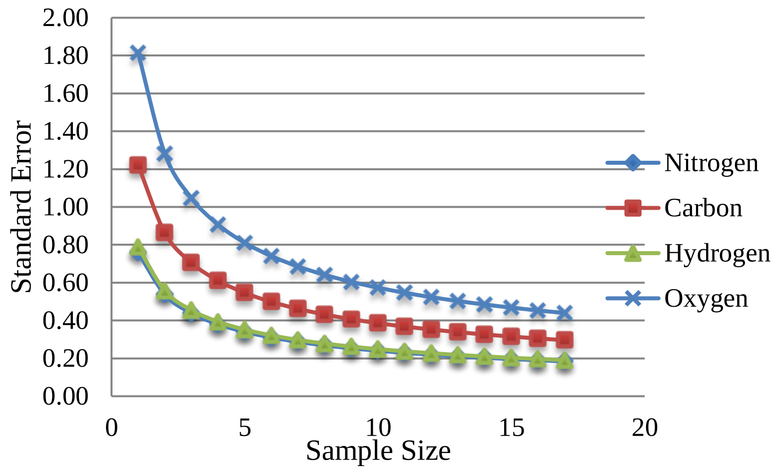

Figure 4-3 Standard error plot example using Venom Sac data

By using this method, it can be inferred from Figure **4-3** that 15 samples are sufficient for the Venom Sac organic composition determination and increasing the sample size would bring minimal improvement in the measurement. Some of the samples required less as it is the nature of the research to inherent the biological variability (see Supplementary Material). Nonetheless, seventeen samples were collected from each tissue as it was confirmed to be sufficient. Each of the 17 samples of each of the tissues was extracted for worker bee that varied in age, nutrition, and size, summing to a total of 119 samples.

4.3.3. Elemental analysis

To determine the organic tissue composition of some of the honeybee organs to be utilized in the input file of the general transport code MCNP. It is evident that the presence of some materials, especially high Z materials can have an impact in the energy deposited in a target. Though it has been shown that honeybees do have some high Z materials in their bodies and byproducts (Formicki et al. 2013), in this research only the organic elements is considered. Each of the 119 samples was oven-dried for 24 hours at 40 ^{o}C. Then, each of the samples were weighted using a micro balance and placed in thin boat of 9 mm X 5mm and processed in a COSTECH Elemental Combustion Systems (ECS) analyzer with zero-blank auto-sampler using the following analysis conditions: Combustion Temperature = 980 ^{o}C; Reduction Temperature = 650 ^{o}C; Gas Chamber Temperature = 65 ^{o}C. Inside the ECS instrument, the material inserted is combusted into organic matter, i.e. CO2, N-oxides and H_2O in the gas phase. Then the reduction oven reduces N-Oxides to N_2 gas, and the gas chromatographic column separates three different peaks: N_2, CO_2 and H_2O, Figure 4-4**,** that are detected by infrared detector (Goñi et al. 2014; Pella 1990).

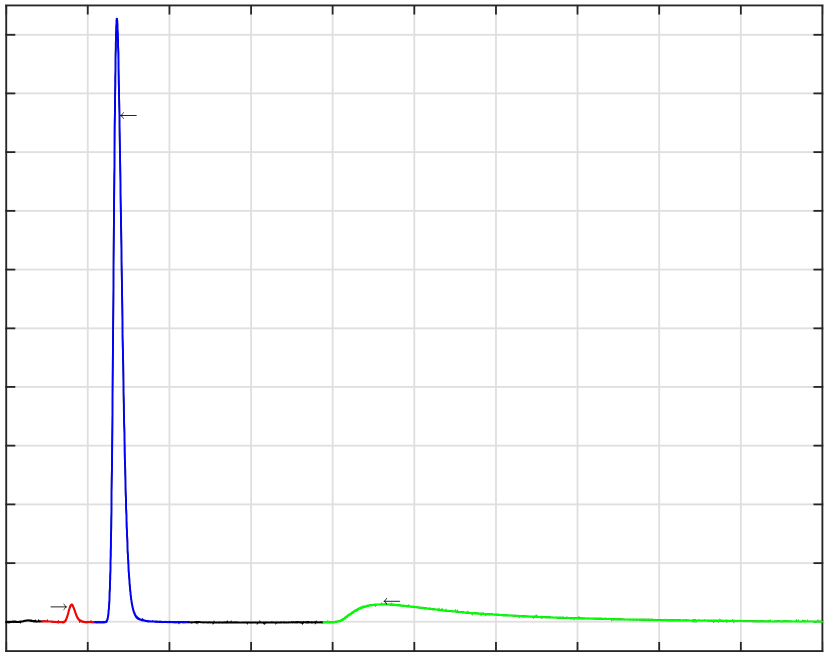

Figure 4-4 Chromatogram example

4.4. Dosimetry Calculations

4.4.1. Dosimetry calculation assumptions

Though voxel phantoms provide more detail than the current methodology and some of the assumptions previously used were discarded, e.g. ellipsoidal shape, due to the inclusion of complex geometries and tissues; the following assumptions form *Publication 108* (ICRP 108 2008) have also been carried out:

- DCFs are calculated for beta and gamma emitters.
- Alpha emissions are assumed to have an absorb fraction of one due to their short range.
- All electrons and photons are simulated as mono-energetic in the range of 0.01-4 MeV.

- Metabolism and various life stages are not considered.

- Density was assumed to be the same as water (1g/cc).

In addition, it is the nature of any model to have its own assumptions. In this case the following assumptions were made:

- Though the biokinetics of the selected radionuclide in honeybee is unknown, the brain, muscles, rectum, intestine and crop were the primarily sources locations.
- Some of the organs were reversed engineered, as the imaging modality was not able to capture.
- Masses were obtained based on the volume calculated by 3D Doctor, shown in Table 4-1.

Table 4-1: Volume and Masses of Different Organs

Object	Volume (m^3)	Mass (kg)
Venom Sac and Stinger	6.93E-02	6.93E-02
Rectum	7.07E-04	7.07E-04
Brain	2.44E-03	2.44E-03
Antenna	6.80E-04	6.80E-04
Eyes	1.51E-06	1.51E-06
Head	2.11E-05	2.11E-05
Intestine	1.61E-06	1.61E-06
Crop	1.90E-06	1.90E-06
Muscle	9.46E-06	9.46E-06
Heart	6.94E-07	6.94E-07
Thorax	4.95E-05	4.95E-05
Abdomen	6.72E-05	6.72E-05
Legs	9.19E-03	9.19E-03

4.4.2. Absorbed Fraction and Dose Conversion Factors

Absorbed Fractions (AF) are derived using one of the common methods currently in use in nuclear medicine, originally developed from an approach by Loevinger and Berman in1968. This method uses tabulated data on absorbed fractions of energy in a target tissue from a specific source region, mathematically referred as $AF(\bar{E}, S \rightarrow T)$ (ICRP 106 2007). Absorbed Fraction were calculated via MCNP using the 2003 U.S. Evaluated Nuclear Data File Six (ENDF-VI) and pulse height tally, *F8 (X-5 Monte Carlo Team 2008b), which are used to calculate the Dose Conversion Factors (DCF) for the voxel model. DCF are defined as absorbed dose rate per activity concentration within the organism or externally. Therefore, DCFs are expressed in the units of [μGy-kg-d^{-1}-Bq^{-1}] and were calculated using the following equation:

$$DCF = C \times \sum_i \bar{E} \times AF(\bar{E}, S \rightarrow T) \times BR \times Y \qquad \text{Equation 4}$$

Where:

- Summed over all i radiation
- $\bar{E}$ is the average energy emission
- $AF(\bar{E}, S \rightarrow T)$ is the absorbed fraction of energy $\bar{E}$ for a particular source-to-target
- BR is the Branching Ratio
- Y is the yield for decay of interest
- C is the activity concentration

In order to compare the results from each model, it is important to mention that the lack of a direct method of comparison of DCFs between the ellipsoidal model and voxel models, as the ellipsoidal model provides a whole-body dose versus an organ-organ dose, makes the comparison unviable. However, the use of ratios has previously been applied by (Gómez-Ros et al. 2008) using a mass-ratio method and by (Ruedig et al. 2015) in which it was illustrated that the dose rate of the voxel to the dose rate of the ellipsoidal is then equal to the ratio of their DCF. Similarly, the following ratio was used to compare the DCFs between both models and determine the elemental composition sensitivity. The ratio, R, was defined as:

$$R = \frac{Voxel_{DCF-ICRU-4component}}{Voxel_{DCF-measured-4component}} \quad \text{Equation 5}$$

Where, the unity represents no change, and any positive or negative represent an increase or decrease in the dose rate respectively.

4.5. Results and Discussion

4.5.1. CHNO distribution in tissues

The measurements of weight percentages contents of Carbon (%C), Nitrogen (%N), Hydrogen (%H) and Oxygen (%O) were carried out for all of the seven distinct tissues. Table 4-2 provides the average value of the organic elemental composition of the different tissues and its standard deviation. Due to the complexity of honeybee anatomy and dissection process, the organs in italic were assumed to be similar to the intestine tissue composition. These results show a significant difference between the standard ICRU four-component human tissue composition (Table 4-3) and each of the measured four-component tissue composition. ICRU four-component human tissue is currently used for dose calculation in the RAPs.

Table 4-2 Average organic elemental weight percentages in honeybee tissues

	Weight (%) Nitrogen	Weight (%) Carbon	Weight (%) Hydrogen	Weight (%) Oxygen
Antenna	11.5±0.2	48.2±0.2	6.4±0.2	33.9±0.4
Head	6.2±0.4	49.1±0.6	7.1±0.1	37.6±0.6
Thorax	6.2±0.4	49.1±0.6	7.1±0.1	37.6±0.6
Abdomen	6.2±0.4	49.1±0.6	7.1±0.1	37.6±0.6
Muscle	11.8±0.1	48.9±0.2	6.9±0.1	32.4±0.5
Legs	11.5±0.2	48.2±0.2	6.4±0.2	33.9±0.4
Brain	6.2±0.4	49.1±0.6	7.1±0.1	37.6±0.6
Eyes	6.2±0.4	49.1±0.6	7.1±0.1	37.6±0.6
Crop	0.2±0.1	36.7±0.3	6.9±0.1	56.1±0.4
Rectum	4.6±0.3	50.8±0.5	7.0±0.1	37.6±0.4
Venom sac	11.1±0.2	48.9±0.3	6.6±0.2	33.3±0.4
Heart	6.2±0.4	49.1±0.6	7.1±0.1	37.6±0.6
Intestine	6.2±0.4	49.1±0.6	7.1±0.1	37.6±0.6

Table 4-3 ICRU four-component human tissue composition

	%N	%C	%H	%O
ICRU four component soft tissue*	2.6	11.1	10.2	76.2

*(Griffiths 1989)

4.5.2. Absorbed Fractions

The AFs data calculated in this study has been classified based on the coefficient of variance (COV) given by MCNP: low [0%, 5%), medium (5%, 10%] and high (>10%). Results with high COV were assigned an AF of zero, which results in missing data points in some of the tabulated data. Figure **4-5** and Figure **4-6** show an example of the tabulated data of a photon and electron source located in the Crop. The energy deposition in the other structures is the highest for very low energy gamma and for electrons of about 600 keV, resulting in the highest dose in the abdomen area. Appendices A, A, C, and D contain detail of AF as a function of energy, source, target and radiation source for both models.

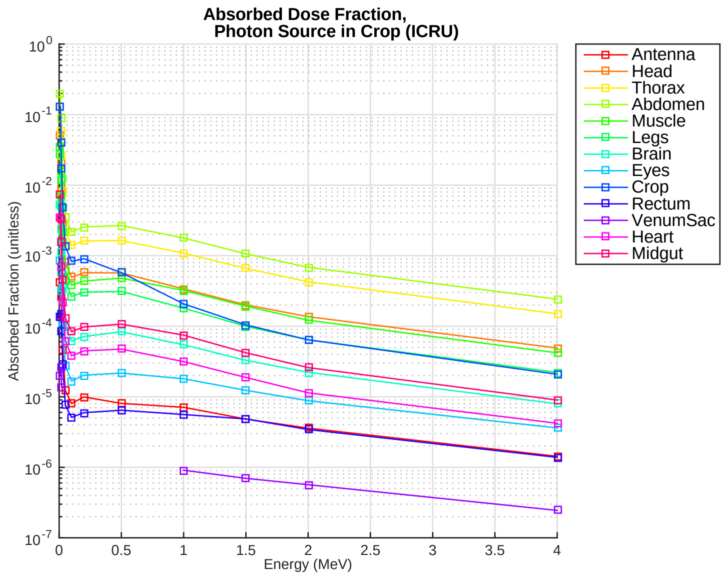

Figure 4-5 Illustration of absorbed fractions in multiple targets using ICRU four-component human tissue for a photon source in the Crop.

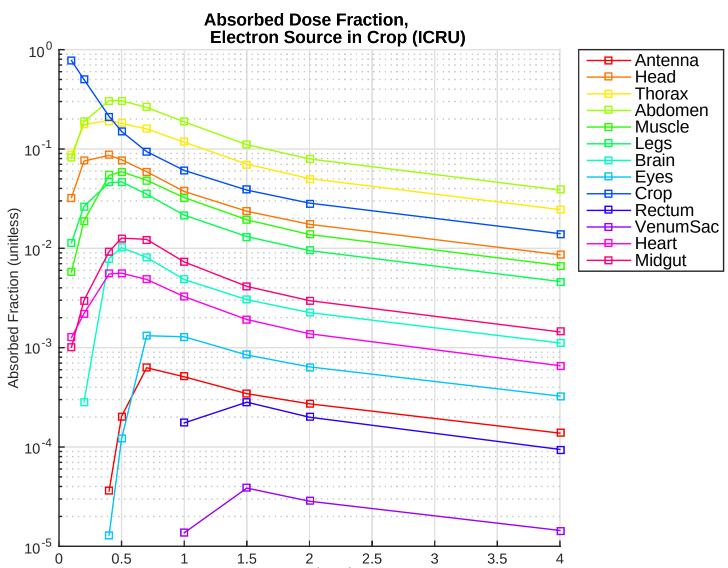

Figure 4-6: Illustration of absorbed fractions in multiple targets using ICRU four-component human tissue for an electron source in the Crop.

4.5.3. Dose conversion Factors

Seven different radionuclides were chosen for analysis. These represent a range of low, medium and high-energy particle emitters. ^{60}Co is a high-energy beta-emitter; ^{137}Cs and ^{90}Y are considered to be medium energy emitters; and, ^{131}I, ^{90}Sr, ^{36}Cl are low energy emitters. Most of these are primarily gamma and beta emitters. Alpha particles are assumed to be fully absorbed within the source, i.e. AF =1, because they have a very small range; however, ^{226}Ra was included for its gamma emission as the elemental composition can have an impact, though its yield is small. Equation was used to calculate their respective DCF for each of the two models and presented in Table 4-4 and Table 4-5. The remaining DCF calculation can be found in the supplementary material of this manuscript.

Table 4-4 Cesium-137 DCFs ICRU-4 Element Human Tissue [μGy-kg-d^{-1}-Bq^{-1}]

Source / Target	Brain	Crop	Intestine	Muscle	Rectum
Antenna	7.00E-06	7.07E-08	3.69E-09	8.39E-08	0.00E+00
Head	8.15E-04	1.71E-04	3.89E-07	1.29E-05	2.62E-07
Thorax	2.13E-05	4.06E-04	2.31E-06	6.18E-04	1.06E-06
Abdomen	1.51E-06	4.61E-04	1.08E-03	4.02E-06	9.25E-04
Muscle	7.53E-06	5.31E-05	5.10E-07	1.85E-03	2.36E-07
Legs	7.25E-07	6.52E-05	1.78E-06	8.35E-06	4.34E-06
Brain	1.60E-03	3.33E-06	6.64E-08	2.00E-06	3.71E-08
Eyes	2.55E-05	1.63E-07	2.96E-08	3.32E-07	1.99E-08
Crop	2.84E-06	1.37E-03	8.52E-06	1.20E-05	1.41E-07
Rectum	0.00E+00	4.81E-08	5.39E-06	1.90E-08	1.28E-03
Venom sac	0.00E+00	2.28E-09	6.19E-08	0.00E+00	7.53E-05
Heart	3.23E-05	6.28E-06	4.62E-07	2.36E-05	6.22E-08
Intestine	5.09E-08	8.88E-06	1.48E-03	9.78E-08	1.40E-05

Table 4-5 Cesium-137 DCFs Honeybee Tissue [μGy-kg-d^{-1}-Bq^{-1}]

Target \ Source	Brain	Crop	Intestine	Muscle	Rectum
Antenna	7.46E-06	7.46E-08	3.04E-09	8.59E-08	0.00E+00
Head	8.27E-04	1.74E-04	3.69E-07	1.33E-05	2.57E-07
Thorax	2.22E-05	4.12E-04	2.25E-06	6.33E-04	1.03E-06
Abdomen	1.47E-06	4.71E-04	1.10E-03	3.91E-06	9.34E-04
Muscle	7.76E-06	5.46E-05	4.92E-07	1.83E-03	2.24E-07
Legs	7.20E-07	6.61E-05	1.82E-06	8.60E-06	4.53E-06
Brain	1.58E-03	3.54E-06	6.31E-08	2.10E-06	3.63E-08
Eyes	2.63E-05	1.58E-07	2.76E-08	3.29E-07	0.00E+00
Crop	3.00E-06	1.34E-03	8.76E-06	1.25E-05	1.36E-07
Rectum	0.00E+00	4.71E-08	5.48E-06	1.91E-08	1.26E-03
Venom sac	0.00E+00	2.08E-09	6.37E-08	0.00E+00	7.58E-05
Heart	3.26E-05	6.41E-06	4.91E-07	2.41E-05	5.60E-08
Intestine	4.88E-08	9.19E-06	1.46E-03	9.91E-08	1.42E-05

Although the effects of the statistical changes given by the general radiation transport code changed in both models, most of the values remained in the same COV category. For instance, it can be observed in Table 4-4 and Table 4-5 that in the Rectum → Eyes configuration the AF on measured honeybee tissue had an COV greater than 10%, which results in a DCF of zero.

4.5.4. Elemental Impact Analysis

The differences between the voxel model that uses ICRU's four-component human tissue and the one using the measured four-component honeybee tissues is basically undistinguishable in the graphical representations. Consequently, to compare the results between both models, the AFs were used to calculate each radionuclide DCF using Equation then, Equation was used to assess the impact of the tissue composition.

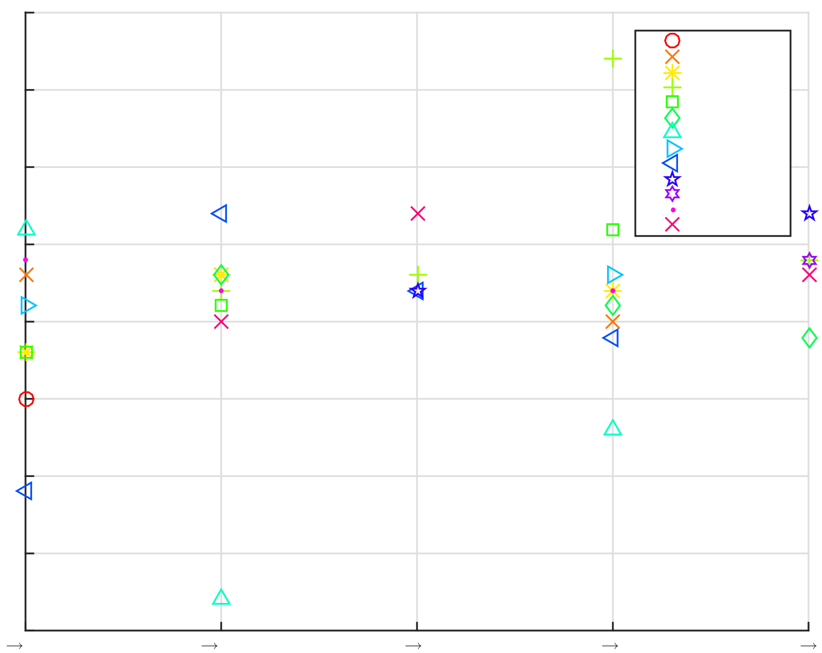

Figure **4-7** and **Figure 4-8** show that the variation could be significant depending on the location of the source. In addition, it can also be observed that the variations also depend on the radionuclide and its characteristics. For instance, it can be observed in Figure **4-7** that for a ^{90}Sr source in the crop there is an elemental effect of about -22% in absorbed dose and Figure **4-8** there is a +21% in a source located in the midgut. The significance of the impact differs for all six radionuclides; however, the elemental composition has an impact in the dose calculation in the honeybee model of roughly ±10%. The results presented somewhat agree with other studies where relatively large species are used (Kinase 2008; Padilla et al. 2008; Ruedig et al. 2015; Caffrey et al. 2015; Caffrey 2012), very little impact was observed as the level of detail increased; nonetheless, in a smaller scale the importance of detail could have a slightly more significant impact depending on the radionuclide of interest, showing that the additional effort is worthwhile.

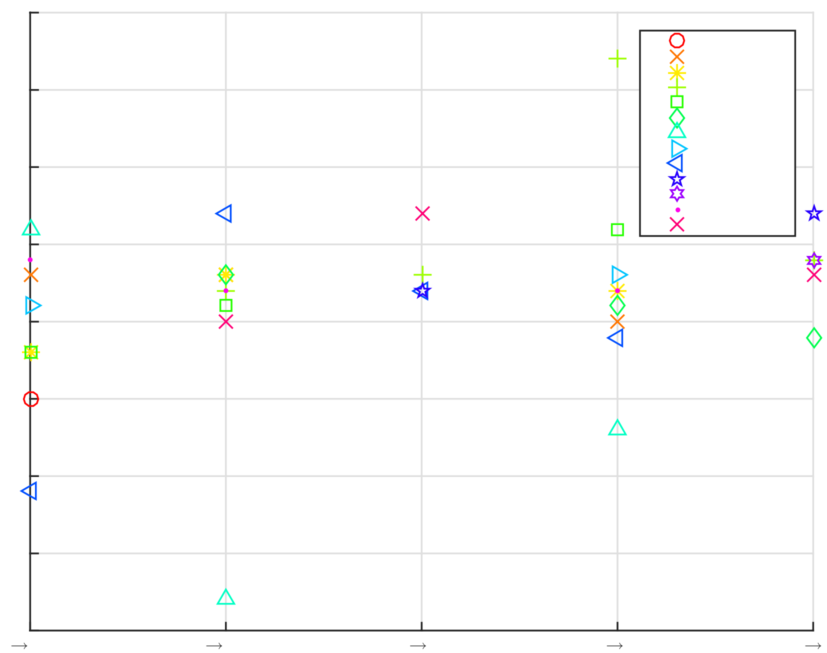

Figure 4-7 Illustration of the elemental impact in all the Source→Target ratios between the both voxel models using a Strontium-90 source, where the value of unity (1.0) represents no change between them.

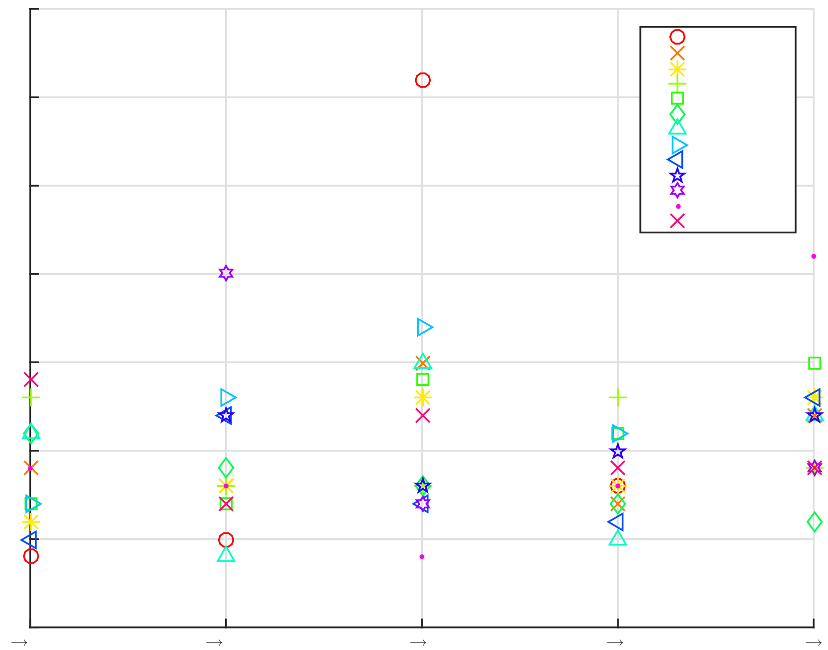

Figure 4-8 Illustration of the elemental impact in all the Source→Target ratios between the both voxel models using a Cesium-137 source, where the unity represents no change between them.

The use of voxel phantoms as a guide for environmental impact analysis does address the internal dosimetry variable of the RAPs in a more realistic way than any other model, where it can provide organ-level doses as opposed to whole-body level only. However, the exploration of the voxel phantom approach still needs to add the external dosimetry variable that can add more complexity to the problem. Additionally, voxel phantoms have had a reputation of requiring extensive amounts of work and computational knowledge to perform the complete analysis, which nowadays can be discarded given the rapid improvement in computational power and the multiple software packages available for data processing. More importantly, the validity of these methods could be questionable as there is a need to prove their accuracy with experimental data and compare whether the homogenous model or the voxel model could provide better approximations of the true dose. This study consider only the AF parameter in Equation , however, further consideration should be attributed to the activity concentration (C) parameter in, which can be impacted by the specific organ where the radionuclide goes to and the biological half-live. Additionally, further studies are required regarding dose to biological effect in this organism as noted by ICRP 108 “there do not appear to be precise data relating mortality of large insects at any stage in their life cycle”, which is challenges the identification of the radiosensitivy of each of the organs. Ultimately, the need of experimental set ups to gather more data and compare the accuracy of the voxelized models.

4.6. Conclusion

The results presented here prove that it is worthwhile considering the voxel phantom models in small organisms or organisms that cannot be modeled as completely spherical e.g. honeybee. The consideration of the elemental composition should not be discarded or considered as a low impact effect in environmental dosimetry since the results in absorbed dose depends on the radionuclides of interest. The use of voxel phantoms can provide DCF that are rather complicated to approximate using the homogenous model. However, these studies do not have an experimental set to should be considered to validate all voxel phantoms and ICRPs models. Overall, the results in this research agree with published literature and the application of voxel phantoms along with tissues properties represents the state of the art method for environmental radiation protection.

4.7. Acknowledgments

The authors extend their gratitude to Dr. Miguel Goñi and Dr. Ramesh Sagilli for facilitating the access to their laboratory equipment, honeybee samples and guidance.

5. Conclusion and Future Work

In this study, the model of the reference bee is presented using the voxel model approach along with an organic elemental analysis composition of different honeybee tissues. The primary purposes of this study were: 1) to construct a voxel phantom model from a micro CT image for its use with the general transport code MCNP, 2) the calculation of absorbed dose fraction and dose conversion factors, and 3) to study the effect of organic elemental composition on radiation absorption. Because honeybees are relatively small insects the absorbed fractions are shown to be small values given that the range of electrons and photons rapidly exceeds the size of the bee as the energy increases, and the particles will escape the medium. In the case of photons, energy deposition from low energy photons is mostly attributed to a photoelectric absorption mechanism, and significantly decreased as the energy of incident photons increase, which implies that there are not many interactions with the material and the photons are simply crossing through it. As for the case of electrons, whose penetration capability is shorter due to is small path length, mass and charge; there is an increase in interaction with the target material as long as the particle's energy is high enough to escape the source organ and penetrate the target. During the calculation of dose conversion factor it was observed that the biggest organs within the small specimen were the most affected by the interaction of ionizing radiation as there is more volume. The elemental composition effect on absorbed fraction and dose conversion factors was shown to be between ±10% for most cases, but there are some values that can be up to 25% from the reference point. Lastly, recent studies has been carried out by varying the age, size, and densities, as well as, evaluating the benefits of such approach (Kinase 2008; Padilla et al. 2008; Ruedig et al. 2015; Caffrey et al. 2015; Caffrey 2012), which also agree with the results presented here. Finally, as study consider only the AF parameter, however, the activity concentration (C) parameter must be consider as further research, which can be impacted by the specific organ where the radionuclide goes to and the biological half-life. Additionally, further studies are required regarding dose to biological effect in this organism as noted by ICRP 108 "*there do not appear to be precise data relating mortality of large insects at any stage in their life cycle*". Ultimately, the need of experimental set ups to gather more data is required to confirm the validity voxelized models.

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7. Appendices

A. Absorbed Fractions Honeybee using ICRU Four-Component Human Tissue: Photons

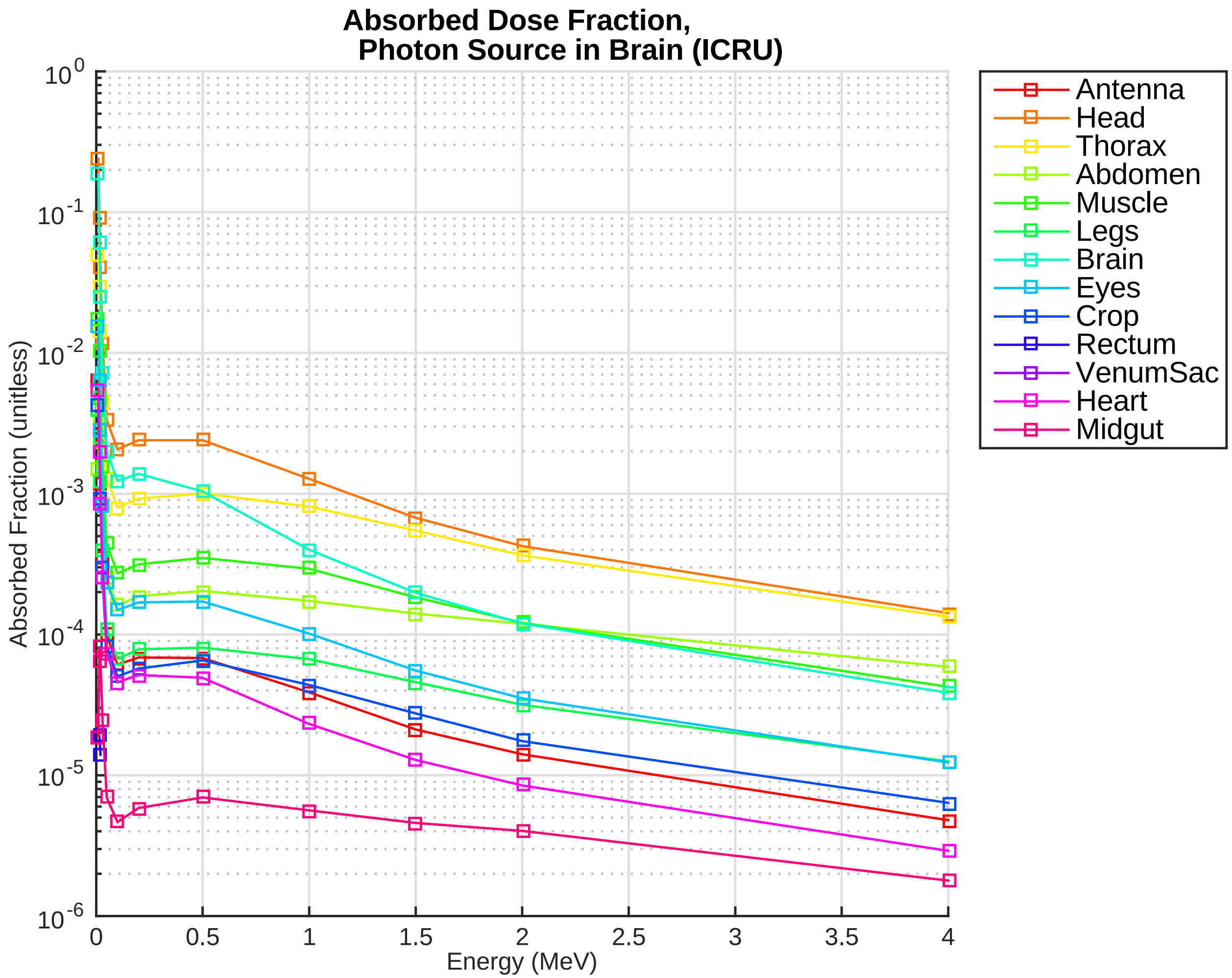
In this appendix the absorbed fraction of the voxel model are given using the standard four-component human tissue composition. These values are generated by MCNP with the option of PAR 2 (photons) of different energies and are further processed by the MATLAB code. A graphs is also presented, representing the absorbed fraction as a function of energy with a source in a specific location

Absorbed Fractions of Photon Energy

Source in Brain

Energy (MeV)

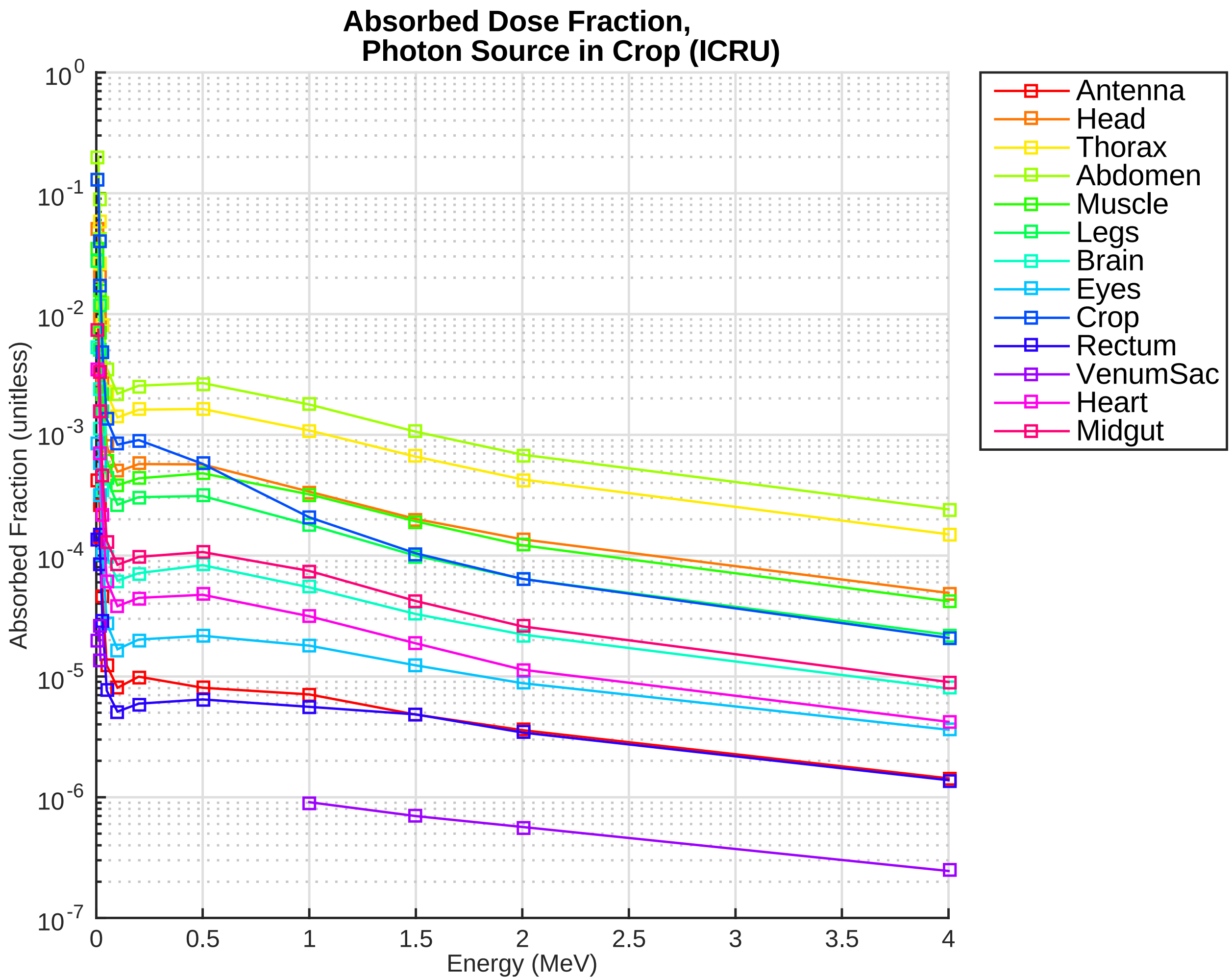
	Target	0.010	0.015	0.02	0.030	0.050	0.100	0.200	0.500	1.000	1.500	2.000	4.000
1	Antenna	6.51E-03	2.66E-03	1.19E-03	3.45E-04	9.88E-05	6.12E-05	6.86E-05	6.80E-05	3.88E-05	2.11E-05	1.41E-05	4.80E-06
2	Head	2.39E-01	9.15E-02	3.99E-02	1.19E-02	3.34E-03	2.07E-03	2.40E-03	2.40E-03	1.27E-03	6.75E-04	4.24E-04	1.42E-04
3	Thorax	4.95E-02	2.93E-02	1.43E-02	4.50E-03	1.28E-03	7.99E-04	9.24E-04	1.00E-03	8.11E-04	5.48E-04	3.65E-04	1.33E-04
4	Abdomen	1.52E-03	3.38E-03	2.30E-03	8.53E-04	2.55E-04	1.61E-04	1.87E-04	2.04E-04	1.73E-04	1.41E-04	1.19E-04	5.88E-05
5	Muscle	1.77E-02	1.02E-02	4.91E-03	1.54E-03	4.38E-04	2.72E-04	3.15E-04	3.50E-04	2.93E-04	1.84E-04	1.21E-04	4.25E-05
6	Legs	3.96E-03	2.48E-03	1.23E-03	4.03E-04	1.11E-04	6.68E-05	7.84E-05	8.06E-05	6.68E-05	4.58E-05	3.17E-05	1.25E-05
7	Brain	1.85E-01	5.96E-02	2.49E-02	7.22E-03	2.01E-03	1.23E-03	1.39E-03	1.04E-03	4.00E-04	1.98E-04	1.20E-04	3.85E-05
8	Eyes	1.53E-02	6.29E-03	2.81E-03	8.34E-04	2.33E-04	1.49E-04	1.69E-04	1.72E-04	1.02E-04	5.55E-05	3.53E-05	1.23E-05
9	Crop	4.25E-03	1.99E-03	9.24E-04	2.97E-04	8.26E-05	5.05E-05	5.74E-05	6.55E-05	4.38E-05	2.75E-05	1.75E-05	6.37E-06
10	Rectum	--	1.90E-05	1.40E-05	--	--	--	--	--	--	--	--	--
11	Venom sac	--	--	--	--	--	--	--	--	--	--	--	--
12	Heart	5.45E-03	1.97E-03	8.54E-04	2.56E-04	7.27E-05	4.58E-05	5.15E-05	4.92E-05	2.32E-05	1.28E-05	8.46E-06	2.90E-06
13	Intestine	1.88E-05	8.23E-05	6.52E-05	2.46E-05	6.91E-06	4.66E-06	5.86E-06	6.97E-06	5.63E-06	4.59E-06	4.03E-06	1.79E-06



Absorbed Dose Fraction,
Photon Source in Brain (ICRU)
Absorbed Fraction (unitless)
Energy (MeV)
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
0
0.5
1
1.5
2
2.5
3
3.5
4
Antenna
Head
Thorax
Abdomen
Muscle
Legs
Brain
Eyes
Crop
Rectum
VenumSac
Heart
Midgut

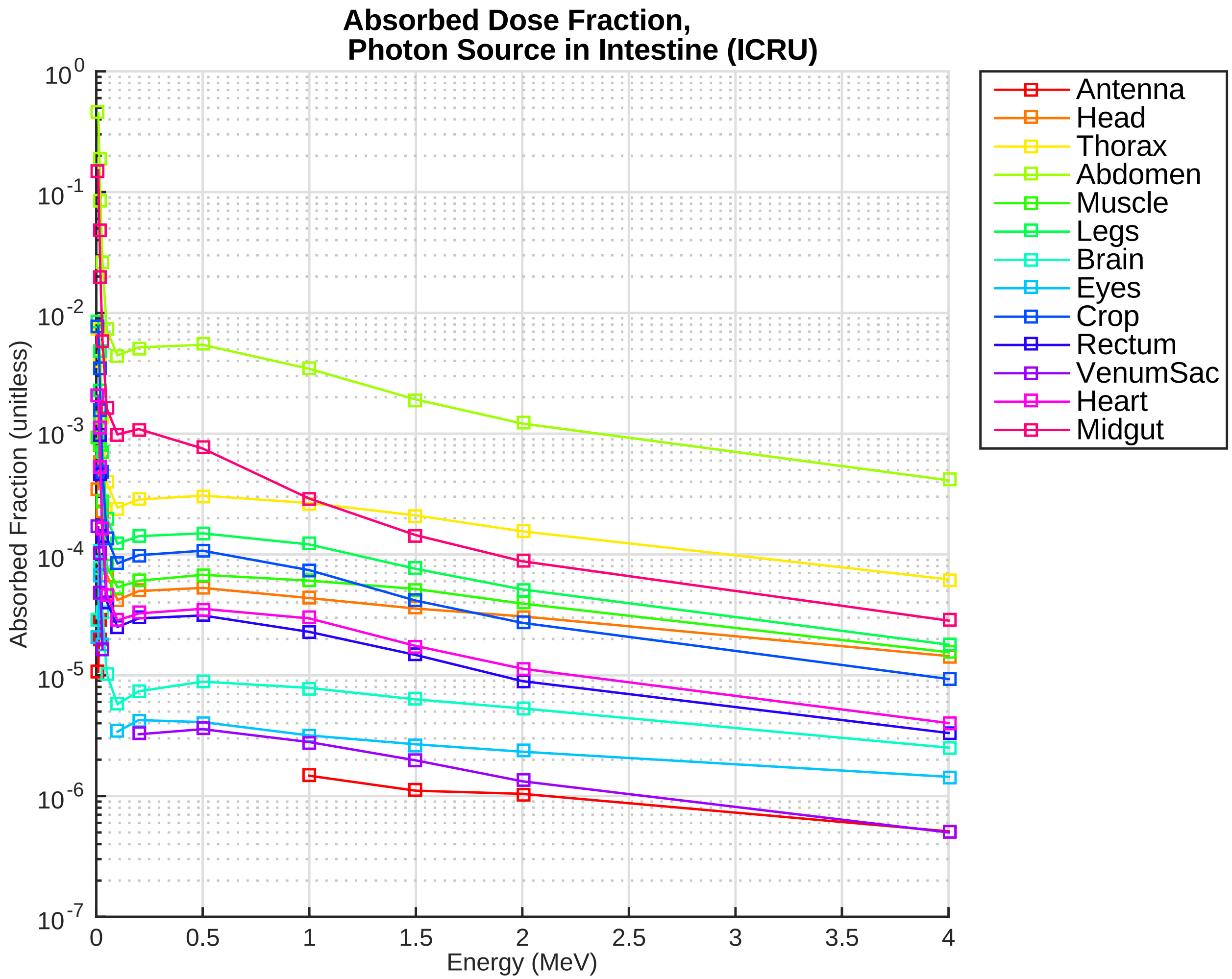
Absorbed Fractions of Photon Energy
Source in Crop
Energy (MeV)

	Target	0.010	0.015	0.02	0.030	0.050	0.100	0.200	0.500	1.000	1.500	2.000	4.000
1	Antenna	4.16E-04	2.67E-04	1.44E-04	4.52E-05	1.23E-05	8.05E-06	9.93E-06	8.05E-06	7.08E-06	4.84E-06	3.59E-06	1.43E-06
2	Head	4.99E-02	2.06E-02	9.28E-03	2.83E-03	8.02E-04	4.94E-04	5.72E-04	5.70E-04	3.39E-04	2.01E-04	1.36E-04	4.91E-05
3	Thorax	1.31E-01	5.75E-02	2.62E-02	7.97E-03	2.24E-03	1.39E-03	1.62E-03	1.64E-03	1.09E-03	6.60E-04	4.28E-04	1.50E-04
4	Abdomen	2.02E-01	8.98E-02	4.11E-02	1.26E-02	3.56E-03	2.19E-03	2.55E-03	2.68E-03	1.78E-03	1.06E-03	6.85E-04	2.41E-04
5	Muscle	3.44E-02	1.55E-02	7.11E-03	2.21E-03	6.12E-04	3.82E-04	4.37E-04	4.80E-04	3.21E-04	1.92E-04	1.22E-04	4.20E-05
6	Legs	2.81E-02	1.16E-02	5.10E-03	1.53E-03	4.34E-04	2.63E-04	3.05E-04	3.11E-04	1.80E-04	9.97E-05	6.41E-05	2.21E-05
7	Brain	5.19E-03	2.44E-03	1.14E-03	3.53E-04	9.94E-05	6.19E-05	7.16E-05	8.33E-05	5.47E-05	3.29E-05	2.22E-05	7.93E-06
8	Eyes	8.57E-04	5.94E-04	3.15E-04	1.04E-04	2.75E-05	1.67E-05	2.02E-05	2.17E-05	1.80E-05	1.23E-05	8.79E-06	3.62E-06
9	Crop	1.30E-01	4.06E-02	1.68E-02	4.91E-03	1.35E-03	8.29E-04	9.06E-04	5.74E-04	7.52E-06	1.04E-04	6.42E-05	2.09E-05
10	Rectum	1.35E-04	1.51E-04	8.47E-05	2.86E-05	7.62E-06	5.10E-06	5.94E-06	6.44E-06	5.61E-06	4.85E-06	3.43E-06	1.38E-06
11	Venom sac	1.99E-05	2.58E-05	1.37E-05	--	--	--	--	--	9.09E-07	6.98E-07	5.66E-07	2.45E-07
12	Heart	3.51E-03	1.54E-03	7.19E-04	2.21E-04	6.20E-05	3.81E-05	4.47E-05	4.73E-05	3.15E-05	1.87E-05	1.14E-05	4.20E-06
13	Intestine	7.41E-03	3.39E-03	1.55E-03	4.67E-04	1.32E-04	8.39E-05	9.76E-05	1.07E-04	7.47E-05	4.20E-05	2.60E-05	8.98E-06


Absorbed Dose Fraction,
Photon Source in Crop (ICRU)
Absorbed Fraction (unitless)
Energy (MeV)
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
0
0.5
1
1.5
2
2.5
3
3.5
4
Antenna
Head
Thorax
Abdomen
Muscle
Legs
Brain
Eyes
Crop
Rectum
VenumSac
Heart
Midgut

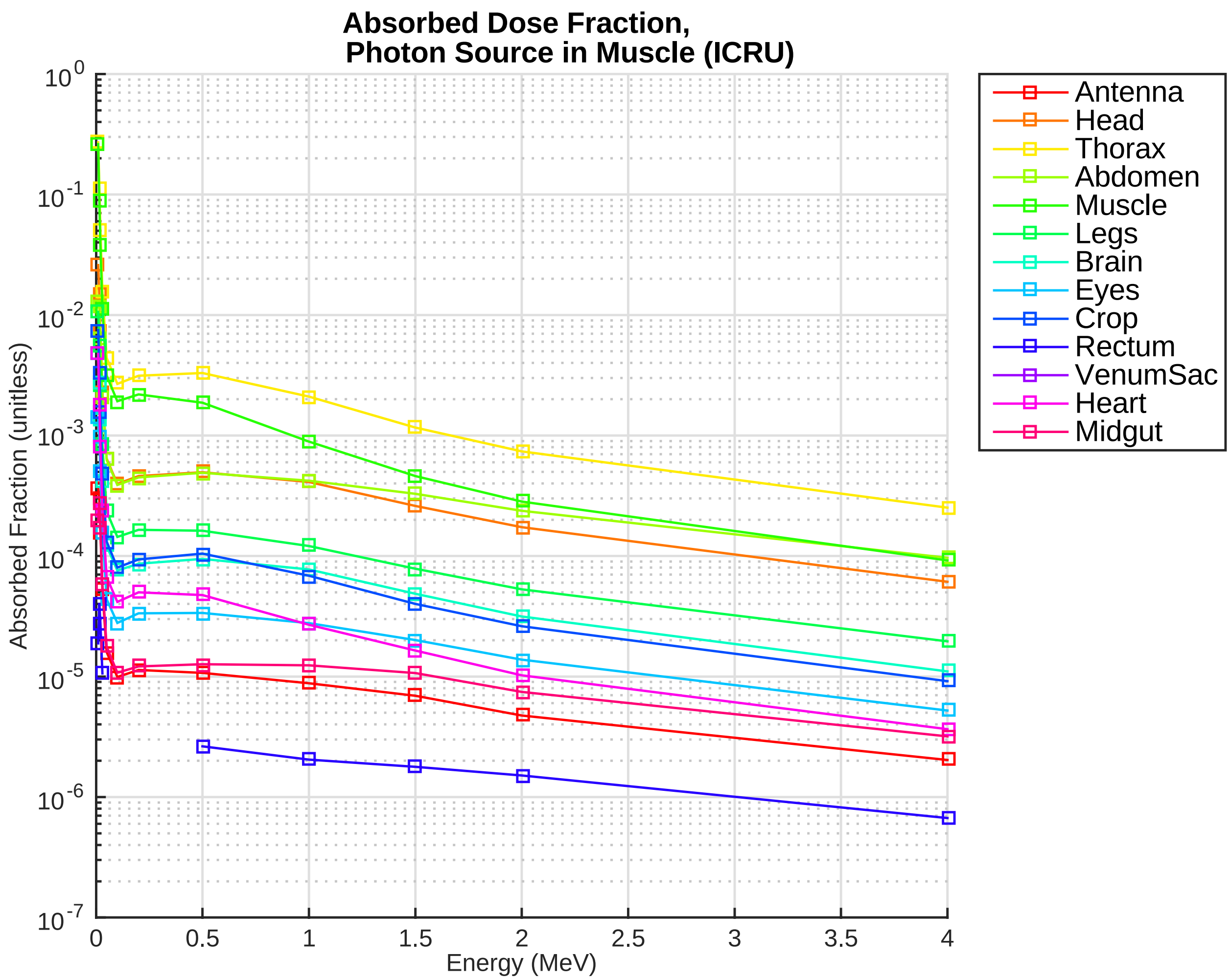
Absorbed Fractions of Photon Energy
Source in Intestine
Energy (MeV)

	Target	0.010	0.015	0.02	0.030	0.050	0.100	0.200	0.500	1.000	1.500	2.000	4.000
1	Antenna	1.06E-05	2.85E-05	2.01E-05	--	--	--	--	--	1.47E-06	1.11E-06	1.04E-06	5.10E-07
2	Head	3.47E-04	8.28E-04	5.74E-04	2.26E-04	6.84E-05	4.19E-05	4.98E-05	5.29E-05	4.36E-05	3.57E-05	3.07E-05	1.44E-05
3	Thorax	7.30E-03	7.30E-03	4.05E-03	1.34E-03	3.91E-04	2.44E-04	2.85E-04	3.07E-04	2.67E-04	2.10E-04	1.56E-04	6.22E-05
4	Abdomen	4.53E-01	1.91E-01	8.52E-02	2.57E-02	7.23E-03	4.45E-03	5.17E-03	5.44E-03	3.44E-03	1.92E-03	1.21E-03	4.11E-04
5	Muscle	9.47E-04	1.34E-03	8.12E-04	2.76E-04	8.06E-05	5.34E-05	6.05E-05	6.78E-05	6.07E-05	5.18E-05	3.92E-05	1.55E-05
6	Legs	8.40E-03	4.75E-03	2.29E-03	7.14E-04	1.99E-04	1.23E-04	1.42E-04	1.50E-04	1.21E-04	7.61E-05	5.13E-05	1.80E-05
7	Brain	2.90E-05	1.05E-04	7.76E-05	3.28E-05	1.02E-05	5.75E-06	7.36E-06	8.85E-06	7.84E-06	6.31E-06	5.31E-06	2.52E-06
8	Eyes	2.10E-05	6.72E-05	4.84E-05	1.81E-05	--	3.41E-06	4.25E-06	4.09E-06	3.18E-06	2.68E-06	2.33E-06	1.44E-06
9	Crop	7.66E-03	3.47E-03	1.60E-03	4.93E-04	1.38E-04	8.43E-05	9.86E-05	1.07E-04	7.41E-05	4.14E-05	2.71E-05	9.31E-06
10	Rectum	2.06E-03	9.80E-04	4.62E-04	1.43E-04	4.07E-05	2.51E-05	2.95E-05	3.13E-05	2.29E-05	1.47E-05	8.95E-06	3.32E-06
11	Venom sac	1.68E-04	1.01E-04	4.75E-05	1.64E-05	--	--	3.24E-06	3.59E-06	2.80E-06	1.98E-06	1.33E-06	5.00E-07
12	Heart	2.05E-03	1.11E-03	5.20E-04	1.61E-04	4.69E-05	2.84E-05	3.25E-05	3.55E-05	2.95E-05	1.75E-05	1.13E-05	4.02E-06
13	Intestine	1.52E-01	4.82E-02	2.01E-02	5.85E-03	1.61E-03	9.87E-04	1.09E-03	7.54E-04	2.90E-04	1.44E-04	8.77E-05	2.83E-05


Absorbed Dose Fraction,
Photon Source in Intestine (ICRU)
Absorbed Fraction (unitless)
Energy (MeV)
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
10^-7
0
0.5
1
1.5
2
2.5
3
3.5
4
Antenna
Head
Thorax
Abdomen
Muscle
Legs
Brain
Eyes
Crop
Rectum
VenumSac
Heart
Midgut

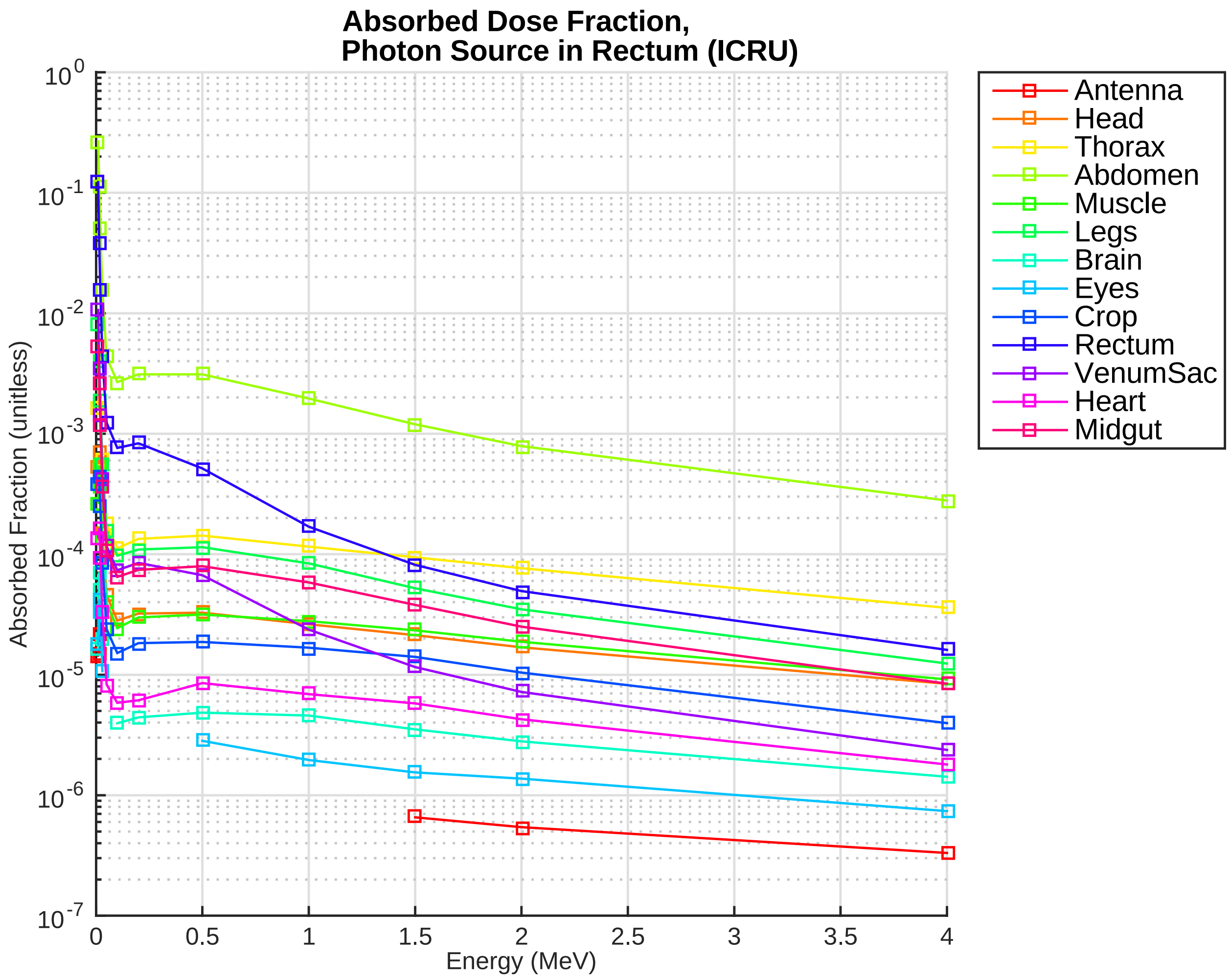
Absorbed Fractions of Photon Energy
Source in Muscle
Energy (MeV)

	Target	0.010	0.015	0.02	0.030	0.050	0.100	0.200	0.500	1.000	1.500	2.000	4.000
1	Antenna	3.68E-04	3.06E-04	1.59E-04	5.22E-05	1.60E-05	9.92E-06	1.13E-05	1.07E-05	8.79E-06	6.91E-06	4.75E-06	2.03E-06
2	Head	2.59E-02	1.50E-02	7.20E-03	2.26E-03	6.40E-04	3.97E-04	4.61E-04	4.96E-04	4.11E-04	2.60E-04	1.73E-04	6.12E-05
3	Thorax	2.71E-01	1.15E-01	5.14E-02	1.55E-02	4.39E-03	2.68E-03	3.14E-03	3.30E-03	2.10E-03	1.16E-03	7.39E-04	2.52E-04
4	Abdomen	1.27E-02	1.16E-02	6.38E-03	2.11E-03	6.28E-04	3.89E-04	4.49E-04	4.90E-04	4.22E-04	3.28E-04	2.37E-04	9.66E-05
5	Muscle	2.62E-01	9.01E-02	3.82E-02	1.12E-02	3.13E-03	1.93E-03	2.19E-03	1.87E-03	8.89E-04	4.60E-04	2.83E-04	9.21E-05
6	Legs	1.06E-02	5.58E-03	2.67E-03	8.30E-04	2.35E-04	1.44E-04	1.65E-04	1.62E-04	1.21E-04	7.83E-05	5.29E-05	1.96E-05
7	Brain	4.75E-03	2.72E-03	1.34E-03	4.25E-04	1.21E-04	7.57E-05	8.63E-05	9.47E-05	7.75E-05	4.86E-05	3.14E-05	1.10E-05
8	Eyes	1.41E-03	9.87E-04	5.02E-04	1.59E-04	4.37E-05	2.79E-05	3.35E-05	3.37E-05	2.78E-05	2.01E-05	1.38E-05	5.23E-06
9	Crop	7.50E-03	3.35E-03	1.55E-03	4.74E-04	1.32E-04	8.01E-05	9.37E-05	1.05E-04	6.86E-05	4.00E-05	2.61E-05	9.14E-06
10	Rectum	1.88E-05	4.08E-05	2.76E-05	1.06E-05	--	--	--	2.63E-06	2.05E-06	1.78E-06	1.51E-06	6.69E-07
11	Venom sac	--	--	--	--	--	--	--	--	--	--	--	--
12	Heart	4.74E-03	1.83E-03	8.06E-04	2.35E-04	6.68E-05	4.17E-05	4.99E-05	4.74E-05	2.69E-05	1.64E-05	1.02E-05	3.65E-06
13	Intestine	1.97E-04	2.79E-04	1.69E-04	5.80E-05	1.77E-05	1.07E-05	1.21E-05	1.26E-05	1.24E-05	1.07E-05	7.44E-06	3.19E-06


Absorbed Dose Fraction,
Photon Source in Muscle (ICRU)
Absorbed Fraction (unitless)
Energy (MeV)
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
10^-7
0
0.5
1
1.5
2
2.5
3
3.5
4
Antenna
Head
Thorax
Abdomen
Muscle
Legs
Brain
Eyes
Crop
Rectum
VenumSac
Heart
Midgut

Absorbed Fractions of Photon Energy
Source in Rectum
Energy (MeV)

	Target	0.010	0.015	0.02	0.030	0.050	0.100	0.200	0.500	1.000	1.500	2.000	4.000
1	Antenna	1.44E-05	2.21E-05	1.49E-05	--	--	--	--	--	--	6.56E-07	5.43E-07	3.30E-07
2	Head	5.33E-04	6.87E-04	4.18E-04	1.49E-04	4.59E-05	2.81E-05	3.21E-05	3.28E-05	2.62E-05	2.13E-05	1.69E-05	8.38E-06
3	Thorax	1.61E-03	2.62E-03	1.67E-03	6.05E-04	1.77E-04	1.12E-04	1.34E-04	1.43E-04	1.16E-04	9.43E-05	7.67E-05	3.60E-05
4	Abdomen	2.66E-01	1.12E-01	5.06E-02	1.53E-02	4.33E-03	2.68E-03	3.11E-03	3.11E-03	1.96E-03	1.19E-03	7.88E-04	2.80E-04
5	Muscle	2.66E-04	5.47E-04	3.66E-04	1.33E-04	3.91E-05	2.44E-05	2.99E-05	3.16E-05	2.78E-05	2.34E-05	1.87E-05	9.13E-06
6	Legs	8.10E-03	3.96E-03	1.84E-03	5.56E-04	1.54E-04	9.72E-05	1.09E-04	1.15E-04	8.38E-05	5.22E-05	3.49E-05	1.24E-05
7	Brain	1.68E-05	7.09E-05	5.06E-05	1.96E-05	--	3.95E-06	4.43E-06	4.84E-06	4.59E-06	3.52E-06	2.80E-06	1.42E-06
8	Eyes	1.79E-05	4.23E-05	3.26E-05	1.07E-05	--	--	--	2.83E-06	1.96E-06	1.55E-06	1.37E-06	7.38E-07
9	Crop	3.82E-04	4.38E-04	2.47E-04	8.36E-05	2.39E-05	1.51E-05	1.83E-05	1.87E-05	1.67E-05	1.40E-05	1.04E-05	3.98E-06
10	Rectum	1.22E-01	3.76E-02	1.55E-02	4.47E-03	1.24E-03	7.62E-04	8.31E-04	5.15E-04	1.69E-04	8.15E-05	4.94E-05	1.61E-05
11	Venom sac	1.06E-02	3.49E-03	1.45E-03	4.29E-04	1.16E-04	7.37E-05	8.49E-05	6.69E-05	2.37E-05	1.16E-05	7.20E-06	2.38E-06
12	Heart	1.39E-04	1.64E-04	9.33E-05	3.34E-05	8.27E-06	5.83E-06	6.14E-06	8.51E-06	6.90E-06	3.80E-05	4.27E-06	1.80E-06
13	Intestine	5.39E-03	2.58E-03	1.20E-03	3.67E-04	1.05E-04	6.48E-05	7.41E-05	7.96E-05	5.84E-05	3.80E-05	2.50E-05	8.43E-06



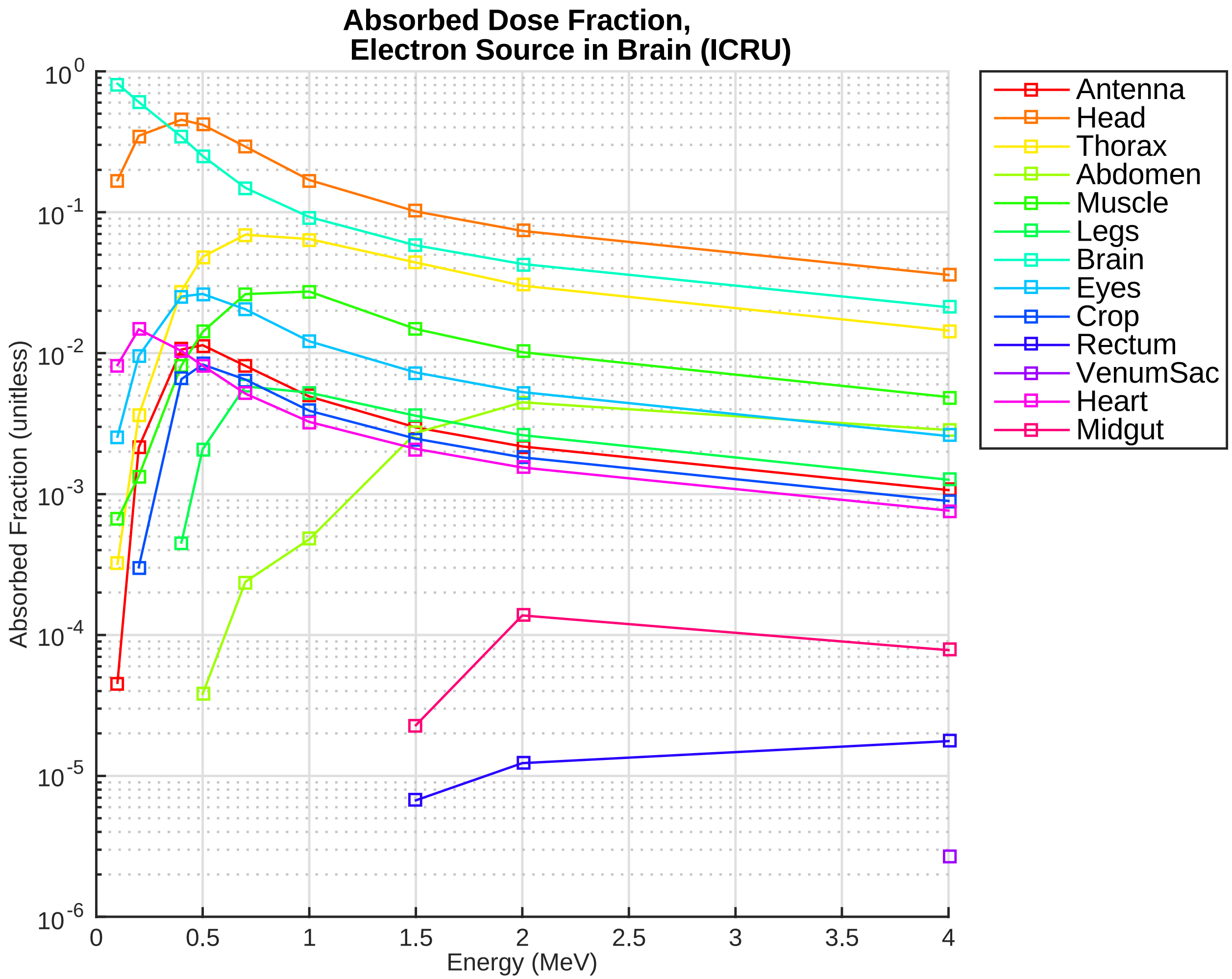
Absorbed Dose Fraction,
Photon Source in Rectum (ICRU)
Absorbed Fraction (unitless)
Energy (MeV)
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
10^-7
0
0.5
1
1.5
2
2.5
3
3.5
4
Antenna
Head
Thorax
Abdomen
Muscle
Legs
Brain
Eyes
Crop
Rectum
VenumSac
Heart
Midgut

A. Absorbed Fractions Honeybee using ICRU Four-Component Human Tissue: Electrons

In this appendix the absorbed fraction of the voxel model are given using the standard four-component human tissue composition. These values are generated by MCNP with the option of PAR 3 (electrons) of different energies and are further processed by the MATLAB code. A graphs is also presented, representing the absorbed fraction as a function of energy with a source in a specific location

Absorbed Fractions of Electron Energy
Source in Brain
Energy (MeV)

	Target	0.100	0.200	0.400	0.500	0.700	1.000	1.500	2.000	4.000
1	Antenna	4.59E-05	2.15E-03	1.06E-02	1.14E-02	8.13E-03	4.92E-03	2.97E-03	2.17E-03	1.07E-03
2	Head	1.68E-01	3.49E-01	4.54E-01	4.17E-01	2.92E-01	1.69E-01	1.01E-01	7.36E-02	3.59E-02
3	Thorax	3.13E-04	3.61E-03	2.76E-02	4.84E-02	6.92E-02	6.47E-02	4.40E-02	3.02E-02	1.44E-02
4	Abdomen	--	--	--	3.80E-05	2.39E-04	4.86E-04	2.72E-03	4.50E-03	2.84E-03
5	Muscle	6.67E-04	1.33E-03	8.08E-03	1.40E-02	2.60E-02	2.70E-02	1.46E-02	1.00E-02	4.81E-03
6	Legs	--	--	4.54E-04	2.08E-03	5.81E-03	5.26E-03	3.59E-03	2.61E-03	1.26E-03
7	Brain	8.16E-01	6.05E-01	3.43E-01	2.50E-01	1.49E-01	9.25E-02	5.82E-02	4.29E-02	2.11E-02
8	Eyes	2.56E-03	9.57E-03	2.52E-02	2.63E-02	2.05E-02	1.22E-02	7.28E-03	5.29E-03	2.58E-03
9	Crop	--	3.02E-04	6.53E-03	8.29E-03	6.49E-03	3.90E-03	2.47E-03	1.82E-03	8.93E-04
10	Rectum	--	--	--	--	--	--	6.25E-06	1.20E-05	1.59E-05
11	Venom sac	--	--	--	--	--	--	--	2.28E-06	3.02E-06
12	Heart	8.22E-03	1.48E-02	1.03E-02	8.15E-03	5.17E-03	3.25E-03	2.09E-03	1.54E-03	7.65E-04
13	Intestine	--	--	--	--	--	--	2.30E-05	1.33E-04	8.19E-05



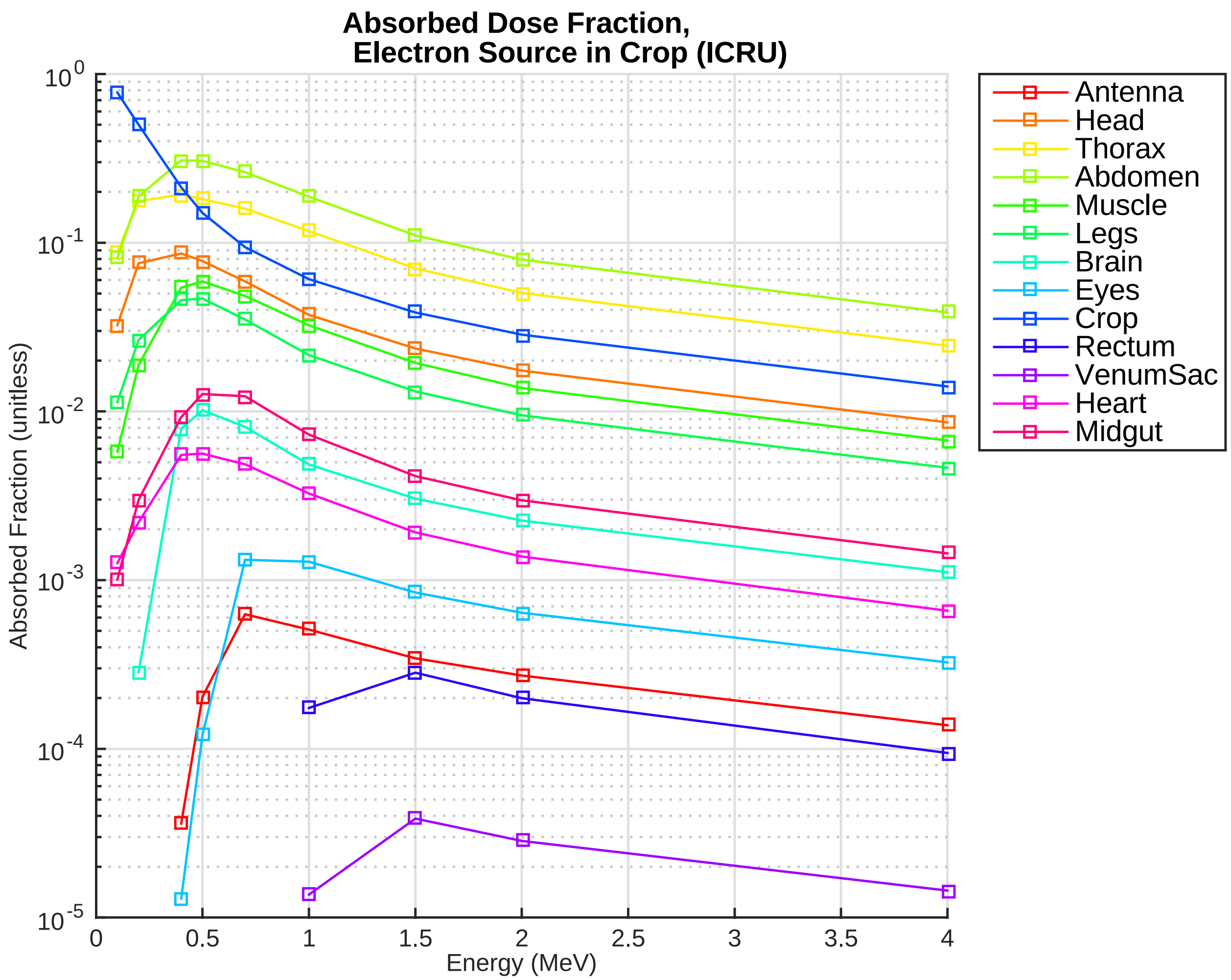
Absorbed Dose Fraction,
Electron Source in Brain (ICRU)
Absorbed Fraction (unitless)
Energy (MeV)
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
0
0.5
1
1.5
2
2.5
3
3.5
4
Antenna
Head
Thorax
Abdomen
Muscle
Legs
Brain
Eyes
Crop
Rectum
VenumSac
Heart
Midgut

Absorbed Fractions of Electron Energy

Source in Crop

Energy (MeV)

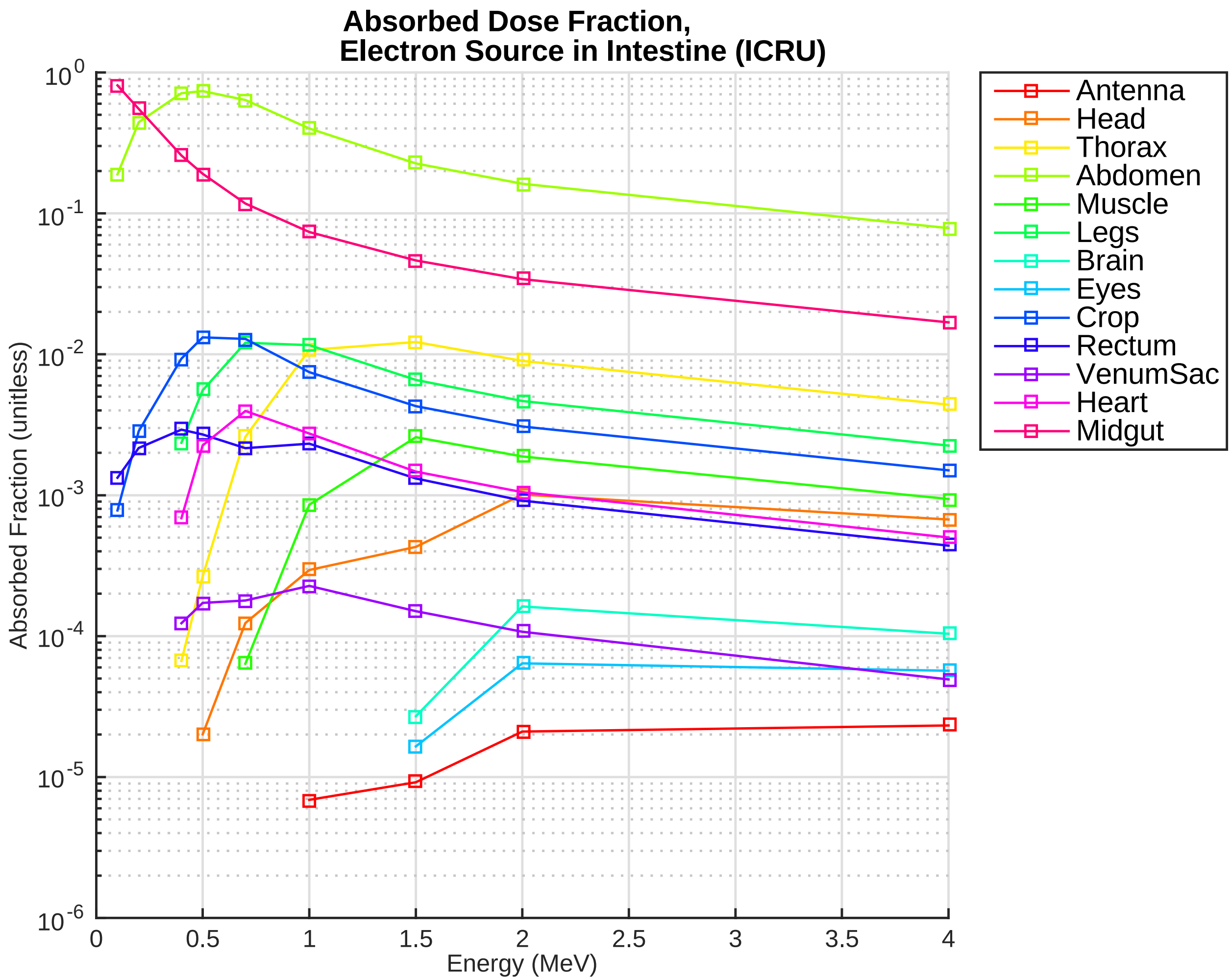
	Target	0.100	0.200	0.400	0.500	0.700	1.000	1.500	2.000	4.000
1	Antenna	--	--	3.58E-05	2.03E-04	6.29E-04	5.08E-04	3.43E-04	2.73E-04	1.38E-04
2	Head	3.24E-02	7.55E-02	8.63E-02	7.79E-02	5.91E-02	3.73E-02	2.36E-02	1.75E-02	8.60E-03
3	Thorax	8.78E-02	1.76E-01	1.93E-01	1.81E-01	1.60E-01	1.17E-01	7.05E-02	5.03E-02	2.45E-02
4	Abdomen	8.10E-02	1.88E-01	3.08E-01	3.05E-01	2.62E-01	1.88E-01	1.11E-01	7.94E-02	3.86E-02
5	Muscle	5.75E-03	1.87E-02	5.39E-02	5.84E-02	4.78E-02	3.20E-02	1.91E-02	1.36E-02	6.63E-03
6	Legs	1.14E-02	2.65E-02	4.56E-02	4.67E-02	3.51E-02	2.16E-02	1.31E-02	9.49E-03	4.63E-03
7	Brain	--	2.84E-04	7.89E-03	1.02E-02	8.09E-03	4.86E-03	3.04E-03	2.26E-03	1.11E-03
8	Eyes	--	--	1.27E-05	1.20E-04	1.32E-03	1.28E-03	8.42E-04	6.41E-04	3.26E-04
9	Crop	7.77E-01	5.01E-01	2.13E-01	1.50E-01	9.40E-02	6.08E-02	3.86E-02	2.85E-02	1.41E-02
10	Rectum	--	--	--	--	--	1.74E-04	2.82E-04	2.00E-04	9.45E-05
11	Venom sac	--	--	--	--	--	1.38E-05	3.84E-05	2.82E-05	1.45E-05
12	Heart	1.26E-03	2.21E-03	5.53E-03	5.62E-03	4.87E-03	3.26E-03	1.92E-03	1.38E-03	6.57E-04
13	Intestine	1.01E-03	2.99E-03	9.24E-03	1.27E-02	1.23E-02	7.28E-03	4.14E-03	2.97E-03	1.44E-03



Absorbed Dose Fraction,
Electron Source in Crop (ICRU)
Absorbed Fraction (unitless)
Energy (MeV)
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
0
0.5
1
1.5
2
2.5
3
3.5
4
Antenna
Head
Thorax
Abdomen
Muscle
Legs
Brain
Eyes
Crop
Rectum
VenumSac
Heart
Midgut

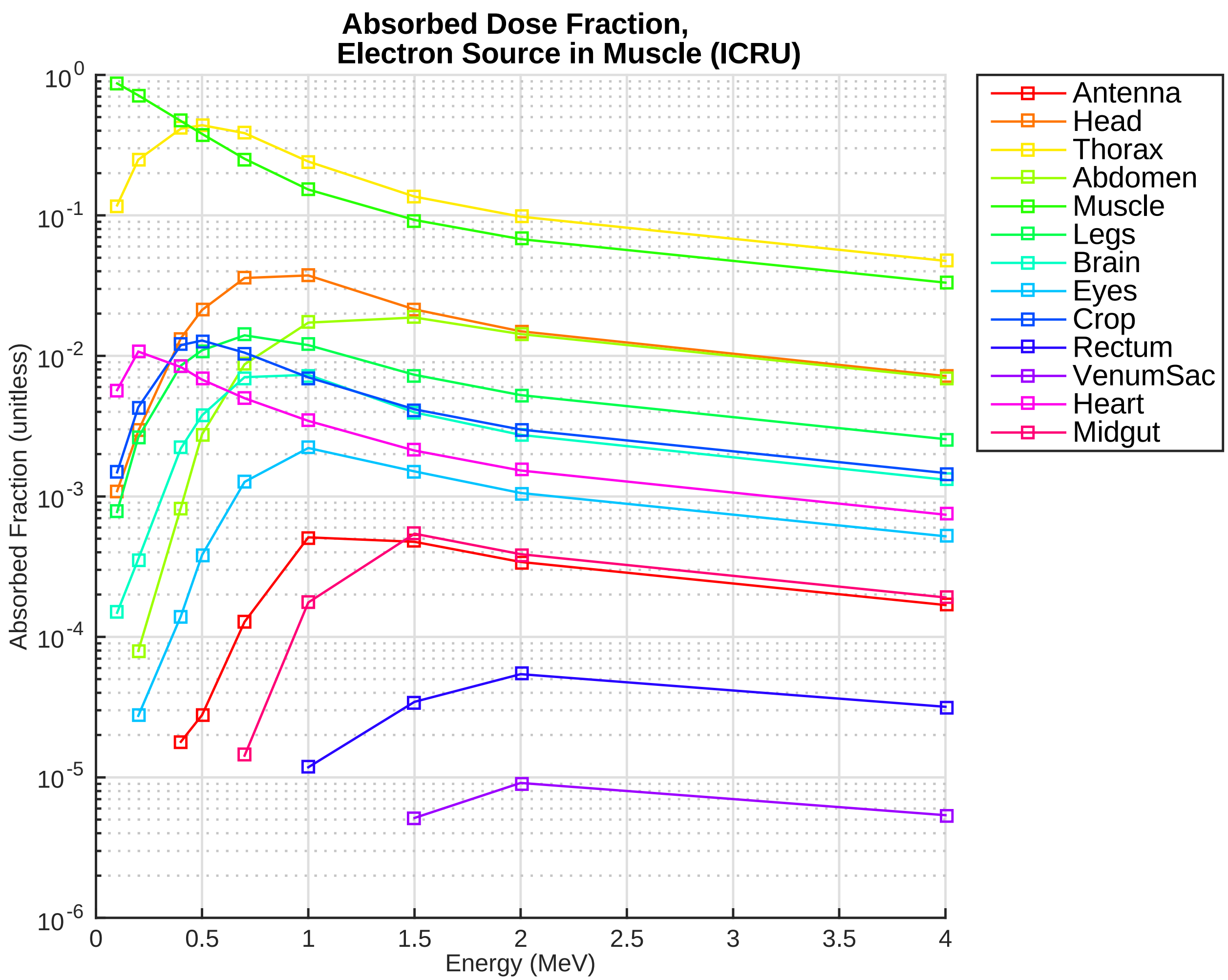
Absorbed Fractions of Electron Energy
Source in Intestine
Energy (MeV)

	Target	0.100	0.200	0.400	0.500	0.700	1.000	1.500	2.000	4.000
1	Antenna	--	--	--	--	--	6.90E-06	9.20E-06	2.10E-05	2.32E-05
2	Head	--	--	--	2.01E-05	1.24E-04	2.94E-04	4.30E-04	1.01E-03	6.71E-04
3	Thorax	--	--	6.67E-05	2.66E-04	2.59E-03	1.07E-02	1.22E-02	8.98E-03	4.39E-03
4	Abdomen	1.89E-01	4.43E-01	7.13E-01	7.37E-01	6.37E-01	4.00E-01	2.26E-01	1.62E-01	7.86E-02
5	Muscle	--	--	--	--	6.38E-05	8.55E-04	2.58E-03	1.89E-03	9.40E-04
6	Legs	--	--	2.35E-03	5.56E-03	1.21E-02	1.16E-02	6.58E-03	4.67E-03	2.25E-03
7	Brain	--	--	--	--	--	--	2.70E-05	1.63E-04	1.04E-04
8	Eyes	--	--	--	--	--	--	1.65E-05	6.40E-05	5.68E-05
9	Crop	7.80E-04	2.84E-03	9.31E-03	1.32E-02	1.29E-02	7.46E-03	4.28E-03	3.07E-03	1.50E-03
10	Rectum	1.33E-03	2.16E-03	2.92E-03	2.70E-03	2.16E-03	2.32E-03	1.31E-03	9.15E-04	4.39E-04
11	Venom sac	--	--	1.23E-04	1.72E-04	1.79E-04	2.27E-04	1.50E-04	1.08E-04	4.94E-05
12	Heart	--	--	6.87E-04	2.26E-03	3.96E-03	2.74E-03	1.47E-03	1.05E-03	5.01E-04
13	Intestine	8.08E-01	5.51E-01	2.58E-01	1.91E-01	1.17E-01	7.38E-02	4.63E-02	3.41E-02	1.68E-02


Absorbed Dose Fraction,
Electron Source in Intestine (ICRU)
Absorbed Fraction (unitless)
Energy (MeV)
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
0
0.5
1
1.5
2
2.5
3
3.5
4
Antenna
Head
Thorax
Abdomen
Muscle
Legs
Brain
Eyes
Crop
Rectum
VenumSac
Heart
Midgut

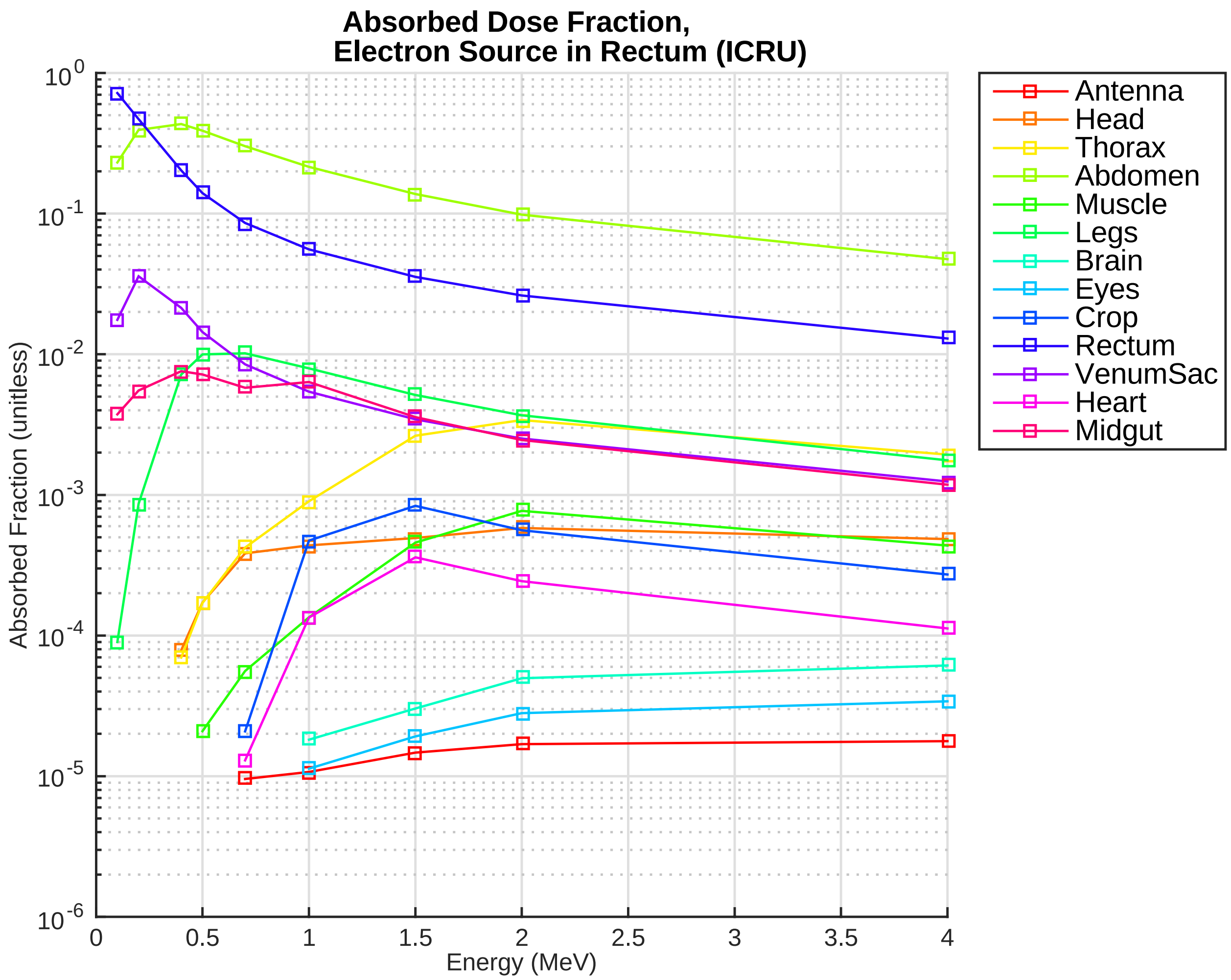
Absorbed Fractions of Electron Energy
Source in Muscle
Energy (MeV)

	Target	0.100	0.200	0.400	0.500	0.700	1.000	1.500	2.000	4.000
1	Antenna	--	--	1.79E-05	2.78E-05	1.28E-04	6.74E-04	4.75E-04	3.41E-04	1.69E-04
2	Head	1.09E-03	2.92E-03	1.33E-02	2.12E-02	3.59E-02	2.87E-02	2.15E-02	1.49E-02	7.18E-03
3	Thorax	1.18E-01	2.49E-01	4.14E-01	4.38E-01	3.84E-01	1.90E-01	1.36E-01	9.79E-02	4.75E-02
4	Abdomen	--	7.95E-05	8.28E-04	2.76E-03	8.70E-03	2.79E-02	1.88E-02	1.43E-02	6.96E-03
5	Muscle	8.69E-01	7.15E-01	4.70E-01	3.80E-01	2.53E-01	1.33E-01	9.26E-02	6.77E-02	3.32E-02
6	Legs	7.75E-04	2.63E-03	8.52E-03	1.10E-02	1.40E-02	1.02E-02	7.33E-03	5.25E-03	2.56E-03
7	Brain	1.48E-04	3.57E-04	2.20E-03	3.77E-03	7.04E-03	5.26E-03	3.96E-03	2.74E-03	1.31E-03
8	Eyes	--	2.74E-05	1.40E-04	3.82E-04	1.27E-03	2.08E-03	1.51E-03	1.06E-03	5.19E-04
9	Crop	1.48E-03	4.31E-03	1.19E-02	1.29E-02	1.05E-02	5.86E-03	4.16E-03	2.99E-03	1.46E-03
10	Rectum	--	--	--	--	--	1.27E-04	3.45E-05	5.42E-05	3.18E-05
11	Venom sac	--	--	--	--	--	2.15E-05	5.14E-06	9.14E-06	5.38E-06
12	Heart	5.71E-03	1.07E-02	8.33E-03	6.78E-03	5.00E-03	2.96E-03	2.12E-03	1.53E-03	7.40E-04
13	Intestine	--	--	--	--	1.43E-05	7.63E-04	5.42E-04	3.88E-04	1.91E-04


Absorbed Dose Fraction,
Electron Source in Muscle (ICRU)
Absorbed Fraction (unitless)
Energy (MeV)
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
0
0.5
1
1.5
2
2.5
3
3.5
4
Antenna
Head
Thorax
Abdomen
Muscle
Legs
Brain
Eyes
Crop
Rectum
VenumSac
Heart
Midgut

Absorbed Fractions of Electron Energy
Source in rectum
Energy (MeV)

	Target	0.100	0.200	0.400	0.500	0.700	1.000	1.500	2.000	4.000
1	Antenna	--	--	--	--	9.54E-06	1.07E-05	1.47E-05	1.69E-05	1.78E-05
2	Head	--	--	7.87E-05	1.72E-04	3.84E-04	4.37E-04	4.94E-04	5.82E-04	4.85E-04
3	Thorax	--	--	6.97E-05	1.71E-04	4.22E-04	9.02E-04	2.63E-03	3.41E-03	1.93E-03
4	Abdomen	2.31E-01	3.92E-01	4.33E-01	3.89E-01	3.01E-01	2.15E-01	1.38E-01	9.81E-02	4.74E-02
5	Muscle	--	--	--	2.09E-05	5.60E-05	1.35E-04	4.58E-04	7.70E-04	4.37E-04
6	Legs	8.99E-05	8.64E-04	7.17E-03	9.99E-03	1.02E-02	7.94E-03	5.13E-03	3.69E-03	1.76E-03
7	Brain	--	--	--	--	--	1.82E-05	3.03E-05	4.98E-05	6.13E-05
8	Eyes	--	--	--	--	--	1.13E-05	1.92E-05	2.81E-05	3.40E-05
9	Crop	--	--	--	--	2.08E-05	4.73E-04	8.35E-04	5.62E-04	2.72E-04
10	Rectum	7.20E-01	4.70E-01	2.03E-01	1.40E-01	8.57E-02	5.56E-02	3.55E-02	2.62E-02	1.29E-02
11	Venom sac	1.76E-02	3.58E-02	2.14E-02	1.44E-02	8.48E-03	5.43E-03	3.44E-03	2.52E-03	1.24E-03
12	Heart	--	--	--	--	1.30E-05	1.34E-04	3.60E-04	2.44E-04	1.13E-04
13	Intestine	3.74E-03	5.51E-03	7.59E-03	7.17E-03	5.77E-03	6.34E-03	3.57E-03	2.45E-03	1.18E-03



Absorbed Dose Fraction,
Electron Source in Rectum (ICRU)
Absorbed Fraction (unitless)
Energy (MeV)
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
0
0.5
1
1.5
2
2.5
3
3.5
4
Antenna
Head
Thorax
Abdomen
Muscle
Legs
Brain
Eyes
Crop
Rectum
VenumSac
Heart
Midgut

B. Dose Conversion Factors using ICRU Four Component Human Tissue

In this appendix the Dose Conversion Factors are presented. This are calculated using the absorbed fractions form Appendix A, Appendix A and Equation .

Dose conversion factors [μGy-kg-d^{-1}-Bq^{-1}]													
Cs-137													
Target / Source	Antenna	Head	Thorax	Abdomen	Muscle	Legs	Brain	Eyes	Crop	Rectum	Venom sac	Heart	Intestine
Brain	6.97E-06	8.15E-04	2.13E-05	1.51E-06	7.49E-06	7.25E-07	1.60E-03	2.55E-05	2.84E-06	0.00E+00	0.00E+00	3.23E-05	5.09E-08
Crop	7.07E-08	1.71E-04	4.06E-04	4.61E-04	5.27E-05	6.51E-05	3.33E-06	1.63E-07	1.37E-03	4.81E-08	2.27E-09	6.29E-06	8.88E-06
Intestine	3.69E-09	3.89E-07	2.31E-06	1.08E-03	5.10E-07	1.78E-06	6.63E-08	2.88E-08	8.51E-06	5.39E-06	6.18E-08	4.61E-07	1.48E-03
Muscle	8.37E-08	1.29E-05	6.18E-04	4.01E-06	1.86E-03	8.35E-06	2.00E-06	3.32E-07	1.20E-05	1.90E-08	0.00E+00	2.36E-05	9.76E-08
Rectum	0.00E+00	2.62E-07	1.07E-06	9.24E-04	2.37E-07	4.34E-06	3.71E-08	1.99E-08	1.41E-07	1.28E-03	7.53E-05	6.22E-08	1.40E-05
Sr-90													
Target / Source	Antenna	Head	Thorax	Abdomen	Muscle	Legs	Brain	Eyes	Crop	Rectum	Venom sac	Heart	Intestine
Brain	4.94E-06	8.52E-04	8.36E-06	0.00E+00	3.25E-06	0.00E+00	1.64E-03	2.27E-05	6.92E-07	0.00E+00	0.00E+00	3.65E-05	0.00E+00
Crop	0.00E+00	1.83E-04	4.30E-04	4.56E-04	4.46E-05	6.42E-05	6.50E-07	0.00E+00	1.39E-03	0.00E+00	0.00E+00	5.45E-06	7.16E-06
Intestine	0.00E+00	0.00E+00	0.00E+00	1.07E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	6.75E-06	5.36E-06	0.00E+00	0.00E+00	1.51E-03
Muscle	0.00E+00	7.03E-06	6.07E-04	1.80E-07	1.91E-03	6.26E-06	8.64E-07	6.27E-08	1.03E-05	0.00E+00	0.00E+00	2.63E-05	0.00E+00
Rectum	0.00E+00	0.00E+00	0.00E+00	9.70E-04	0.00E+00	2.01E-06	0.00E+00	0.00E+00	0.00E+00	1.30E-03	8.75E-05	0.00E+00	1.38E-05
Y-90													
Target / Source	Antenna	Head	Thorax	Abdomen	Muscle	Legs	Brain	Eyes	Crop	Rectum	Venom sac	Heart	Intestine
Brain	6.85E-03	2.81E-03	7.19E-04	3.03E-06	2.76E-04	6.00E-05	1.45E-03	1.98E-04	6.28E-05	0.00E+00	0.00E+00	5.03E-05	0.00E+00

Crop	6.36E-06	5.76E-04	1.59E-03	2.60E-03	4.70E-04	3.41E-04	7.83E-05	1.38E-05	9.19E-04	3.66E-07	2.90E-08	4.78E-05	1.19E-04
Intestine	1.45E-08	1.66E-06	4.43E-05	6.20E-03	2.34E-06	1.26E-04	0.00E+00	0.00E+00	1.24E-04	2.31E-05	1.98E-06	3.91E-05	1.14E-03
Muscle	2.50E-06	3.63E-04	3.63E-03	1.32E-04	2.41E-03	1.39E-04	7.03E-05	1.51E-05	1.01E-04	2.67E-07	4.52E-08	4.83E-05	1.73E-06
Rectum	1.03E-07	4.15E-06	5.45E-06	2.99E-03	7.55E-07	1.03E-04	3.83E-08	2.38E-08	1.17E-06	8.38E-04	8.28E-05	3.91E-07	6.19E-05
Co-60													
Target Source	Antenna	Head	Thorax	Abdomen	Muscle	Legs	Brain	Eyes	Crop	Rectum	Venom sac	Heart	Intestine
Brain	1.28E-06	2.96E-04	2.42E-05	5.43E-06	9.25E-06	1.94E-06	1.46E-05	2.73E-06	1.23E-06	0.00E+00	1.26E-05	6.19E-07	4.29E-07
Crop	2.05E-07	6.06E-05	1.67E-04	1.77E-04	1.84E-05	2.28E-05	1.53E-06	5.22E-07	1.12E-03	1.81E-07	2.77E-08	2.79E-06	3.38E-06
Intestine	4.45E-08	1.37E-06	8.24E-06	3.92E-04	1.95E-06	3.39E-06	2.44E-07	1.01E-07	3.31E-06	2.67E-06	8.24E-08	8.08E-07	1.17E-03
Muscle	2.71E-07	1.33E-05	2.41E-04	1.30E-05	1.28E-03	4.73E-06	2.41E-06	8.29E-07	4.29E-06	6.62E-08	0.00E+00	9.56E-06	4.00E-07
Rectum	1.17E-08	8.21E-07	3.63E-06	4.07E-04	8.85E-07	2.54E-06	1.40E-07	6.06E-08	5.31E-07	1.04E-03	2.80E-05	7.95E-07	7.30E-06
I-131													
Target Source	Antenna	Head	Thorax	Abdomen	Muscle	Legs	Brain	Eyes	Crop	Rectum	Venom sac	Heart	Intestine
Brain	6.01E-06	9.14E-04	1.48E-05	1.02E-06	5.34E-06	4.23E-07	1.63E-03	2.57E-05	1.25E-06	0.00E+00	0.00E+00	3.84E-05	3.36E-08
Crop	9.45E-10	1.94E-04	4.54E-04	4.87E-04	4.88E-05	6.86E-05	9.19E-07	3.35E-10	1.36E-03	0.00E+00	0.00E+00	5.80E-06	7.83E-06
Intestine	0.00E+00	0.00E+00	1.76E-09	1.15E-03	0.00E+00	6.21E-08	0.00E+00	0.00E+00	7.43E-06	5.61E-06	3.25E-09	1.81E-08	1.49E-03
Muscle	4.73E-10	7.77E-06	6.46E-04	2.21E-07	1.91E-03	6.88E-06	9.66E-07	7.23E-08	1.12E-05	0.00E+00	0.00E+00	2.76E-05	0.00E+00
Rectum	0.00E+00	2.08E-09	1.84E-09	1.02E-03	0.00E+00	2.36E-06	0.00E+00	0.00E+00	0.00E+00	1.28E-03	9.19E-05	0.00E+00	1.44E-05
Cl-36													
Target Source	Antenna	Head	Thorax	Abdomen	Muscle	Legs	Brain	Eyes	Crop	Rectum	Venom sac	Heart	Intestine
Brain	1.18E-05	1.18E-03	2.58E-05	5.46E-08	8.28E-06	2.85E-07	1.89E-03	3.98E-05	4.60E-06	0.00E+00	0.00E+00	4.49E-05	1.87E-09
Crop	2.29E-08	2.49E-04	5.75E-04	6.73E-04	8.05E-05	9.62E-05	5.35E-06	1.32E-08	1.54E-03	1.73E-09	5.37E-12	9.03E-06	1.32E-05

Intestine	8.68E-12	1.42E-08	1.21E-07	1.58E-03	1.82E-08	1.40E-06	2.37E-09	1.09E-09	1.29E-05	7.38E-06	7.24E-08	4.08E-07	1.70E-03
Muscle	1.33E-08	1.55E-05	8.95E-04	8.21E-07	2.25E-03	1.19E-05	2.24E-06	1.62E-07	1.83E-05	7.03E-10	0.00E+00	3.30E-05	3.39E-09
Rectum	0.00E+00	5.45E-08	7.87E-08	1.28E-03	8.47E-09	6.46E-06	1.30E-09	7.56E-10	5.01E-09	1.45E-03	1.06E-04	2.28E-09	1.89E-05
Po-210													
Target / Source	Antenna	Head	Thorax	Abdomen	Muscle	Legs	Brain	Eyes	Crop	Rectum	Venom sac	Heart	Intestine
Brain	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	7.34E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Crop	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	7.34E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Intestine	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	7.34E-02
Muscle	0.00E+00	0.00E+00	0.00E+00	0.00E+00	7.34E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Rectum	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	7.34E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Ra-226													
Target / Source	Antenna	Head	Thorax	Abdomen	Muscle	Legs	Brain	Eyes	Crop	Rectum	Venom sac	Heart	Intestine
Brain	6.24E-09	2.18E-07	8.38E-08	1.69E-08	2.86E-08	7.10E-09	6.61E-02	1.54E-08	5.22E-09	0.00E+00	0.00E+00	4.69E-09	5.26E-10
Crop	8.93E-10	5.19E-08	1.47E-07	2.31E-07	3.97E-08	2.76E-08	6.49E-09	1.82E-09	6.61E-02	5.38E-10	0.00E+00	4.05E-09	8.84E-09
Intestine	0.00E+00	4.50E-09	2.58E-08	4.69E-07	5.50E-09	1.29E-08	6.59E-10	3.82E-10	8.93E-09	2.67E-09	2.58E-10	2.95E-09	6.61E-02
Muscle	1.03E-09	4.18E-08	2.84E-07	4.07E-08	6.61E-02	1.50E-08	7.84E-09	3.02E-09	8.48E-09	0.00E+00	0.00E+00	4.51E-09	1.10E-09
Rectum	0.00E+00	2.92E-09	1.21E-08	2.82E-07	2.69E-09	9.92E-09	4.03E-10	0.00E+00	1.65E-09	6.61E-02	7.70E-09	5.64E-10	6.73E-09

C. Absorbed Fractions in Honeybee using Organic Elemental Analysis: Photons

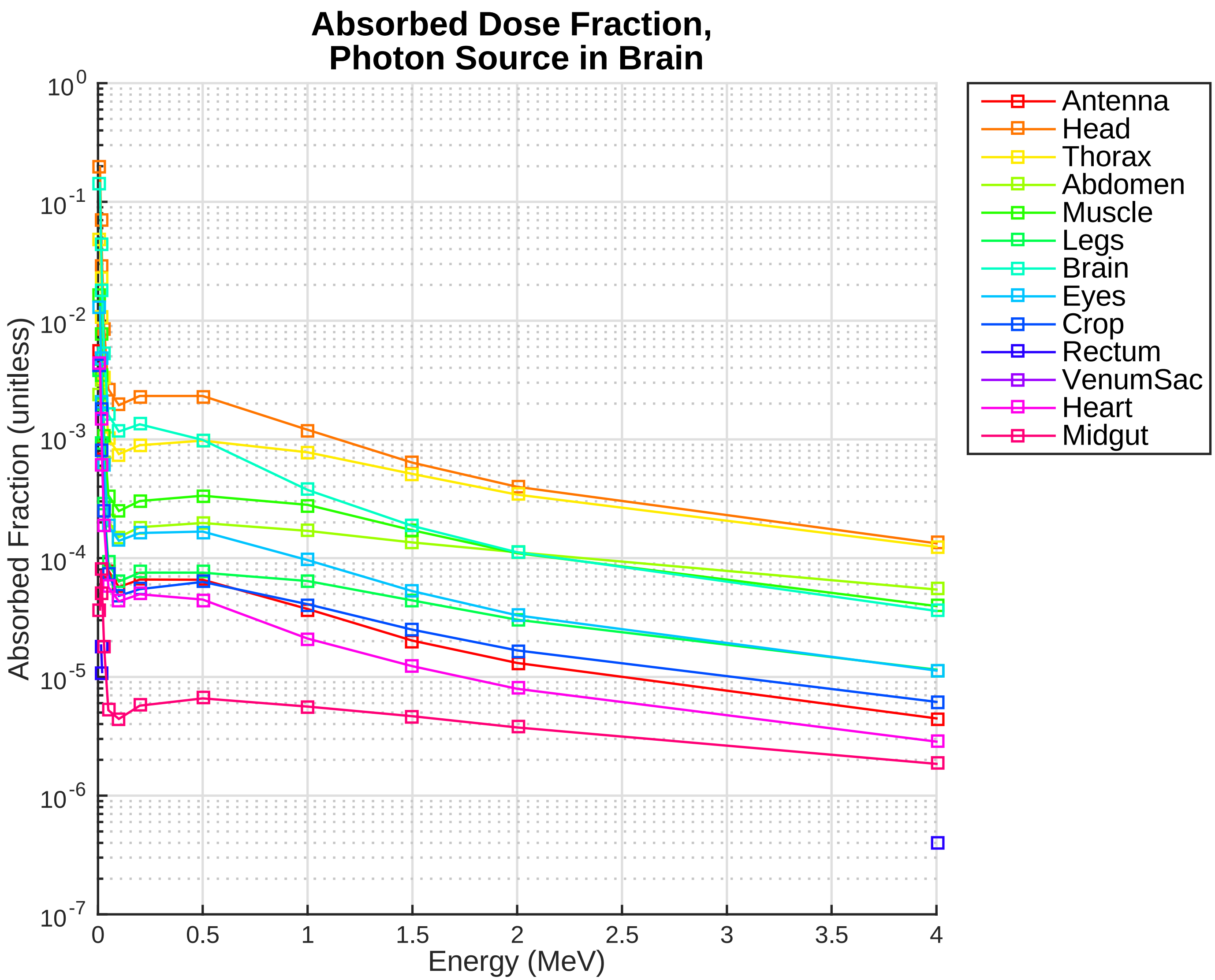
In this appendix the absorbed fraction of the voxel model are given using the measured four-component human tissue composition. These values are generated by MCNP with the option of PAR 2 (photons) of different energies and are further processed by the MATLAB code. A graphs is also presented, representing the absorbed fraction as a function of energy with a source in a specific location

Absorbed Fractions of Photon Energy

Source in Brain

Energy (MeV)

	Target	0.010	0.015	0.02	0.030	0.050	0.100	0.200	0.500	1.000	1.500	2.000	4.000
1	Antenna	5.49E-03	2.02E-03	8.59E-04	2.48E-04	7.84E-05	5.72E-05	6.60E-05	6.57E-05	3.72E-05	2.02E-05	1.31E-05	4.48E-06
2	Head	1.97E-01	6.89E-02	2.92E-02	8.63E-03	2.66E-03	1.94E-03	2.32E-03	2.32E-03	1.21E-03	6.37E-04	3.98E-04	1.33E-04
3	Thorax	4.73E-02	2.33E-02	1.07E-02	3.31E-03	1.02E-03	7.51E-04	8.93E-04	9.74E-04	7.77E-04	5.12E-04	3.42E-04	1.24E-04
4	Abdomen	2.34E-03	3.11E-03	1.84E-03	6.35E-04	2.04E-04	1.50E-04	1.82E-04	1.98E-04	1.70E-04	1.36E-04	1.12E-04	5.44E-05
5	M	1.63E-02	7.69E-03	3.53E-03	1.08E-03	3.38E-04	2.49E-04	3.02E-04	3.35E-04	2.81E-04	1.72E-04	1.10E-04	3.94E-05
6	Legs	3.82E-03	1.95E-03	9.18E-04	2.92E-04	9.11E-05	6.35E-05	7.55E-05	7.55E-05	6.42E-05	4.40E-05	3.03E-05	1.15E-05
7	Brain	1.44E-01	4.40E-02	1.81E-02	5.23E-03	1.61E-03	1.16E-03	1.34E-03	9.87E-04	3.75E-04	1.87E-04	1.12E-04	3.59E-05
8	Eyes	1.29E-02	4.78E-03	2.05E-03	6.04E-04	1.87E-04	1.40E-04	1.63E-04	1.68E-04	9.62E-05	5.27E-05	3.30E-05	1.13E-05
9	Crop	4.28E-03	1.80E-03	8.03E-04	2.52E-04	7.25E-05	4.81E-05	5.48E-05	6.31E-05	4.09E-05	2.50E-05	1.67E-05	6.17E-06
10	Rectum	--	1.84E-05	1.10E-05	--	--	--	--	--	--	--	--	--
11	Venom sac	--	--	--	--	--	--	--	--	--	--	--	--
12	Heart	4.38E-03	1.49E-03	6.20E-04	1.88E-04	5.72E-05	4.32E-05	4.96E-05	4.48E-05	2.10E-05	1.23E-05	7.95E-06	2.85E-06
13	Intestine	3.69E-05	7.98E-05	5.09E-05	1.78E-05	5.23E-06	4.42E-06	5.71E-06	6.58E-06	5.62E-06	4.66E-06	3.74E-06	1.85E-06



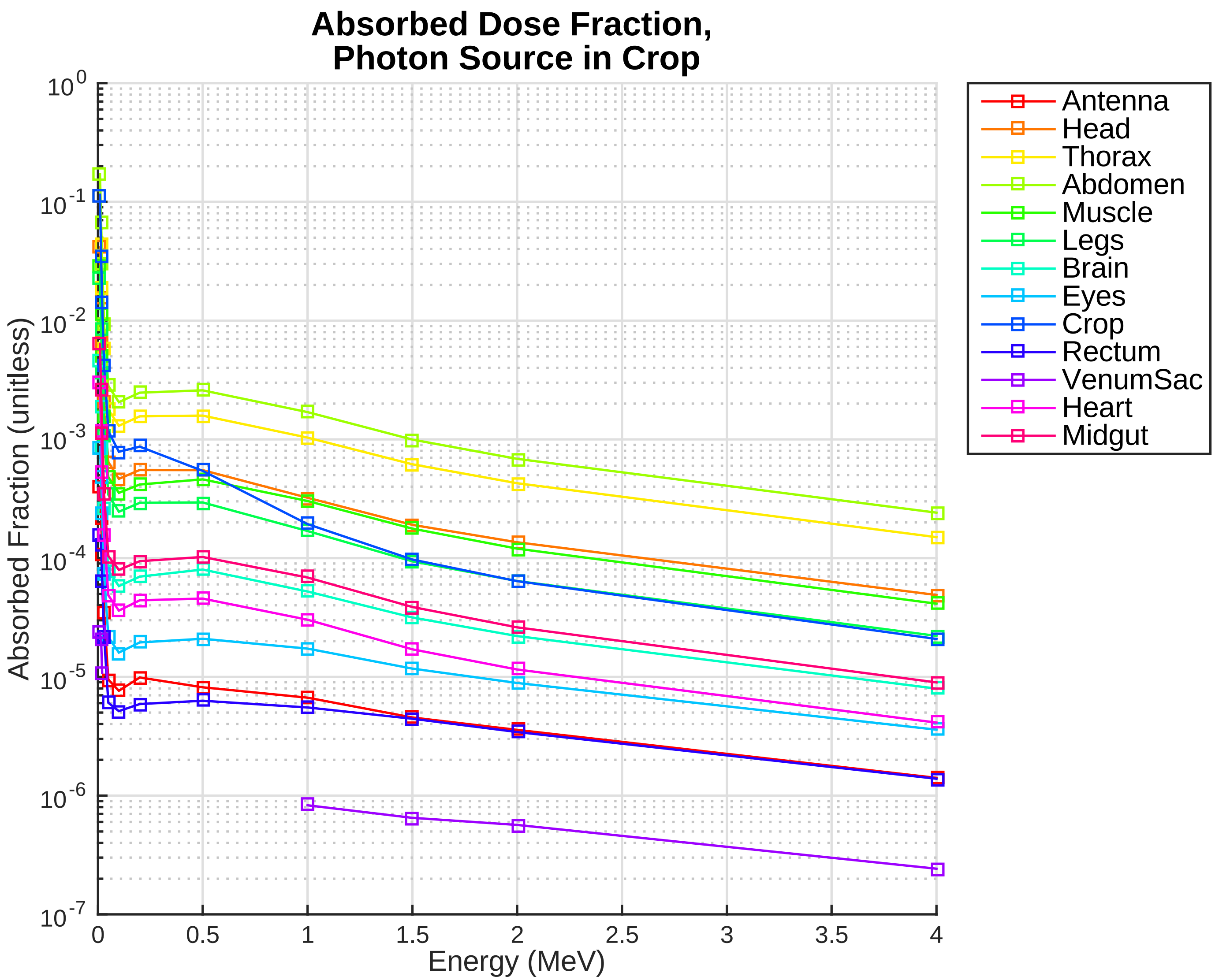
Absorbed Dose Fraction,
Photon Source in Brain
Absorbed Fraction (unitless)
Energy (MeV)
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
10^-7
0
0.5
1
1.5
2
2.5
3
3.5
4
Antenna
Head
Thorax
Abdomen
Muscle
Legs
Brain
Eyes
Crop
Rectum
VenumSac
Heart
Midgut

Absorbed Fractions of Photon Energy

Source in Crop

Energy (MeV)

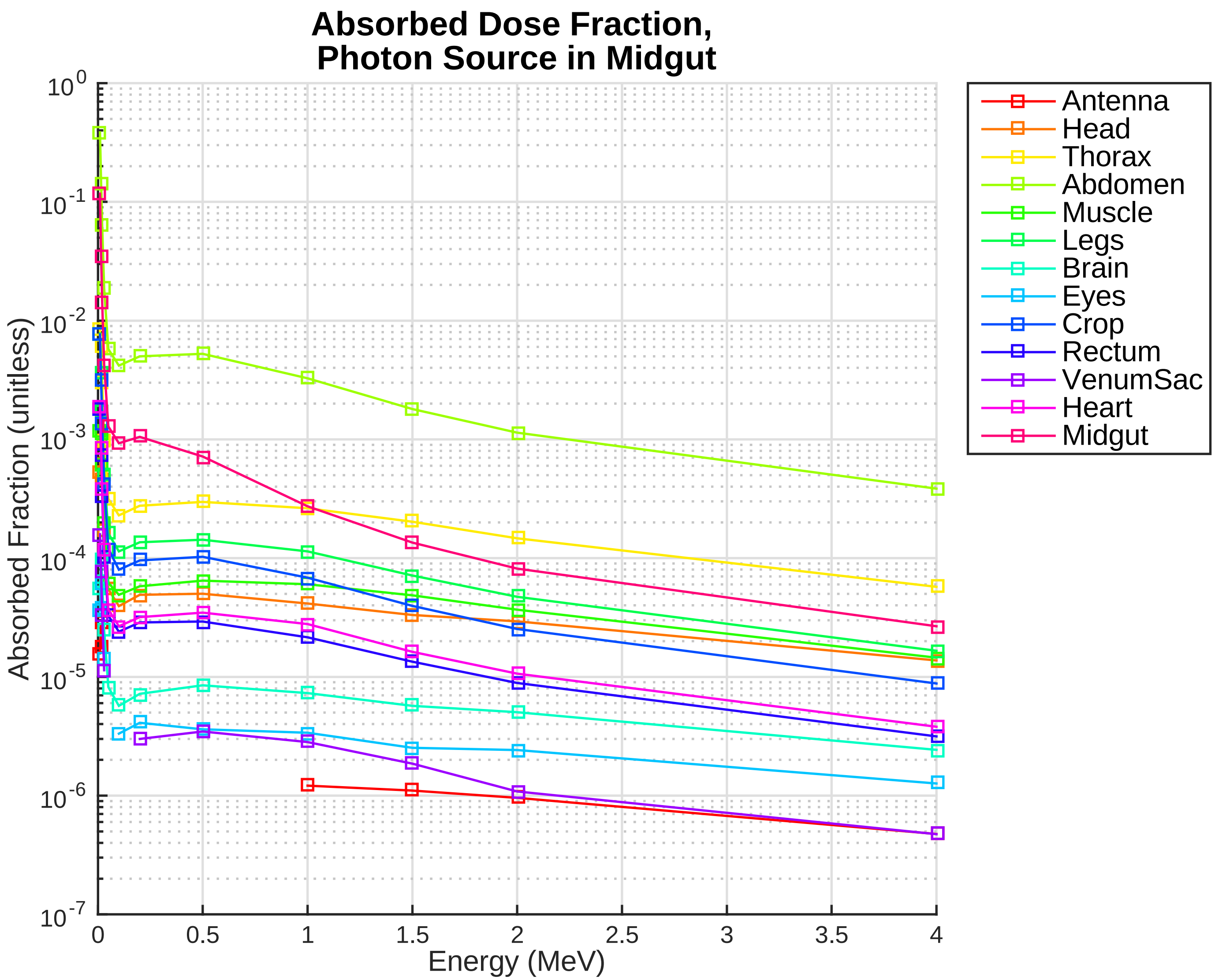
	Target	0.010	0.015	0.02	0.030	0.050	0.100	0.200	0.500	1.000	1.500	2.000	4.000
1	Antenna	3.94E-04	2.19E-04	1.07E-04	3.40E-05	9.46E-06	7.63E-06	9.89E-06	8.17E-06	6.67E-06	4.55E-06	3.57E-06	1.41E-06
2	Head	4.13E-02	1.57E-02	6.82E-03	2.06E-03	6.43E-04	4.66E-04	5.52E-04	5.51E-04	3.22E-04	1.91E-04	1.36E-04	4.89E-05
3	Thorax	1.11E-01	4.40E-02	1.93E-02	5.82E-03	1.78E-03	1.30E-03	1.57E-03	1.58E-03	1.03E-03	6.18E-04	4.27E-04	1.50E-04
4	Abdomen	1.71E-01	6.86E-02	3.03E-02	9.17E-03	2.82E-03	2.06E-03	2.47E-03	2.59E-03	1.70E-03	9.97E-04	6.85E-04	2.41E-04
5	M	2.86E-02	1.15E-02	5.06E-03	1.54E-03	4.80E-04	3.55E-04	4.18E-04	4.60E-04	3.02E-04	1.77E-04	1.20E-04	4.12E-05
6	Legs	2.31E-02	8.63E-03	3.69E-03	1.10E-03	3.41E-04	2.46E-04	2.92E-04	2.94E-04	1.69E-04	9.39E-05	6.43E-05	2.22E-05
7	Brain	4.50E-03	1.90E-03	8.43E-04	2.56E-04	7.84E-05	5.82E-05	6.98E-05	8.00E-05	5.24E-05	3.16E-05	2.21E-05	7.96E-06
8	Eyes	8.62E-04	4.81E-04	2.36E-04	7.41E-05	2.16E-05	1.60E-05	1.95E-05	2.09E-05	1.73E-05	1.17E-05	8.89E-06	3.59E-06
9	Crop	1.15E-01	3.48E-02	1.42E-02	4.13E-03	1.17E-03	7.87E-04	8.69E-04	5.43E-04	1.94E-04	9.71E-05	6.40E-05	2.09E-05
10	Rectum	1.55E-04	1.28E-04	6.40E-05	2.17E-05	6.05E-06	5.15E-06	5.90E-06	6.29E-06	5.53E-06	4.45E-06	3.43E-06	1.39E-06
11	Venom sac	2.35E-05	2.07E-05	1.08E-05	--	--	--	--	--	8.29E-07	6.51E-07	5.66E-07	2.42E-07
12	Heart	2.95E-03	1.19E-03	5.27E-04	1.59E-04	4.86E-05	3.61E-05	4.42E-05	4.56E-05	3.03E-05	1.71E-05	1.15E-05	4.13E-06
13	Intestine	6.33E-03	2.57E-03	1.14E-03	3.43E-04	1.04E-04	7.97E-05	9.44E-05	1.02E-04	6.87E-05	3.87E-05	2.61E-05	8.97E-06



Absorbed Dose Fraction,
Photon Source in Crop
Absorbed Fraction (unitless)
Energy (MeV)
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
0
0.5
1
1.5
2
2.5
3
3.5
4
Antenna
Head
Thorax
Abdomen
Muscle
Legs
Brain
Eyes
Crop
Rectum
VenumSac
Heart
Midgut

Absorbed Fractions of Photon Energy
Source in Intestine
Energy (MeV)

	Target	0.010	0.015	0.02	0.030	0.050	0.100	0.200	0.500	1.000	1.500	2.000	4.000
1	Antenna	1.58E-05	2.85E-05	1.76E-05	--	--	--	--	--	1.21E-06	1.10E-06	9.57E-07	4.75E-07
2	Head	5.28E-04	7.67E-04	4.66E-04	1.69E-04	5.48E-05	3.95E-05	4.91E-05	5.02E-05	4.15E-05	3.33E-05	2.94E-05	1.37E-05
3	Thorax	8.29E-03	6.10E-03	3.08E-03	9.91E-04	3.15E-04	2.29E-04	2.76E-04	2.97E-04	2.63E-04	2.03E-04	1.47E-04	5.74E-05
4	Abdomen	3.85E-01	1.45E-01	6.26E-02	1.87E-02	5.76E-03	4.19E-03	5.00E-03	5.25E-03	3.26E-03	1.80E-03	1.14E-03	3.85E-04
5	Muscle	1.19E-03	1.12E-03	6.12E-04	1.99E-04	6.19E-05	4.91E-05	5.79E-05	6.45E-05	6.02E-05	4.86E-05	3.68E-05	1.45E-05
6	Legs	7.79E-03	3.69E-03	1.68E-03	5.13E-04	1.61E-04	1.14E-04	1.36E-04	1.43E-04	1.14E-04	7.13E-05	4.73E-05	1.66E-05
7	Brain	5.52E-05	9.80E-05	6.33E-05	2.46E-05	8.20E-06	5.69E-06	7.19E-06	8.50E-06	7.28E-06	5.70E-06	5.04E-06	2.43E-06
8	Eyes	3.61E-05	6.23E-05	3.90E-05	1.41E-05	--	3.32E-06	4.11E-06	3.61E-06	3.39E-06	2.52E-06	2.42E-06	1.27E-06
9	Crop	7.64E-03	3.10E-03	1.38E-03	4.19E-04	1.20E-04	7.97E-05	9.57E-05	1.02E-04	6.83E-05	3.96E-05	2.53E-05	8.80E-06
10	Rectum	1.81E-03	7.49E-04	3.38E-04	1.04E-04	3.28E-05	2.40E-05	2.88E-05	2.92E-05	2.15E-05	1.34E-05	8.89E-06	3.15E-06
11	Venom sac	1.59E-04	7.88E-05	3.35E-05	1.14E-05	--	--	3.00E-06	3.46E-06	2.82E-06	1.86E-06	1.08E-06	4.74E-07
12	Heart	1.91E-03	8.64E-04	3.86E-04	1.20E-04	3.70E-05	2.67E-05	3.19E-05	3.47E-05	2.79E-05	1.62E-05	1.06E-05	3.81E-06
13	Intestine	1.17E-01	3.55E-02	1.45E-02	4.25E-03	1.28E-03	9.29E-04	1.05E-03	7.19E-04	2.73E-04	1.35E-04	8.17E-05	2.67E-05

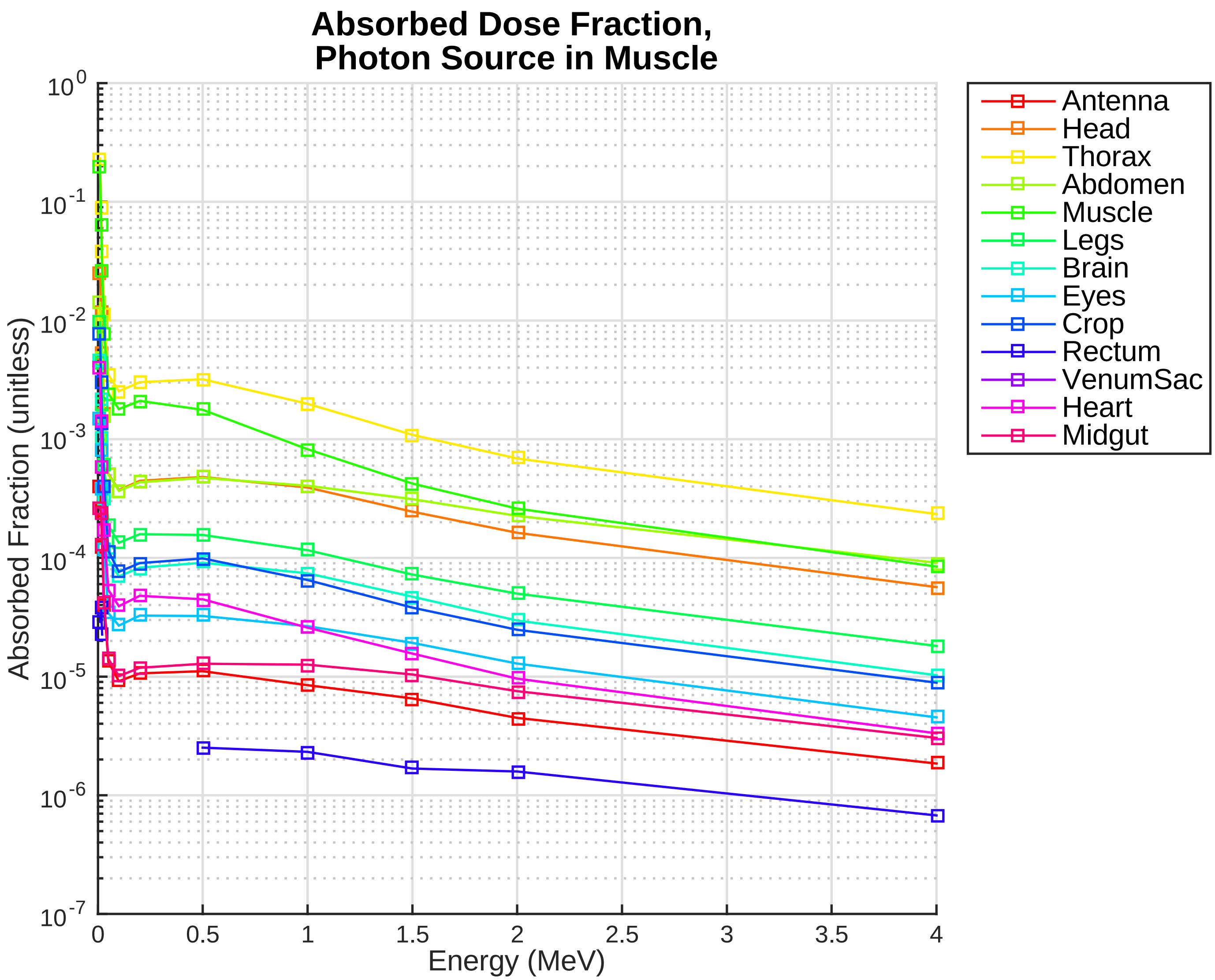

Absorbed Dose Fraction,
Photon Source in Midgut
Absorbed Fraction (unitless)
Energy (MeV)
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
0
0.5
1
1.5
2
2.5
3
3.5
4
Antenna
Head
Thorax
Abdomen
Muscle
Legs
Brain
Eyes
Crop
Rectum
VenumSac
Heart
Midgut

Absorbed Fractions of Photon Energy

Source in Muscle

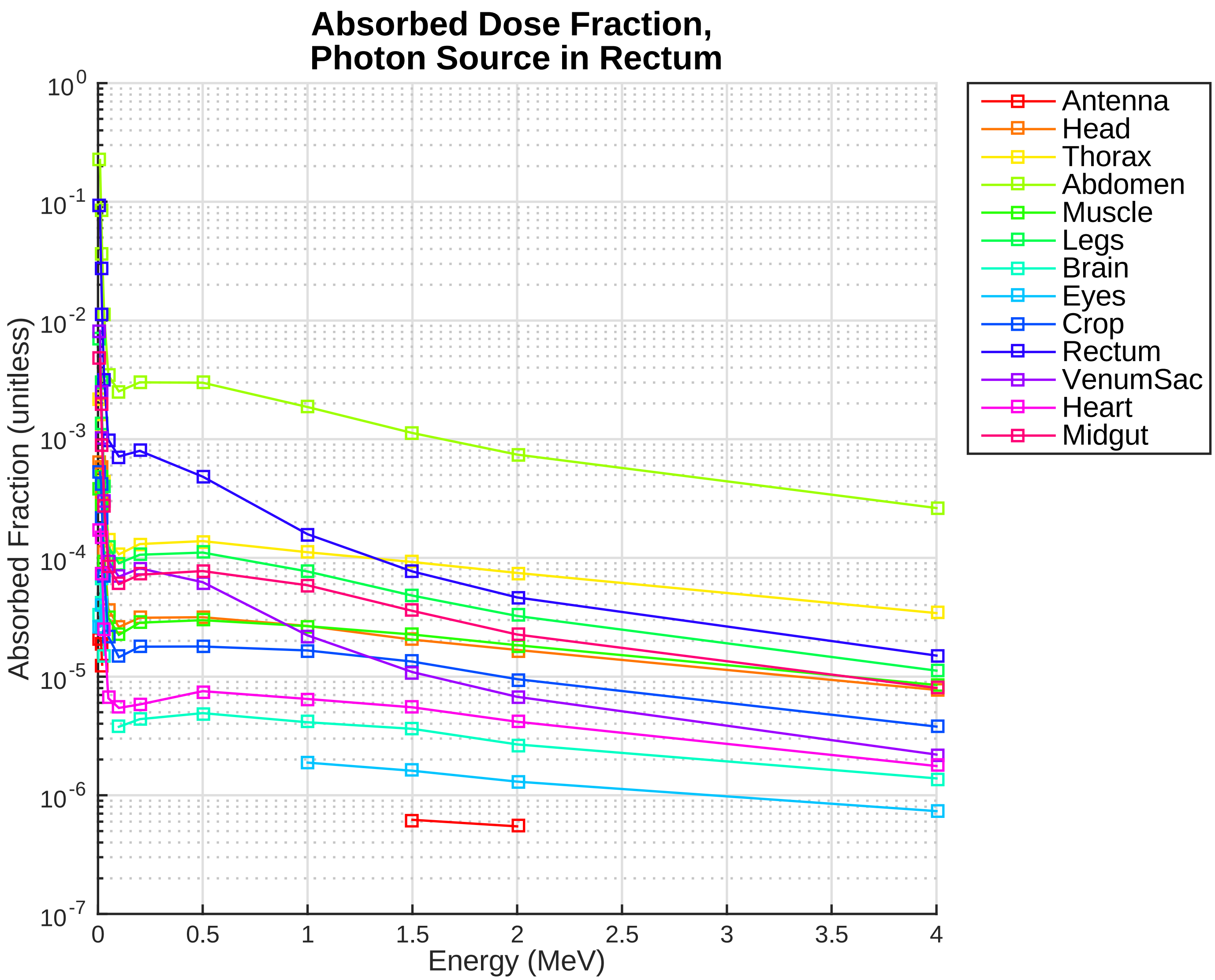
Energy (MeV)

	Target	0.010	0.015	0.02	0.030	0.050	0.100	0.200	0.500	1.000	1.500	2.000	4.000
1	Antenna	4.06E-04	2.51E-04	1.21E-04	3.92E-05	1.33E-05	9.13E-06	1.06E-05	1.11E-05	8.46E-06	6.55E-06	4.49E-06	1.85E-06
2	Head	2.47E-02	1.18E-02	5.37E-03	1.65E-03	5.10E-04	3.72E-04	4.47E-04	4.81E-04	3.92E-04	2.45E-04	1.62E-04	5.67E-05
3	Thorax	2.33E-01	8.76E-02	3.78E-02	1.13E-02	3.49E-03	2.53E-03	3.03E-03	3.20E-03	1.99E-03	1.09E-03	6.88E-04	2.34E-04
4	Abdomen	1.41E-02	9.72E-03	4.86E-03	1.56E-03	5.02E-04	3.67E-04	4.34E-04	4.72E-04	4.06E-04	3.12E-04	2.26E-04	9.09E-05
5	Muscle	2.01E-01	6.45E-02	2.68E-02	7.84E-03	2.42E-03	1.79E-03	2.10E-03	1.77E-03	8.23E-04	4.23E-04	2.60E-04	8.45E-05
6	Legs	9.68E-03	4.33E-03	1.98E-03	6.03E-04	1.88E-04	1.34E-04	1.58E-04	1.56E-04	1.16E-04	7.23E-05	4.99E-05	1.81E-05
7	Brain	4.53E-03	2.16E-03	1.00E-03	3.11E-04	9.66E-05	6.99E-05	8.28E-05	9.11E-05	7.41E-05	4.70E-05	2.97E-05	1.03E-05
8	Eyes	1.46E-03	7.95E-04	3.77E-04	1.18E-04	3.43E-05	2.69E-05	3.26E-05	3.24E-05	2.66E-05	1.92E-05	1.29E-05	4.53E-06
9	Crop	7.55E-03	3.01E-03	1.33E-03	4.02E-04	1.15E-04	7.62E-05	9.04E-05	9.90E-05	6.51E-05	3.81E-05	2.48E-05	8.89E-06
10	Rectum	2.90E-05	3.80E-05	2.26E-05	0.00E+00	--	--	--	2.52E-06	2.32E-06	1.68E-06	1.58E-06	6.77E-07
11	Venom sac	--	--	--	--	--	--	--	--	--	--	--	--
12	Heart	3.93E-03	1.39E-03	5.85E-04	1.69E-04	5.35E-05	3.92E-05	4.79E-05	4.47E-05	2.58E-05	1.56E-05	9.59E-06	3.32E-06
13	Intestine	2.59E-04	2.40E-04	1.31E-04	4.21E-05	1.41E-05	1.01E-05	1.19E-05	1.28E-05	1.26E-05	1.04E-05	7.52E-06	3.04E-06


Absorbed Dose Fraction,
Photon Source in Muscle
Absorbed Fraction (unitless)
Energy (MeV)
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
0
0.5
1
1.5
2
2.5
3
3.5
4
Antenna
Head
Thorax
Abdomen
Muscle
Legs
Brain
Eyes
Crop
Rectum
VenumSac
Heart
Midgut

Absorbed Fractions of Photon Energy
Source in Rectum
Energy (MeV)

	Target	0.010	0.015	0.02	0.030	0.050	0.100	0.200	0.500	1.000	1.500	2.000	4.000
1	Antenna	2.11E-05	1.93E-05	1.26E-05	--	--	--	--	--	--	6.20E-07	5.47E-07	0.00E+00
2	Head	6.54E-04	5.93E-04	3.30E-04	1.11E-04	3.70E-05	2.62E-05	3.13E-05	3.17E-05	2.67E-05	2.05E-05	1.68E-05	7.72E-06
3	Thorax	2.17E-03	2.34E-03	1.31E-03	4.42E-04	1.42E-04	1.07E-04	1.31E-04	1.38E-04	1.11E-04	9.23E-05	7.48E-05	3.43E-05
4	Abdomen	2.25E-01	8.56E-02	3.72E-02	1.12E-02	3.45E-03	2.52E-03	3.01E-03	2.99E-03	1.87E-03	1.13E-03	7.41E-04	2.63E-04
5	Muscle	3.77E-04	4.93E-04	2.77E-04	9.45E-05	3.12E-05	2.24E-05	2.84E-05	2.99E-05	2.65E-05	2.26E-05	1.84E-05	8.49E-06
6	Legs	7.18E-03	3.04E-03	1.35E-03	3.99E-04	1.24E-04	9.01E-05	1.06E-04	1.11E-04	7.68E-05	4.81E-05	3.24E-05	1.12E-05
7	Brain	3.33E-05	6.66E-05	4.14E-05	1.52E-05	--	3.77E-06	4.38E-06	4.91E-06	4.13E-06	3.62E-06	2.68E-06	1.39E-06
8	Eyes	2.64E-05	4.07E-05	2.67E-05	0.00E+00	--	--	--	0.00E+00	1.89E-06	1.61E-06	1.30E-06	7.35E-07
9	Crop	5.27E-04	4.26E-04	2.19E-04	6.99E-05	2.17E-05	1.46E-05	1.79E-05	1.79E-05	1.66E-05	1.34E-05	9.51E-06	3.79E-06
10	Rectum	9.28E-02	2.74E-02	1.12E-02	3.24E-03	9.86E-04	7.15E-04	7.98E-04	4.84E-04	1.58E-04	7.68E-05	4.63E-05	1.50E-05
11	Venom sac	8.21E-03	2.53E-03	1.05E-03	3.06E-04	9.32E-05	6.93E-05	8.14E-05	6.23E-05	2.22E-05	1.09E-05	6.76E-06	2.20E-06
12	Heart	1.74E-04	1.46E-04	7.36E-05	2.47E-05	6.57E-06	5.44E-06	5.82E-06	7.54E-06	6.47E-06	5.50E-06	4.16E-06	1.76E-06
13	Intestine	4.74E-03	2.00E-03	8.79E-04	2.70E-04	8.30E-05	6.01E-05	7.20E-05	7.73E-05	5.88E-05	3.58E-05	2.26E-05	8.02E-06


Absorbed Dose Fraction,
Photon Source in Rectum
Absorbed Fraction (unitless)
Energy (MeV)
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
0
0.5
1
1.5
2
2.5
3
3.5
4
Antenna
Head
Thorax
Abdomen
Muscle
Legs
Brain
Eyes
Crop
Rectum
VenumSac
Heart
Midgut

D. Absorbed Fractions in Honeybee using Organic Elemental Analysis: Electrons

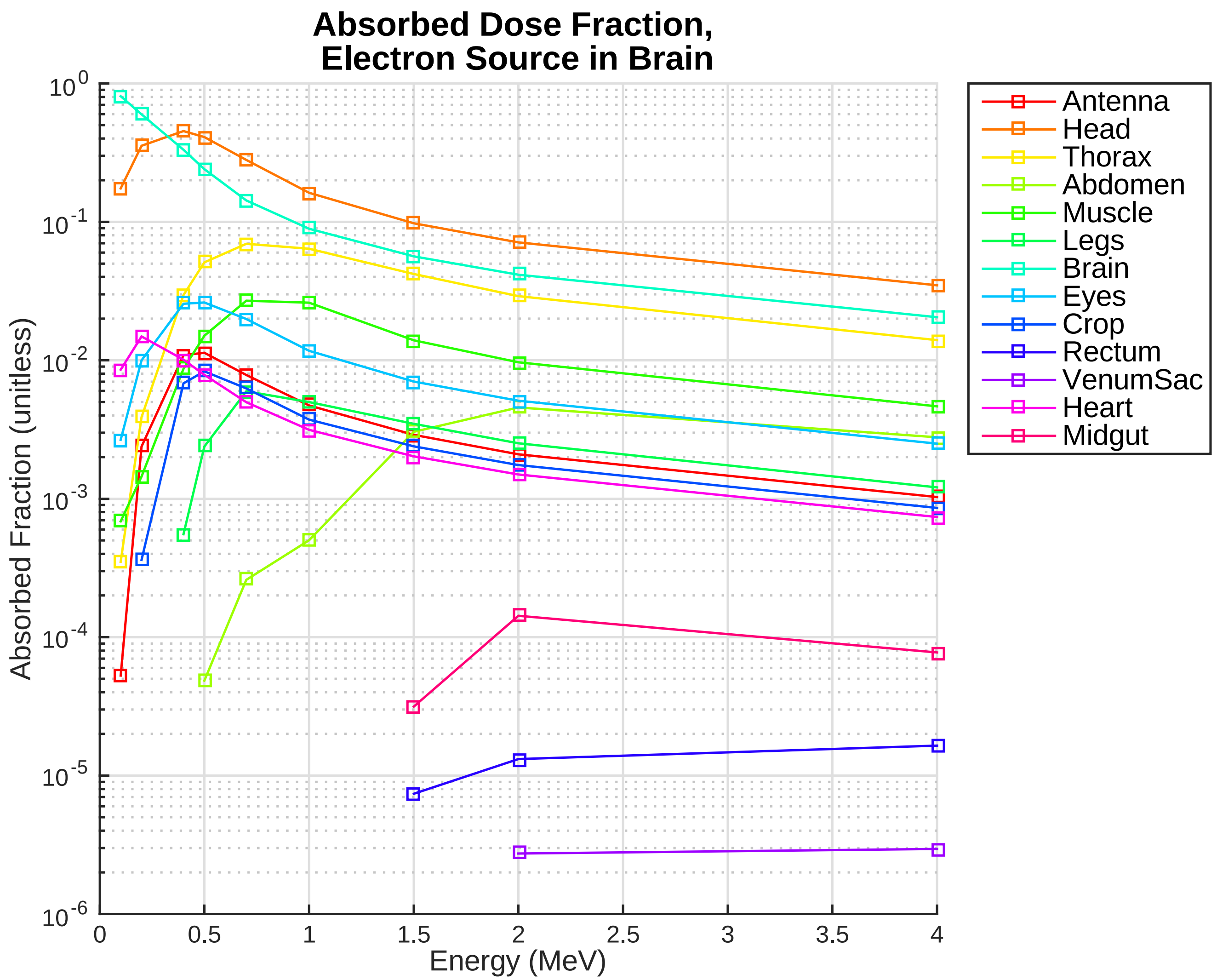
In this appendix the absorbed fraction of the voxel model are given using the measured four-component human tissue composition. These values are generated by MCNP with the option of PAR 3 (electrons) of different energies and are further processed by the MATLAB code. A graphs is also presented, representing the absorbed fraction as a function of energy with a source in a specific location

Absorbed Fractions of Electron Energy

Source in Brain

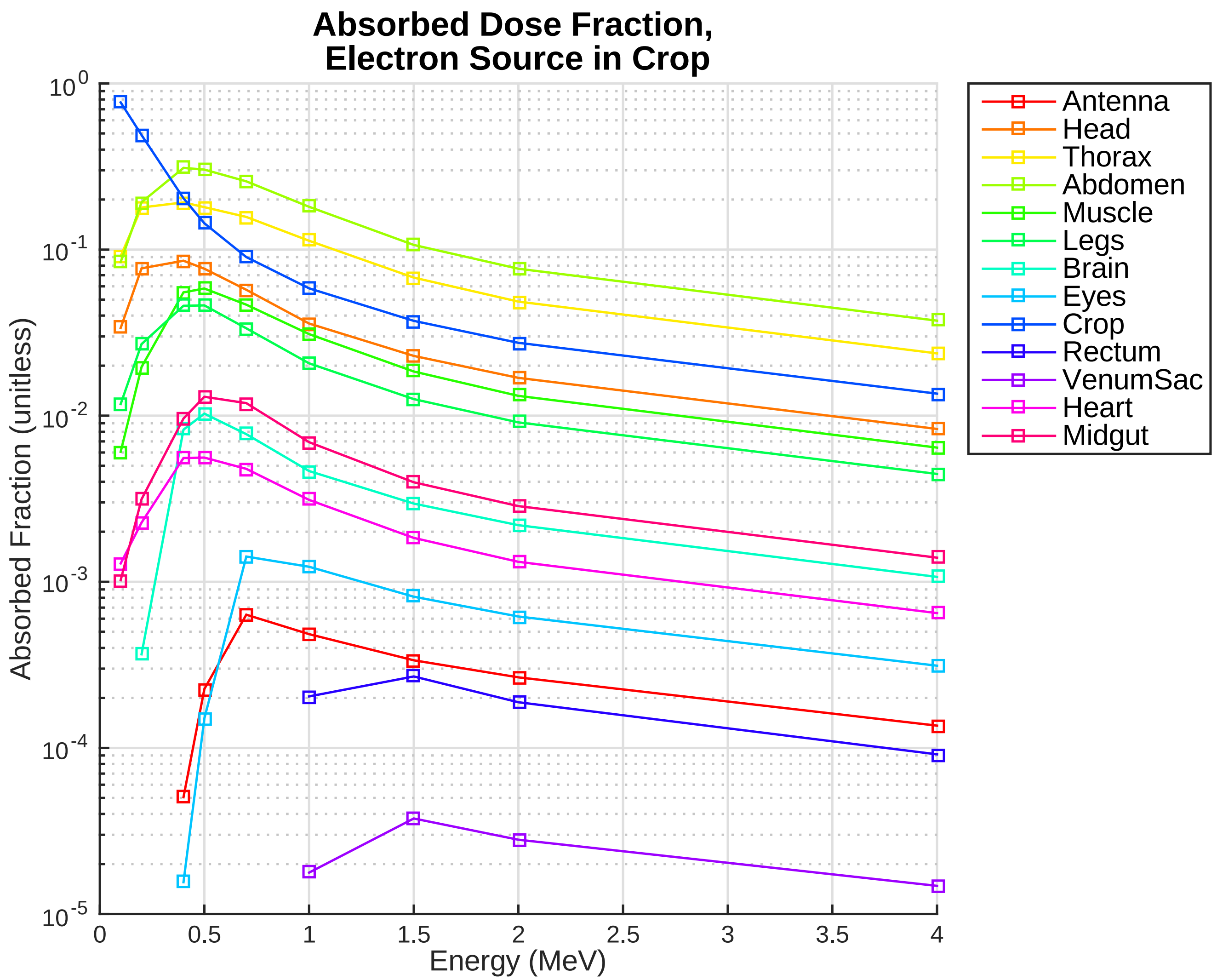
Energy (MeV)

	Target	0.100	0.200	0.400	0.500	0.700	1.000	1.500	2.000	4.000
1	Antenna	5.28E-05	2.38E-03	1.09E-02	1.13E-02	7.83E-03	4.72E-03	2.89E-03	2.09E-03	1.03E-03
2	Head	1.74E-01	3.54E-01	4.52E-01	4.10E-01	2.80E-01	1.62E-01	9.76E-02	7.12E-02	3.48E-02
3	Thorax	3.50E-04	3.89E-03	2.96E-02	5.10E-02	6.94E-02	6.39E-02	4.20E-02	2.91E-02	1.40E-02
4	Abdomen	0.00E+00	0.00E+00	0.00E+00	4.85E-05	2.60E-04	5.01E-04	3.04E-03	4.56E-03	2.78E-03
5	M	6.86E-04	1.45E-03	8.68E-03	1.50E-02	2.70E-02	2.61E-02	1.39E-02	9.69E-03	4.65E-03
6	Legs	0.00E+00	0.00E+00	5.53E-04	2.38E-03	5.98E-03	5.00E-03	3.48E-03	2.51E-03	1.21E-03
7	Brain	8.10E-01	5.97E-01	3.32E-01	2.40E-01	1.43E-01	8.93E-02	5.63E-02	4.15E-02	2.05E-02
8	Eyes	2.66E-03	1.00E-02	2.56E-02	2.62E-02	1.98E-02	1.17E-02	7.03E-03	5.10E-03	2.50E-03
9	Crop	0.00E+00	3.61E-04	6.82E-03	8.32E-03	6.26E-03	3.72E-03	2.39E-03	1.75E-03	8.59E-04
10	Rectum	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	7.39E-06	1.32E-05	1.64E-05
11	Venom sac	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.74E-06	2.95E-06
12	Heart	8.55E-03	1.49E-02	1.01E-02	7.87E-03	4.99E-03	3.14E-03	2.02E-03	1.50E-03	7.39E-04
13	Intestine	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.15E-05	1.43E-04	7.74E-05


Absorbed Dose Fraction,
Electron Source in Brain
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
Absorbed Fraction (unitless)
0
0.5
1
1.5
2
2.5
3
3.5
4
Energy (MeV)
Antenna
Head
Thorax
Abdomen
Muscle
Legs
Brain
Eyes
Crop
Rectum
VenumSac
Heart
Midgut

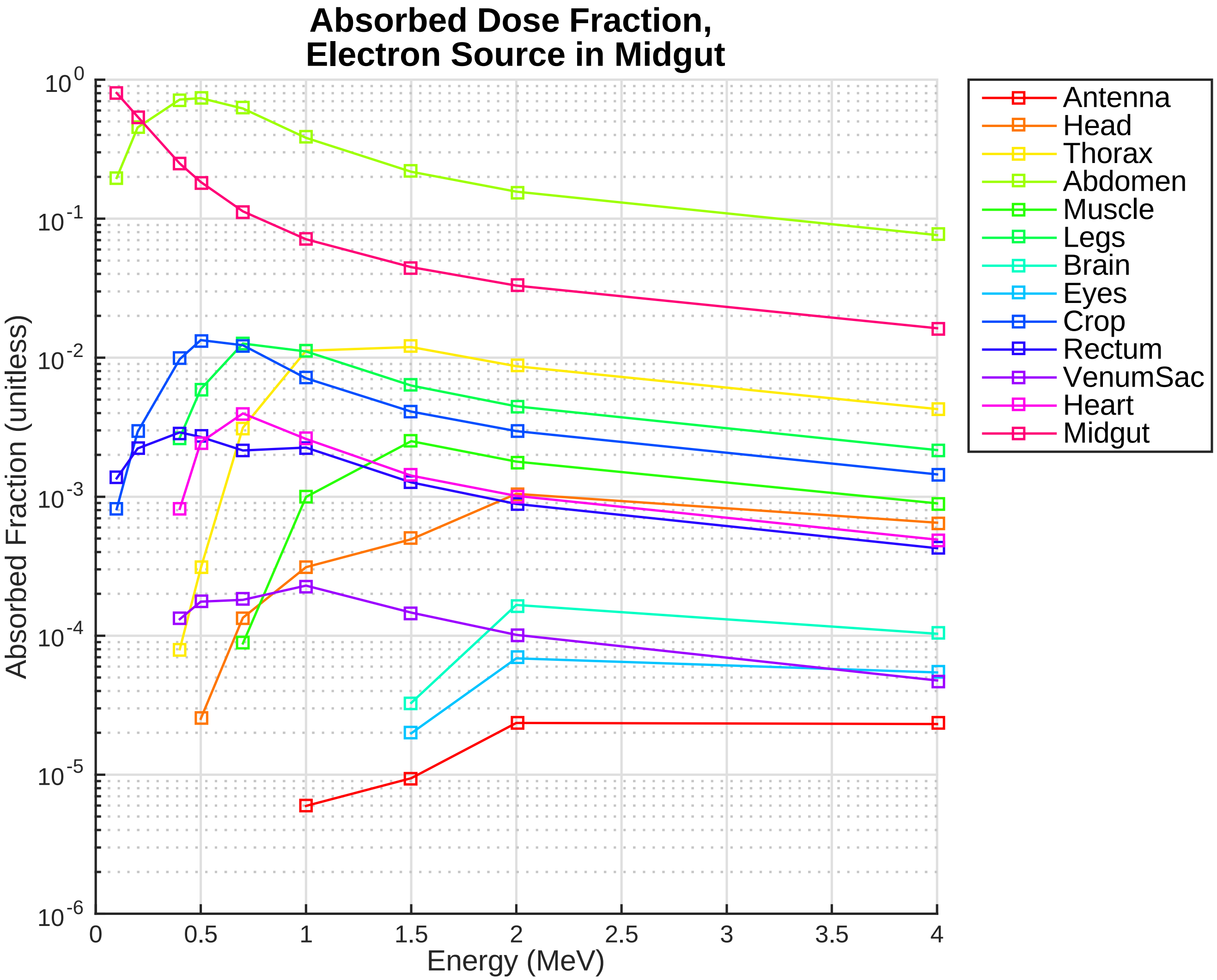
Absorbed Fractions of Electron Energy
Source in Crop
Energy (MeV)

	Target	0.100	0.200	0.400	0.500	0.700	1.000	1.500	2.000	4.000
1	Antenna	0.00E+00	0.00E+00	5.05E-05	2.27E-04	6.33E-04	4.84E-04	3.37E-04	2.66E-04	1.36E-04
2	Head	3.37E-02	7.71E-02	8.57E-02	7.67E-02	5.72E-02	3.59E-02	2.29E-02	1.69E-02	8.33E-03
3	Thorax	9.12E-02	1.79E-01	1.92E-01	1.80E-01	1.57E-01	1.13E-01	6.78E-02	4.86E-02	2.37E-02
4	Abdomen	8.42E-02	1.93E-01	3.10E-01	3.03E-01	2.57E-01	1.81E-01	1.07E-01	7.67E-02	3.74E-02
5	M	6.06E-03	1.96E-02	5.53E-02	5.83E-02	4.66E-02	3.10E-02	1.85E-02	1.32E-02	6.43E-03
6	Legs	1.18E-02	2.70E-02	4.59E-02	4.61E-02	3.36E-02	2.06E-02	1.26E-02	9.11E-03	4.46E-03
7	Brain	0.00E+00	3.66E-04	8.24E-03	1.03E-02	7.74E-03	4.65E-03	2.95E-03	2.19E-03	1.07E-03
8	Eyes	0.00E+00	0.00E+00	1.55E-05	1.51E-04	1.42E-03	1.23E-03	8.14E-04	6.18E-04	3.13E-04
9	Crop	7.69E-01	4.89E-01	2.04E-01	1.44E-01	9.01E-02	5.85E-02	3.72E-02	2.75E-02	1.36E-02
10	Rectum	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.04E-04	2.70E-04	1.88E-04	9.15E-05
11	Venom sac	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.78E-05	3.76E-05	2.80E-05	1.48E-05
12	Heart	1.29E-03	2.27E-03	5.57E-03	5.59E-03	4.78E-03	3.11E-03	1.84E-03	1.32E-03	6.49E-04
13	Intestine	1.02E-03	3.14E-03	9.60E-03	1.30E-02	1.19E-02	6.93E-03	3.97E-03	2.86E-03	1.40E-03


Absorbed Dose Fraction,
Electron Source in Crop
Absorbed Fraction (unitless)
Energy (MeV)
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
0
0.5
1
1.5
2
2.5
3
3.5
4
Antenna
Head
Thorax
Abdomen
Muscle
Legs
Brain
Eyes
Crop
Rectum
VenumSac
Heart
Midgut

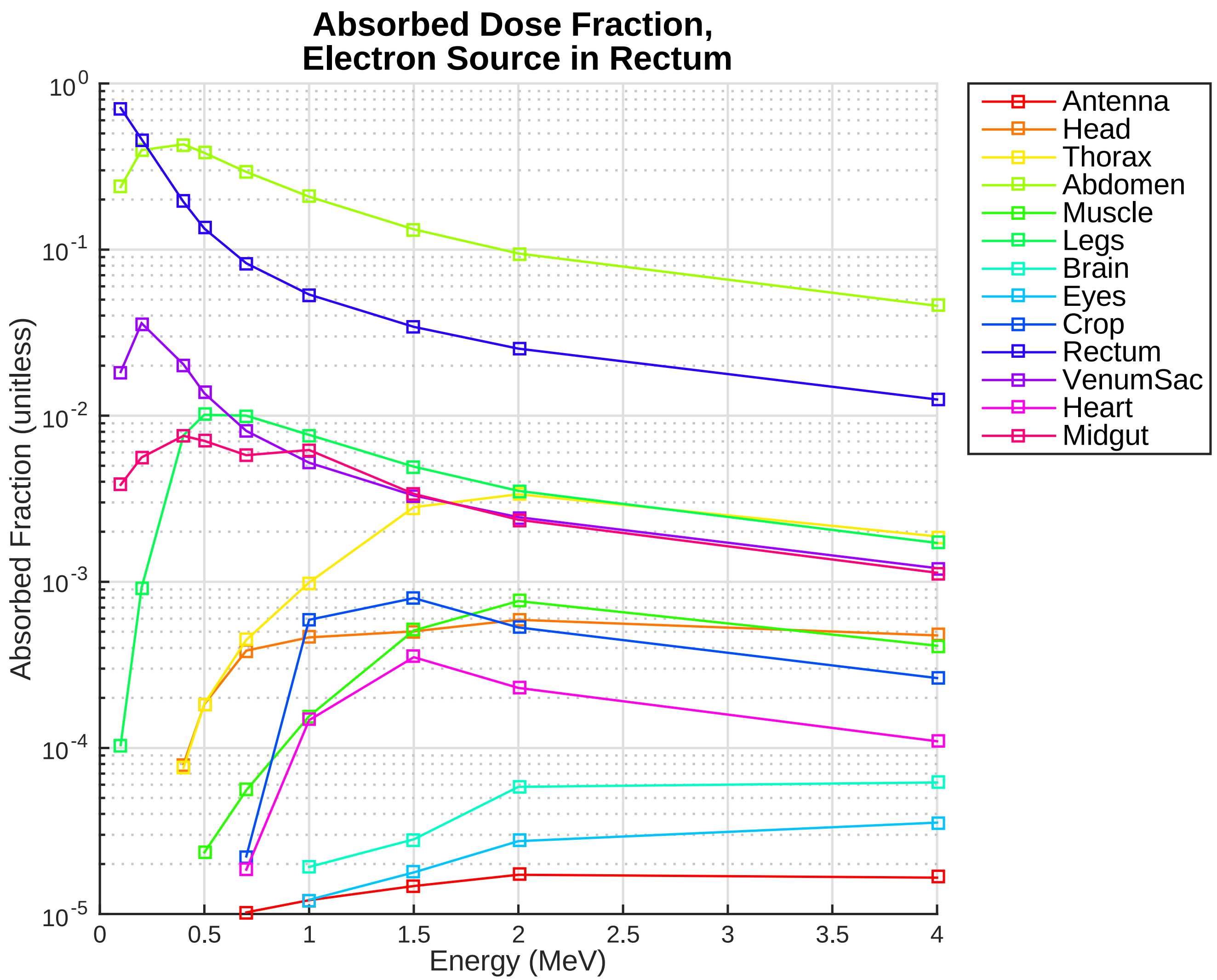
Absorbed Fractions of Electron Energy
Source in Intestine
Energy (MeV)

	Target	0.100	0.200	0.400	0.500	0.700	1.000	1.500	2.000	4.000
1	Antenna	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.97E-06	9.45E-06	2.36E-05	2.32E-05
2	Head	0.00E+00	0.00E+00	0.00E+00	2.53E-05	1.35E-04	3.11E-04	4.95E-04	1.05E-03	6.49E-04
3	Thorax	0.00E+00	0.00E+00	7.99E-05	3.06E-04	3.14E-03	1.12E-02	1.19E-02	8.69E-03	4.27E-03
4	Abdomen	1.96E-01	4.53E-01	7.19E-01	7.36E-01	6.21E-01	3.81E-01	2.17E-01	1.56E-01	7.61E-02
5	M	0.00E+00	0.00E+00	0.00E+00	0.00E+00	8.81E-05	9.97E-04	2.51E-03	1.79E-03	8.95E-04
6	Legs	0.00E+00	0.00E+00	2.66E-03	5.93E-03	1.26E-02	1.11E-02	6.30E-03	4.47E-03	2.17E-03
7	Brain	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.29E-05	1.66E-04	1.03E-04
8	Eyes	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.99E-05	6.87E-05	5.44E-05
9	Crop	8.13E-04	2.93E-03	9.76E-03	1.34E-02	1.23E-02	7.12E-03	4.10E-03	2.96E-03	1.45E-03
10	Rectum	1.35E-03	2.22E-03	2.90E-03	2.69E-03	2.15E-03	2.26E-03	1.27E-03	8.88E-04	4.25E-04
11	Venom sac	0.00E+00	0.00E+00	1.32E-04	1.76E-04	1.81E-04	2.29E-04	1.47E-04	1.01E-04	4.77E-05
12	Heart	0.00E+00	0.00E+00	8.18E-04	2.47E-03	3.98E-03	2.60E-03	1.42E-03	1.01E-03	4.91E-04
13	Intestine	8.01E-01	5.41E-01	2.49E-01	1.84E-01	1.13E-01	7.11E-02	4.48E-02	3.30E-02	1.63E-02


Absorbed Dose Fraction,
Electron Source in Midgut
Absorbed Fraction (unitless)
Energy (MeV)
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
0
0.5
1
1.5
2
2.5
3
3.5
4
Antenna
Head
Thorax
Abdomen
Muscle
Legs
Brain
Eyes
Crop
Rectum
VenumSac
Heart
Midgut

Absorbed Fractions of Electron Energy
Source in Muscle
Energy (MeV)

	Target	0.100	0.200	0.400	0.500	0.700	1.000	1.500	2.000	4.000
1	Antenna	0.00E+00	0.00E+00	2.11E-05	3.37E-05	1.49E-04	5.47E-04	4.66E-04	3.32E-04	1.63E-04
2	Head	1.16E-03	3.07E-03	1.42E-02	2.26E-02	3.70E-02	3.65E-02	2.05E-02	1.44E-02	6.92E-03
3	Thorax	1.23E-01	2.56E-01	4.21E-01	4.41E-01	3.76E-01	2.30E-01	1.31E-01	9.45E-02	4.60E-02
4	Abdomen	0.00E+00	7.07E-05	9.86E-04	3.11E-03	9.29E-03	1.79E-02	1.85E-02	1.38E-02	6.75E-03
5	M	8.63E-01	7.06E-01	4.56E-01	3.66E-01	2.40E-01	1.45E-01	8.85E-02	6.48E-02	3.18E-02
6	Legs	8.22E-04	2.75E-03	8.80E-03	1.13E-02	1.41E-02	1.15E-02	7.00E-03	5.04E-03	2.45E-03
7	Brain	1.53E-04	4.09E-04	2.34E-03	4.09E-03	7.35E-03	7.11E-03	3.78E-03	2.64E-03	1.27E-03
8	Eyes	0.00E+00	2.79E-05	1.61E-04	4.36E-04	1.38E-03	2.23E-03	1.44E-03	1.02E-03	4.94E-04
9	Crop	1.52E-03	4.57E-03	1.22E-02	1.28E-02	1.02E-02	6.74E-03	3.99E-03	2.88E-03	1.40E-03
10	Rectum	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.35E-05	3.59E-05	5.59E-05	3.05E-05
11	Venom sac	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.78E-06	8.83E-06	5.38E-06
12	Heart	6.02E-03	1.10E-02	8.11E-03	6.62E-03	4.84E-03	3.33E-03	2.04E-03	1.48E-03	7.19E-04
13	Intestine	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.80E-05	2.11E-04	5.43E-04	3.67E-04	1.82E-04


Absorbed Dose Fraction,
Electron Source in Rectum
Absorbed Fraction (unitless)
Energy (MeV)
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
0
0.5
1
1.5
2
2.5
3
3.5
4
Antenna
Head
Thorax
Abdomen
Muscle
Legs
Brain
Eyes
Crop
Rectum
VenumSac
Heart
Midgut

E. Dose Conversion Factors in Honeybee with Organic Elemental Analysis

In this appendix the Dose Conversion Factors are presented. This are calculated using the absorbed fractions form Appendix C, Appendix D and Equation .

Dose conversion factors [μGy-kg-d^{-1}-Bq^{-1}]

Cs-137

Source \ Target	Antenna	Head	Thorax	Abdomen	Muscle	Legs	Brain	Eyes	Crop	Rectum	Venom sac	Heart	Intestine
Brain	7.46E-06	8.27E-04	2.22E-05	1.47E-06	7.76E-06	7.20E-07	1.58E-03	2.63E-05	3.00E-06	0.00E+00	0.00E+00	3.26E-05	4.88E-08
Crop	7.46E-08	1.74E-04	4.12E-04	4.71E-04	5.46E-05	6.61E-05	3.54E-06	1.58E-07	1.34E-03	4.71E-08	2.08E-09	6.41E-06	9.19E-06
Intestine	3.04E-09	3.69E-07	2.25E-06	1.10E-03	4.92E-07	1.82E-06	6.31E-08	2.76E-08	8.76E-06	5.48E-06	6.37E-08	4.91E-07	1.46E-03
Muscle	8.59E-08	1.33E-05	6.33E-04	3.91E-06	1.83E-03	8.60E-06	2.10E-06	3.29E-07	1.25E-05	1.91E-08	0.00E+00	2.41E-05	9.91E-08
Rectum	0.00E+00	2.57E-07	1.03E-06	9.34E-04	2.24E-07	4.53E-06	3.63E-08	0.00E+00	1.36E-07	1.26E-03	7.58E-05	5.60E-08	1.42E-05

Sr-90

Source \ Target	Antenna	Head	Thorax	Abdomen	Muscle	Legs	Brain	Eyes	Crop	Rectum	Venom sac	Heart	Intestine
Brain	5.47E-06	8.66E-04	9.02E-06	0.00E+00	3.53E-06	0.00E+00	1.62E-03	2.37E-05	8.28E-07	0.00E+00	0.00E+00	3.67E-05	0.00E+00
Crop	0.00E+00	1.87E-04	4.39E-04	4.68E-04	4.69E-05	6.55E-05	8.39E-07	0.00E+00	1.36E-03	0.00E+00	0.00E+00	5.61E-06	7.51E-06
Intestine	0.00E+00	0.00E+00	0.00E+00	1.10E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	6.95E-06	5.51E-06	0.00E+00	0.00E+00	1.49E-03
Muscle	0.00E+00	7.40E-06	6.25E-04	1.62E-07	1.89E-03	6.55E-06	9.84E-07	6.39E-08	1.10E-05	0.00E+00	0.00E+00	2.70E-05	0.00E+00
Rectum	0.00E+00	0.00E+00	0.00E+00	9.82E-04	0.00E+00	2.14E-06	0.00E+00	0.00E+00	0.00E+00	1.28E-03	8.82E-05	0.00E+00	1.40E-05

Y-90

Source \ Target	Antenna	Head	Thorax	Abdomen	Muscle	Legs	Brain	Eyes	Crop	Rectum	Venom sac	Heart	Intestine
Brain	7.58E-05	2.70E-03	7.19E-04	3.24E-06	2.82E-04	6.08E-05	1.39E-03	1.92E-04	6.05E-05	0.00E+00	0.00E+00	4.86E-05	0.00E+00
Crop	6.35E-06	5.57E-04	1.56E-03	2.55E-03	4.57E-04	3.26E-04	7.49E-05	1.45E-05	8.81E-04	4.30E-07	3.74E-08	4.68E-05	1.15E-04

Intestine	1.26E-08	1.79E-06	5.00E-05	6.03E-03	2.84E-06	1.30E-04	0.00E+00	0.00E+00	1.18E-04	2.28E-05	2.01E-06	3.89E-05	1.10E-03
Muscle	2.40E-06	3.88E-04	3.65E-03	1.16E-04	2.33E-03	1.43E-04	7.68E-05	1.63E-05	9.96E-05	2.84E-08	0.00E+00	4.77E-05	5.94E-07
Rectum	1.12E-07	4.22E-06	5.84E-06	2.91E-03	7.94E-07	1.00E-04	4.04E-08	2.56E-08	1.43E-06	8.08E-04	7.92E-05	4.65E-07	6.17E-05

Co-60

Target / Source	Antenna	Head	Thorax	Abdomen	Muscle	Legs	Brain	Eyes	Crop	Rectum	Venom sac	Heart	Intestine
Brain	1.27E-06	3.03E-04	2.30E-05	5.28E-06	8.86E-06	1.86E-06	1.18E-03	7.11E-06	1.17E-06	0.00E+00	0.00E+00	1.37E-05	1.78E-07
Crop	1.93E-07	6.21E-05	1.70E-04	1.79E-04	1.83E-05	2.31E-05	1.48E-06	5.00E-07	1.11E-03	1.72E-07	2.56E-08	2.79E-06	3.53E-06
Intestine	4.01E-08	1.29E-06	8.03E-06	3.97E-04	1.88E-06	3.19E-06	2.24E-07	1.02E-07	3.23E-06	2.66E-06	8.06E-08	7.58E-07	1.16E-03
Muscle	2.59E-07	1.28E-05	2.45E-04	1.24E-05	1.27E-03	4.61E-06	2.33E-06	7.93E-07	4.27E-06	6.89E-08	0.00E+00	9.97E-06	3.97E-07
Rectum	1.11E-08	8.14E-07	3.52E-06	4.14E-04	8.51E-07	2.37E-06	1.34E-07	6.04E-08	5.17E-07	1.02E-03	2.90E-05	2.07E-07	7.40E-06

I-131

Target / Source	Antenna	Head	Thorax	Abdomen	Muscle	Legs	Brain	Eyes	Crop	Rectum	Venom sac	Heart	Intestine
Brain	6.59E-06	9.32E-04	1.54E-05	9.89E-07	5.60E-06	4.04E-07	1.61E-03	2.69E-05	1.39E-06	0.00E+00	0.00E+00	3.88E-05	3.22E-08
Crop	4.70E-08	2.02E-04	4.73E-04	5.14E-04	5.36E-05	7.17E-05	1.52E-06	1.05E-07	1.32E-03	3.17E-08	2.08E-10	6.22E-06	8.74E-06
Intestine	3.04E-10	2.56E-07	1.49E-06	1.20E-03	3.21E-07	7.92E-07	4.12E-08	1.97E-08	8.19E-06	5.95E-06	2.03E-08	1.95E-07	1.46E-03
Muscle	5.67E-08	1.06E-05	6.83E-04	2.56E-06	1.89E-03	8.01E-06	1.56E-06	2.42E-07	1.24E-05	7.85E-09	0.00E+00	2.87E-05	6.46E-08
Rectum	0.00E+00	1.65E-07	6.99E-07	1.05E-03	1.51E-07	3.08E-06	2.42E-08	0.00E+00	9.28E-08	1.25E-03	9.33E-05	3.54E-08	1.51E-05

Cl-36

Target / Source	Antenna	Head	Thorax	Abdomen	Muscle	Legs	Brain	Eyes	Crop	Rectum	Venom sac	Heart	Intestine
Brain	1.26E-05	1.19E-03	2.75E-05	2.65E-08	8.88E-06	3.31E-07	1.76E-03	4.12E-05	4.91E-06	0.00E+00	0.00E+00	4.50E-05	8.82E-10
Crop	3.04E-08	2.52E-04	5.82E-04	6.87E-04	8.38E-05	9.76E-05	5.76E-06	1.18E-08	1.40E-03	8.43E-10	2.45E-12	9.21E-06	1.38E-05
Intestine	3.59E-12	6.72E-09	8.62E-08	1.61E-03	8.66E-09	1.56E-06	1.14E-09	4.85E-10	1.34E-05	7.52E-06	7.69E-08	4.79E-07	1.56E-03
Muscle	1.37E-08	1.64E-05	9.18E-04	8.21E-07	2.12E-03	1.23E-05	2.44E-06	1.71E-07	1.91E-05	3.38E-10	0.00E+00	3.36E-05	1.72E-09

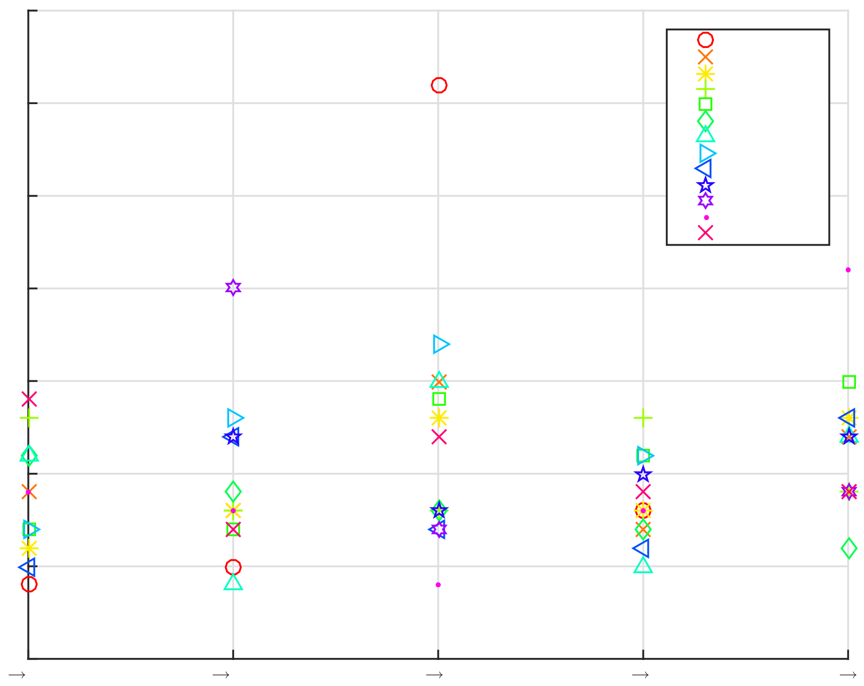
Rectum	0.00E+00	5.05E-08	6.26E-08	1.29E-03	4.00E-09	6.85E-06	6.58E-10	0.00E+00	2.40E-09	1.32E-03	1.06E-04	1.01E-09	1.91E-05

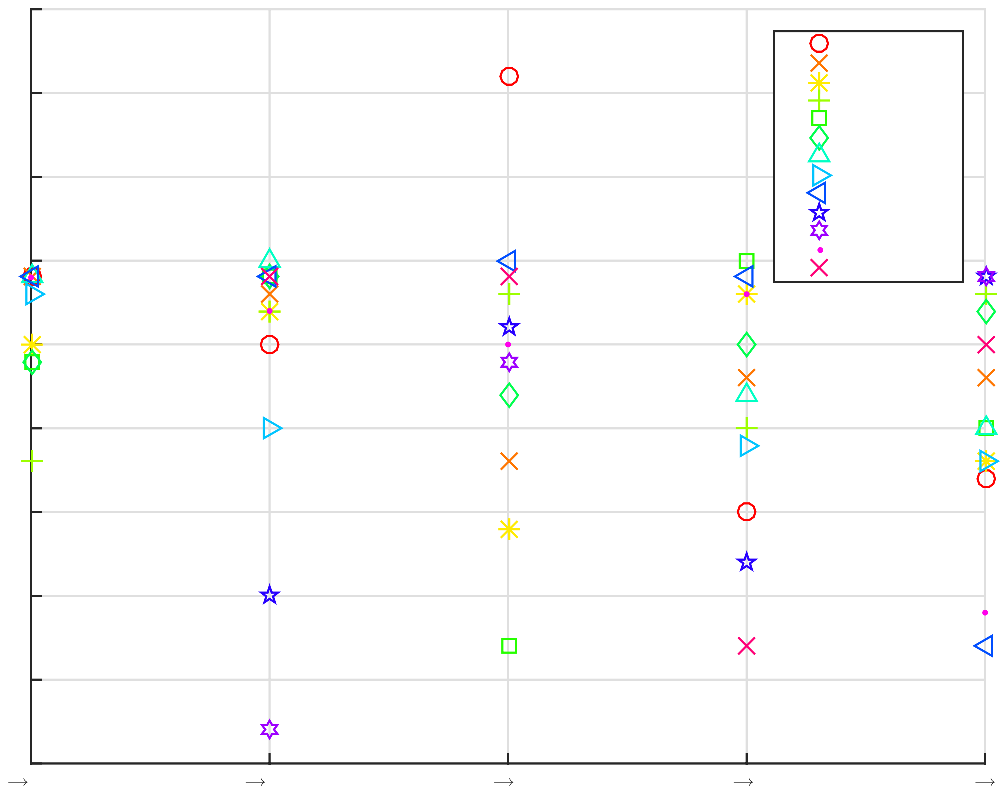
Ra-226

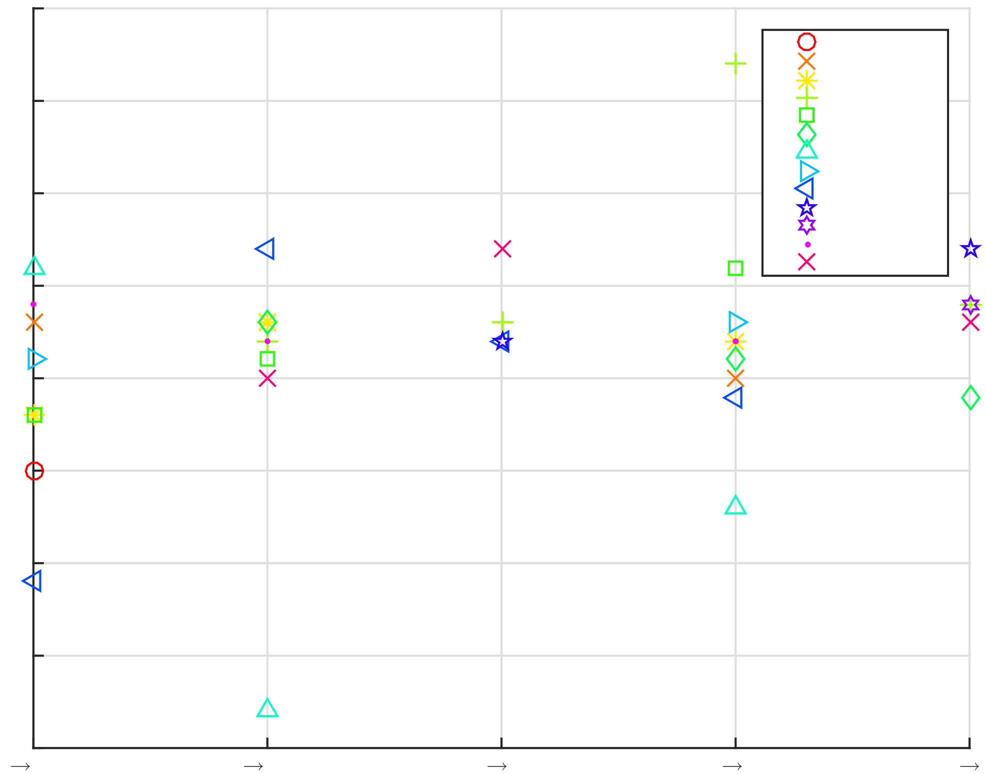
Target / Source	Antenna	Head	Thorax	Abdomen	Muscle	Legs	Brain	Eyes	Crop	Rectum	Venom sac	Heart	Intestine
Brain	5.99E-09	2.09E-07	8.07E-08	1.64E-08	2.73E-08	6.82E-09	1.21E-07	1.47E-08	4.98E-09	0.00E+00	0.00E+00	4.51E-09	5.11E-10
Crop	8.85E-10	4.99E-08	1.41E-07	2.23E-07	3.78E-08	2.64E-08	6.30E-09	1.76E-09	7.92E-08	5.35E-10	0.00E+00	3.98E-09	8.54E-09
Intestine	0.00E+00	4.41E-09	2.49E-08	4.52E-07	5.24E-09	1.23E-08	6.45E-10	3.70E-10	8.64E-09	2.60E-09	2.38E-10	2.88E-09	9.54E-08
Muscle	9.64E-10	4.03E-08	2.73E-07	3.92E-08	1.90E-07	1.43E-08	7.48E-09	2.94E-09	8.17E-09	0.00E+00	0.00E+00	4.32E-09	1.07E-09
Rectum	0.00E+00	2.82E-09	1.18E-08	2.72E-07	2.55E-09	9.61E-09	3.97E-10	0.00E+00	1.61E-09	7.26E-08	7.37E-09	5.33E-10	6.50E-09

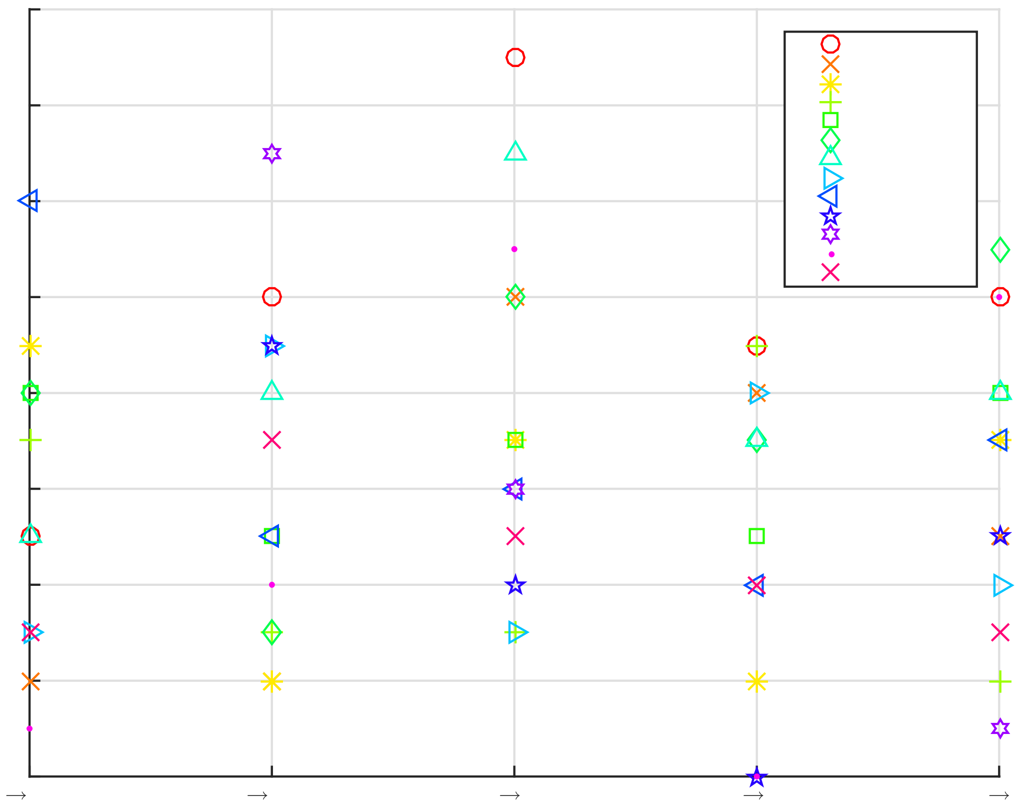
F. Elemental Impact Analysis

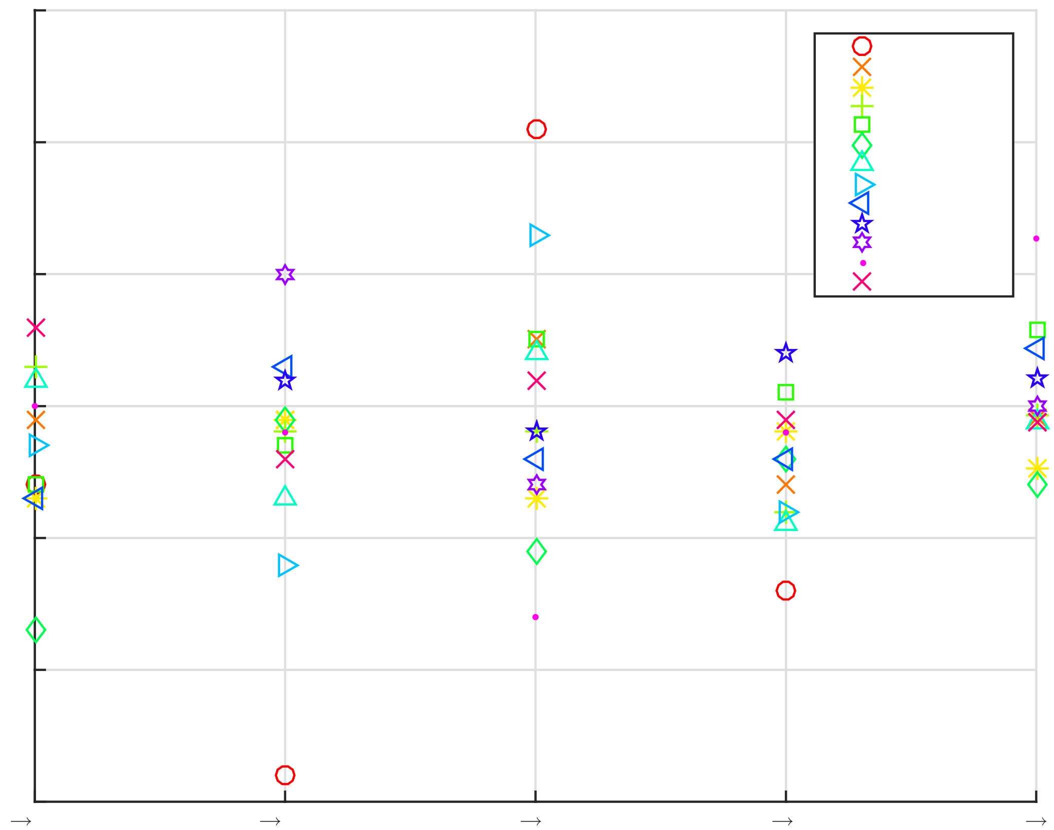
In this appendix the ration (Equation) between the dose conversion factors of both voxel models is plotted. A ratio of ones represents no difference between models or that the impact of elemental composition in negligible. A ratio grater than one respresent that the ICRU four component human tissue composition in more conservative than the measured four component tissue compositon. The opposite can be said when the ration is less than one.

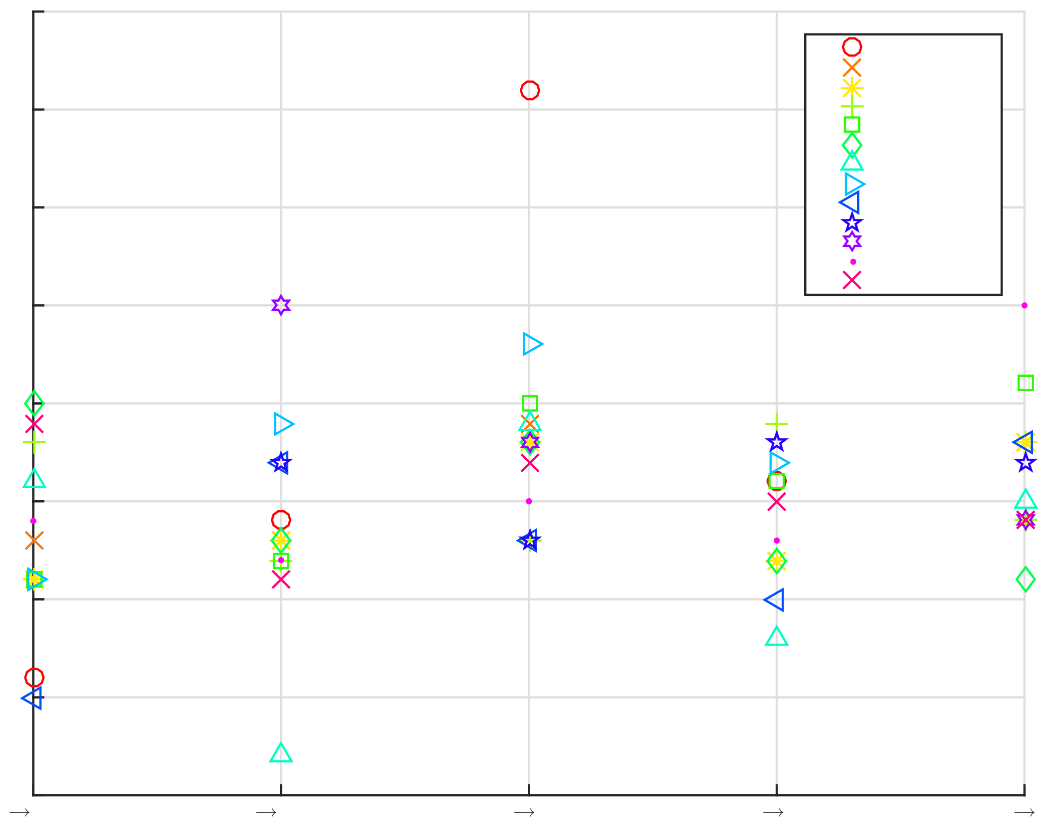


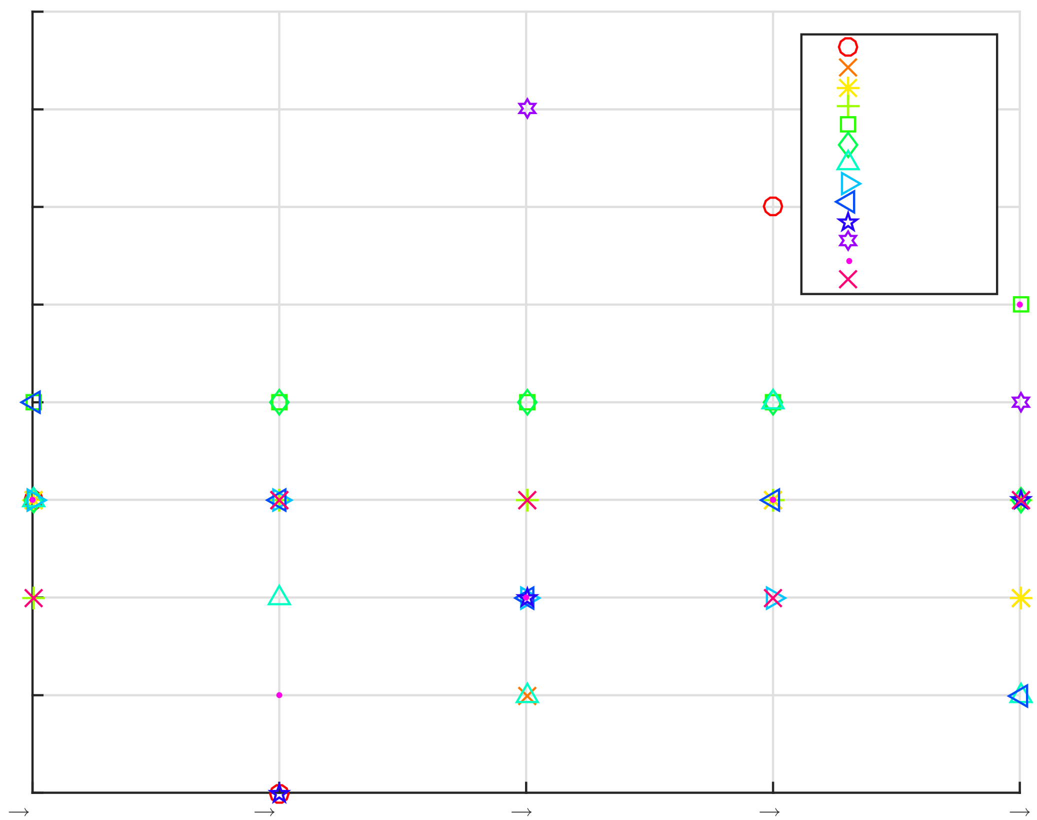












G. Organic Elemental Analysis Results

In this appendix, the results of the elemental analysis are provided for each of the seven different tissues, where the area under the curve shown in Figure **4-4** Chromatogram example represents the mass of the specific element in the sample. The oxygen content is calculated by weight difference between the dried sample and the analyzed sample.

a. Venom Sac

Tray	Sample Code	Sample Amount	Area [mV.s]			Weight [mg]				Weight [%]			
Location			Nitrogen	Carbon	Hydrogen	Nitrogen	Carbon	Hydrogen	Oxygen	Nitrogen	Carbon	Hydrogen	Oxygen
	Venom Sac + Stinger												
A1	20150428_006_VenomSac	0.466	33	382	171	0.054	0.227	0.032	0.153	11.6	48.6	6.8	33.0
A2	20150429_013_VenomSac	0.48	33	395	192	0.055	0.234	0.036	0.155	11.6	48.8	7.4	32.2
A3	20150429_021_VenomSac	0.716	48	600	281	0.079	0.359	0.053	0.225	11.1	50.2	7.3	31.4
A4	20150429_029_VenomSac	0.377	26	308	134	0.042	0.182	0.025	0.128	11.3	48.3	6.6	33.9
A5	20150429_036_VenomSac	0.367	24	308	129	0.040	0.182	0.024	0.121	10.8	49.6	6.5	33.2
A1	20150508_004_VenomSac	0.36	23.696	291.824	110.948	0.04	0.174	0.02	0.126	11.17	48.41	5.67	34.8
A2	20150508_011_VenomSac	0.358	23.315	284.316	111.043	0.04	0.17	0.02	0.128	11.05	47.41	5.7	35.8
A3	20150508_019_VenomSac	0.424	27.252	337.794	155.253	0.046	0.202	0.029	0.147	10.9	47.64	6.79	34.7
A4	20150508_026_VenomSac	0.275	17.508	218.835	85.835	0.03	0.13	0.016	0.099	10.82	47.42	5.68	36.1
A5	20150509_034_VenomSac	0.29	17.771	228.351	92.85	0.03	0.136	0.017	0.107	10.41	46.94	5.85	36.8
A6	20150509_042_VenomSac	0.371	25.796	311.727	131.737	0.044	0.186	0.024	0.117	11.8	50.2	6.56	31.4
A7	20150510_004_VenomSac	0.492	32.578	387.953	143.285	0.059	0.242	0.03	0.161	11.99	49.19	6.10	32.7
A8	20150510_011_VenomSac	0.172	10.64	136.357	38.47	0.019	0.084	0.01	0.059	11.05	48.84	5.81	34.3
A9	20150510_019_VenomSac	0.404	19.528	335.386	156.731	0.035	0.209	0.033	0.127	8.66	51.73	8.17	31.4
A10	20150510_026_VenomSac	0.456	29.437	358.533	171.272	0.053	0.224	0.036	0.143	11.62	49.12	7.89	31.4
A11	20150511_034_VenomSac	0.226	14.103	183.16	63.094	0.026	0.113	0.015	0.072	11.50	50.00	6.64	31.9
A12	20150511_042_VenomSac	0.341	21.958	269.445	114.325	0.04	0.168	0.025	0.108	11.73	49.27	7.33	31.7

b. Intestine

Tray Location	Sample Code	Sample Amount	Area [mV.s] Nitrogen	Carbon	Hydrogen	Weight [mg] Nitrogen	Carbon	Hydrogen	Oxygen	Weight [%] Nitrogen	Carbon	Hydrogen	Oxygen
	Intestine												
B1	20150428_007_Intestine	0.489	27	389	180	0.044	0.231	0.033	0.181	9.0	47.3	6.8	36.9
B2	20150429_014_Intestine	0.403	23	335	150	0.038	0.199	0.028	0.138	9.6	49.3	6.9	34.3
B3	20150429_022_Intestine	0.665	27	536	261	0.045	0.320	0.049	0.251	6.7	48.2	7.3	37.8
B4	20150429_030_Intestine	0.618	23	491	246	0.037	0.293	0.046	0.242	6.1	47.4	7.4	39.2
B5	20150429_037_Intestine	0.636	22	538	250	0.037	0.321	0.047	0.231	5.9	50.5	7.3	36.3
C1	20150508_006_Intestine	1.032	36.707	789.474	391.82	0.062	0.479	0.074	0.417	6.03	46.38	7.14	40.5
C2	20150508_013_Intestine	0.463	15.472	369.948	165.872	0.026	0.221	0.031	0.185	5.68	47.82	6.66	39.8
C3	20150508_021_Intestine	0.824	33.38	603.735	274.863	0.057	0.364	0.052	0.351	6.87	44.16	6.25	42.7
C4	20150509_029_Intestine	0.523	19.943	398.263	182.261	0.034	0.239	0.034	0.216	6.48	45.61	6.49	41.4
C5	20150509_036_Intestine	0.327	9.394	286.824	118.574	0.016	0.171	0.022	0.118	4.9	52.37	6.68	36.1
C6	20150509_044_Intestine	0.34	10.778	277.99	117.247	0.018	0.166	0.022	0.134	5.4	48.8	6.35	39.5
C7	20150510_006_Intestine	0.316	9.79	260.065	112.852	0.018	0.162	0.024	0.112	5.70	51.27	7.59	35.4
C8	20150510_013_Intestine	0.58	17.544	467.82	212.646	0.032	0.293	0.044	0.211	5.52	50.52	7.59	36.4
C9	20150510_021_Intestine	0.588	17.66	471.294	213.204	0.032	0.295	0.044	0.217	5.44	50.17	7.48	36.9
C10	20150511_029_Intestine	1.142	29.553	948.729	434.373	0.053	0.596	0.088	0.405	4.64	52.19	7.71	35.5
C11	20150511_036_Intestine	0.471	18.601	378.02	167.625	0.034	0.236	0.035	0.166	7.22	50.11	7.43	35.2
C12	20150511_044_Intestine	0.36	7.104	305.175	131.466	0.013	0.19	0.028	0.129	3.61	52.78	7.78	35.8

c. Rectum

Tray	Sample Code	Sample Amount	Area [mV.s]			Weight [mg]				Weight [%]			
Location			Nitrogen	Carbon	Hydrogen	Nitrogen	Carbon	Hydrogen	Oxygen	Nitrogen	Carbon	Hydrogen	Oxygen
	Rectum												
C1	20150428_008_Rectum	0.814	34	662	312	0.057	0.398	0.058	0.301	7.0	48.9	7.2	37.0
C2	20150429_015_Rectum	0.735	31	593	273	0.051	0.355	0.051	0.278	6.9	48.3	7.0	37.9
C3	20150429_023_Rectum	0.439	17	360	156	0.029	0.214	0.029	0.167	6.5	48.6	6.6	38.3
C4	20150429_031_Rectum	0.66	21	531	243	0.034	0.317	0.045	0.264	5.2	48.1	6.9	39.9
C5	20150429_039_Rectum	0.688	22	554	254	0.036	0.332	0.047	0.273	5.2	48.2	6.9	39.7
B1	20150508_005_Rectum	1.103	24.186	914.533	419.987	0.041	0.557	0.079	0.426	3.72	50.47	7.17	38.6
B2	20150508_012_Rectum	1.032	22.768	860.952	399.445	0.039	0.523	0.075	0.395	3.74	50.7	7.28	38.3
B3	20150508_020_Rectum	0.361	9.409	311.527	113.67	0.016	0.186	0.021	0.138	4.44	51.56	5.79	38.2
B4	20150508_027_Rectum	0.529	12.362	440.944	175.305	0.021	0.264	0.033	0.211	3.98	49.99	6.16	39.9
B5	20150509_035_Rectum	0.412	9.471	353.738	148.526	0.016	0.212	0.028	0.156	3.92	51.36	6.68	38.0
B6	20150509_043_Rectum	0.53	11.577	442.889	175.571	0.02	0.266	0.033	0.211	3.72	50.12	6.16	40.0
B7	20150510_005_Rectum	0.369	7.898	322.463	130.95	0.014	0.201	0.028	0.126	3.79	54.47	7.59	34.1
B8	20150510_012_Rectum	1.004	22.117	843.469	386.969	0.04	0.53	0.078	0.356	3.98	52.79	7.77	35.5
B9	20150510_020_Rectum	0.814	18.125	679.875	295.659	0.033	0.426	0.06	0.295	4.05	52.33	7.37	36.2
B10	20150511_027_Rectum	0.912	20.021	771.134	339.814	0.036	0.484	0.069	0.323	3.95	53.07	7.57	35.4
B11	20150511_035_Rectum	0.96	21.361	801.733	359.466	0.039	0.503	0.073	0.345	4.06	52.40	7.60	35.9
B12	20150511_043_Rectum	0.571	13.53	480.696	205.48	0.024	0.301	0.043	0.203	4.20	52.71	7.53	35.6

d. Exoskeleton

Tray Location	Sample Code	Sample Amount	Area [mV.s]			Weight [mg]				Weight [%]			
			Nitrogen	Carbon	Hydrogen	Nitrogen	Carbon	Hydrogen	Oxygen	Nitrogen	Carbon	Hydrogen	Oxygen
	Exoskeleton												
D1	20150428_009_Exoskeleton	0.439	26	369	158	0.042	0.219	0.029	0.149	9.6	49.9	6.7	33.8
D2	20150429_017_Exoskeleton	1.119	58	1025	525	0.096	0.624	0.099	0.300	8.6	55.8	8.8	26.8
D3	20150429_024_Exoskeleton	0.922	55	777	366	0.092	0.469	0.069	0.292	10.0	50.9	7.4	31.7
D4	20150429_032_Exoskeleton	0.305	23	257	95	0.037	0.152	0.017	0.099	12.3	49.7	5.7	32.3
D5	20150429_040_Exoskeleton	1.084	30	786	404	0.050	0.474	0.076	0.484	4.6	43.7	7.0	44.7
E1	20150508_008_Exoskeleton	0.733	40.343	592.678	267.026	0.068	0.357	0.05	0.258	9.33	48.72	6.82	35.1
E2	20150508_016_Exoskeleton	0.409	22.109	337.485	147.513	0.038	0.202	0.027	0.142	9.18	49.34	6.68	34.8
E3	20150508_023_Exoskeleton	0.547	30.449	434.222	181.238	0.052	0.26	0.034	0.201	9.44	47.6	6.17	36.8
E4	20150509_031_Exoskeleton	0.624	32.074	533.277	241.821	0.054	0.321	0.045	0.204	8.72	51.4	7.25	32.6
E5	20150509_038_Exoskeleton	0.447	22.349	384.539	170.477	0.038	0.23	0.032	0.147	8.49	51.51	7.09	32.9
E6	20150509_046_Exoskeleton	1.007	18.181	852.907	426.202	0.031	0.518	0.08	0.378	3.07	51.46	7.97	37.5
E7	20150510_008_Exoskeleton	0.752	17.172	688.062	350.899	0.031	0.432	0.071	0.218	4.12	57.45	9.44	29.0
E8	20150510_016_Exoskeleton	1.227	23.713	914.932	484.313	0.043	0.575	0.098	0.511	3.50	46.86	7.99	41.6
E9	20150510_023_Exoskeleton	0.742	39.144	602.653	272.457	0.071	0.378	0.056	0.237	9.57	50.94	7.55	31.9
E10	20150511_031_Exoskeleton	0.584	17.02	526.707	265.068	0.031	0.33	0.054	0.169	5.31	56.51	9.25	28.9
E11	20150511_038_Exoskeleton	0.625	30.545	505.439	236.921	0.055	0.316	0.049	0.205	8.80	50.56	7.84	32.8
E12	20150511_046_Exoskeleton	0.494	27.726	391.792	153.994	0.05	0.245	0.033	0.166	10.12	49.60	6.68	33.6

e. Crop

Tray Location	Sample Code	Sample Amount	Area [mV.s]			Weight [mg]				Weight [%]			
			Nitrogen	Carbon	Hydrogen	Nitrogen	Carbon	Hydrogen	Oxygen	Nitrogen	Carbon	Hydrogen	Oxygen
	Crop												
E1	20150428_010_Crop	0.547	4	364	204	0.006	0.216	0.038	0.287	1.2	39.4	6.9	52.5
E2	20150429_018_Crop	0.824	1	522	305	0.001	0.312	0.057	0.454	0.2	37.8	6.9	55.1
E3	20150429_025_Crop	0.641	3	419	238	0.005	0.249	0.044	0.343	0.8	38.9	6.9	53.5
E4	20150429_033_Crop	1.131	3	714	430	0.004	0.429	0.081	0.617	0.3	38.0	7.1	54.6
E5	20150429_041_Crop	1.219	1	756	458	0.001	0.456	0.086	0.676	0.1	37.4	7.0	55.5
D1	20150508_007_Crop	0.882	0.467	517.782	317.871	0.001	0.311	0.06	0.510	0.1	35.29	6.77	57.8
D2	20150508_014_Crop	0.977	0.444	570.402	363.743	0.001	0.343	0.068	0.565	0.09	35.16	7	57.8
D3	20150508_022_Crop	1.269	0.989	747.424	457.974	0.002	0.453	0.086	0.728	0.14	35.66	6.8	57.4
D4	20150509_030_Crop	1.233	0.47	724.187	444.119	0.001	0.438	0.084	0.710	0.07	35.54	6.78	57.6
D5	20150509_037_Crop	0.669	0.492	395.463	228.593	0.001	0.237	0.043	0.388	0.14	35.41	6.39	58.1
D6	20150509_045_Crop	0.917	2.286	549.634	314.014	0.004	0.331	0.059	0.523	0.43	36.07	6.43	57.1
D7	20150510_007_Crop	1.018	0.45	600.159	365.369	0.001	0.376	0.074	0.567	0.10	36.94	7.27	55.7
D8	20150510_014_Crop	1.479	0.707	822.166	492.366	0.001	0.516	0.099	0.863	0.07	34.89	6.69	58.4
D9	20150510_022_Crop	0.731	0.646	439.9	260.532	0.001	0.275	0.054	0.401	0.14	37.62	7.39	54.9
D10	20150511_030_Crop	1.341	0.585	772.067	462.524	0.001	0.485	0.093	0.762	0.07	36.17	6.94	56.8
D11	20150511_037_Crop	0.642	0.662	385.082	230.664	0.001	0.24	0.048	0.353	0.16	37.38	7.48	55.0
D12	20150511_045_Crop	1.369	0.776	798.415	461.197	0.001	0.501	0.093	0.774	0.07	36.60	6.79	56.5

f. Legs

Tray Location	Sample Code	Sample Amount	Area [mV.s]			Weight [mg]				Weight [%]			
			Nitrogen	Carbon	Hydrogen	Nitrogen	Carbon	Hydrogen	Oxygen	Nitrogen	Carbon	Hydrogen	Oxygen
	Leg												
F1	20150428_011_Leg	0.349	25	286	106	0.041	0.169	0.019	0.120	11.7	48.4	5.6	34.3
F2	20150429_019_Leg	0.573	39	460	198	0.065	0.274	0.037	0.197	11.4	47.9	6.4	34.3
F3	20150429_026_Leg	0.645	46	530	238	0.076	0.316	0.044	0.209	11.8	49.1	6.9	32.3
F4	20150429_034_Leg	0.682	47	555	252	0.078	0.332	0.047	0.225	11.4	48.6	6.9	33.1
F5	20150429_042_Leg	0.584	42	483	197	0.070	0.288	0.037	0.189	12.0	49.3	6.3	32.5
F1	20150508_009_Leg	0.444	29.647	345.155	137.507	0.05	0.206	0.025	0.163	11.33	46.49	5.73	36.5
F2	20150508_017_Leg	0.542	32.585	442.812	189.536	0.055	0.266	0.035	0.186	10.2	49	6.52	34.3
F3	20150508_024_Leg	0.502	27.253	411.594	168.341	0.046	0.247	0.031	0.178	9.21	49.13	6.23	35.4
F4	20150509_032_Leg	0.406	28.043	316.285	110.824	0.048	0.189	0.02	0.149	11.72	46.55	5.02	36.7
F5	20150509_039_Leg	0.325	21.872	253.484	94.629	0.037	0.151	0.017	0.120	11.43	46.52	5.32	36.7
F6	20150509_047_Leg	0.647	40.947	511.866	224.052	0.069	0.308	0.042	0.228	10.73	47.55	6.47	35.3
F7	20150508_009_Leg	0.958	59.87	725.262	335.999	0.108	0.455	0.068	0.327	11.27	47.49	7.10	34.1
F8	20150508_017_Leg	0.537	36.813	422.101	183.266	0.067	0.264	0.038	0.168	12.48	49.16	7.08	31.3
F9	20150508_024_Leg	0.666	45.924	515.014	226.71	0.083	0.322	0.047	0.214	12.46	48.35	7.06	32.1
F10	20150509_032_Leg	0.46	31.279	357.231	149.833	0.057	0.223	0.032	0.148	12.39	48.48	6.96	32.2
F11	20150509_039_Leg	0.488	33.773	379.979	132.858	0.061	0.237	0.028	0.162	12.50	48.57	5.74	33.2
F12	20150509_047_Leg	0.536	35.921	412.125	181.186	0.065	0.258	0.038	0.175	12.13	48.13	7.09	32.6

g. Muscle

Tray Location	Sample Code	Sample Amount	Area [mV.s]			Weight [mg]				Weight [%]			
			Nitrogen	Carbon	Hydrogen	Nitrogen	Carbon	Hydrogen	Oxygen	Nitrogen	Carbon	Hydrogen	Oxygen
	Muscle												
G1	20150428_012_Muscle	0.951	70	781	367	0.117	0.471	0.069	0.294	12.3	49.5	7.2	31.0
G2	20150429_020_Muscle	0.696	50	576	270	0.083	0.345	0.050	0.218	11.9	49.6	7.2	31.3
G3	20150429_028_Muscle	0.819	59	677	323	0.099	0.406	0.060	0.254	12.1	49.6	7.4	30.9
G4	20150429_035_Muscle	0.488	37	412	189	0.061	0.245	0.035	0.147	12.5	50.2	7.2	30.1
G5	20150429_043_Muscle	0.802	61	668	297	0.103	0.401	0.056	0.242	12.8	50.0	6.9	30.2
G1	20150508_010_Muscle	0.508	33.645	406.317	176.666	0.057	0.243	0.033	0.175	11.23	47.92	6.47	34.4
G2	20150508_018_Muscle	0.828	55.175	649.366	300.53	0.093	0.392	0.056	0.287	11.29	47.34	6.81	34.6
G3	20150508_025_Muscle	0.626	40.816	493.621	213.085	0.069	0.297	0.04	0.220	11.05	47.37	6.35	35.2
G4	20150509_033_Muscle	0.283	18.543	229.004	84.188	0.031	0.137	0.015	0.100	11.13	48.24	5.41	35.2
G5	20150509_041_Muscle	0.365	23.886	292.091	122.034	0.041	0.174	0.023	0.127	11.11	47.79	6.16	34.9
G6	20150509_048_Muscle	0.398	25.482	319.246	143.283	0.043	0.191	0.027	0.137	10.86	47.94	6.67	34.5
G7	20150510_010_Muscle	0.692	48.157	554.995	256.084	0.087	0.348	0.053	0.204	12.57	50.29	7.66	29.5
G8	20150510_018_Muscle	0.856	56.317	672.134	325.279	0.102	0.422	0.066	0.266	11.92	49.30	7.71	31.1
G9	20150510_025_Muscle	1.045	71.065	815.116	387.257	0.128	0.512	0.078	0.327	12.25	49.00	7.46	31.3
G10	20150511_033_Muscle	0.588	37.14	461.185	203.733	0.067	0.288	0.042	0.191	11.39	48.98	7.14	32.5
G11	20150511_041_Muscle	0.783	51.521	613.907	267.094	0.093	0.385	0.055	0.250	11.88	49.17	7.02	31.9
G12	20150511_048_Muscle	0.726	47.266	562.629	243.55	0.085	0.352	0.05	0.239	11.71	48.48	6.89	32.9

H. MCNP Input deck with source located in the brain

In this appendix a sample MCNP input deck is provided. If the replication of the results is desired, then the following cards need to be changed under the data card: ERG, SI4 and PAR.

```
c This input file was made with the MCNP Lattice Tool
c originally created by Erick Daniel Cardenas-Mendez (a.k.a. Ace Wave)
c for the Human Monitoring Laboratory of Health Canada
c
c Input file originally created on:
c Thu May 9 2015
c
c Empty space universe: 14
c compression factor: 5
c
c
c
c ++++++++++++++++++++++++++++++++++++++++++++++++++++++
c
c    Cells
c
c ++++++++++++++++++++++++++++++++++++++++++++++++++++++
c
  999  0 999                  imp:p 0 imp:e 0      $ outside
  998  1 -.1205E-02  -999  1111   imp:p 1 imp:e 1      $ air
c
c Filling Universes
   1    9   -1.0500    -4444   u = 1    imp:p 1 imp:e 1  $antenna
   100   0             4444   u = 1    imp:p 0 imp:e 0
   2    9   -1.0500    -4444   u = 2    imp:p 1 imp:e 1  $Head
   200   0             4444   u = 2    imp:p 0 imp:e 0
   3    9   -1.0500    -4444   u = 3    imp:p 1 imp:e 1  $Thorax
   300   0             4444   u = 3    imp:p 0 imp:e 0
   4    9   -1.0500    -4444   u = 4    imp:p 1 imp:e 1  $Abdomen
   400   0             4444   u = 4    imp:p 0 imp:e 0
   5    2   -1.0400    -4444   u = 5    imp:p 1 imp:e 1  $StriatedMuscle
   500   0             4444   u = 5    imp:p 0 imp:e 0
   6    3   -1.0500    -4444   u = 6    imp:p 1 imp:e 1  $Legs
   600   0             4444   u = 6    imp:p 0 imp:e 0
   7    9   -1.0500    -4444   u = 7    imp:p 1 imp:e 1  $Brain
   700   0             4444   u = 7    imp:p 0 imp:e 0
   8    9   -1.0500    -4444   u = 8    imp:p 1 imp:e 1  $Eyes
   800   0             4444   u = 8    imp:p 0 imp:e 0
   9    4   -1.0500    -4444   u = 9    imp:p 1 imp:e 1  $Crop
```

```
   900   0              4444   u = 9     imp:p 0 imp:e 0
   10    6   -1.0500     -4444   u = 10    imp:p 1 imp:e 1  $Rectum
   1000  0              4444   u = 10    imp:p 0 imp:e 0
   11    8   -1.0500     -4444   u = 11    imp:p 1 imp:e 1  $Venom Sac
   1100  0              4444   u = 11    imp:p 0 imp:e 0
   12    9   -1.0500     -4444   u = 12    imp:p 1 imp:e 1  $Heart
   1200  0              4444   u = 12    imp:p 0 imp:e 0
   13    7   -1.0500     -4444   u = 13    imp:p 1 imp:e 1  $Intestine
   1300  0              4444   u = 13    imp:p 0 imp:e 0
   14    1   -.1205E-02  -4444   u = 14    imp:p 1 imp:e 1  $Air Volume
   1400  0              4444   u = 14    imp:p 0 imp:e 0
c
c Lattice Unit Cell
c
   996   0   -3333    lat = 1 u = 996     imp:p 1 imp:e 1
              fill = 0:102  0:102 0:511
    14 2296218r 1 14 102r 1 14 10502r 1 3r 14 100r 1 1r 14 10500r 1
    2r 14 102r 1 1r 14 10499r 1 3r 14 1 14 100r 1 1r 14 10498r 1
    5r 14 410r 2 1r 14 100r 2 1r 14 10086r 1 1r 14 100r 1 14 210r 2
    14 99r 2 2r 14 100r 2 1r 14 10188r 1 1r 14 106r 2 14 100r 2
    3r 14 98r 2 3r 14 98r 2 2r 14 101r 2 14 10085r 1 1r 14 106r 2
    1r 14 99r 2 3r 14 97r 2 5r 14 97r 2 3r 14 100r 2 14 10084r 1
    2r 14 2r 2 1r 14 94r 1 14 3r 2 3r 14 93r 1 14 2r 2 5r 14 96r 2
    6r 14 96r 2 5r 14 96r 2 4r 14 99r 2 14 9983r 1 14 4r 2 14 94r 1
    14 3r 2 4r 14 93r 1 1r 14 1r 2 5r 14 95r 2 7r 14 94r 2 7r 14
    95r 2 3r 14 99r 2 2r 14 9880r 1 14 99r 1 14 4r 2 2r 14 93r 1
    1r 14 1r 2 6r 14 92r 1 1r 14 2 6r 14 94r 2 7r 14 95r 2 7r 14
    94r 2 6r 14 96r 2 3r 14 9885r 2 14 93r 1 14 3r 2 5r 14 91r 1
    1r 14 1r 2 6r 14 93r 1 2r 2 6r 14 94r 2 8r 14 93r 2 6r 14 93r 1
    1r 2 6r 14 97r 2 3r 14 9881r 2 4r 14 93r 1 14 1r 2 7r 14 91r 1
    1r 14 2 8r 14 91r 1 2r 2 7r 14 92r 2 1 2 7r 14 92r 1 2r 2 6r 14
    91r 1 3r 2 5r 14 92r 1 14 3r 2 4r 14 9776r 8 2r 14 99r 8 2 3r 14
    97r 2 7r 14 92r 1 2 8r 14 93r 1 2 7r 14 93r 2 9r 14 93r 2 8r 14
    91r 1 1r 2 7r 14 95r 2 6r 14 95r 8 1r 2 3r 14 93r 1 14 101r 1
    14 102r 1 1r 14 102r 1 1r 14 9265r 8 2r 2 1r 14 97r 8 2 5r 14
    96r 2 7r 14 93r 2 8r 14 93r 2 8r 14 93r 2 9r 14 92r 2 9r 14
    91r 1 2r 2 6r 14 91r 1 1r 14 8 2 6r 14 91r 1 14 2r 8 1r 14 2r 2
    14 93r 1 14 101r 1 1r 14 100r 1 2r 14 101r 1 1r 14 9266r 8 4r 2
    14 96r 8 2 6r 14 94r 2 7r 14 94r 2 8r 14 93r 2 1r 7 2 5r 14
    93r 2 1r 7 1r 2 5r 14 92r 2 9r 14 91r 1 1r 2 8r 14 91r 1 14
    8 2 6r 14 92r 1 14 1r 8 2r 2 2r 14 93r 1 14 101r 1 14 102r 1
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3r 4 2r 14 92r 4 2r 9 3r 4 2r 14 92r 4 3r 9 2r 4 1r 14 6r 6
2r 14 83r 4 7r 14 7r 6 1r 14 84r 4 5r 14 96r 4 3r 14 3r 6 1r 14
101r 6 14 313r 6 1r 14 8943r 4 7r 14 93r 4 9r 14 91r 4 12r 14
89r 4 12r 14 89r 4 12r 14 89r 4 12r 14 89r 4 6r 9 4 4r 14 90r 4
3r 9 3r 4 3r 14 90r 4 3r 9 3r 4 3r 14 90r 4 4r 9 2r 4 2r 14
5r 6 2r 14 82r 4 8r 14 7r 6 1r 14 83r 4 5r 14 97r 4 2r 14 4r 6
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12r 14 89r 4 12r 14 89r 4 13r 14 88r 4 12 4 11r 14 88r 4 5r 9
2r 4 4r 14 88r 4 5r 9 2r 4 3r 14 89r 4 5r 9 2r 4 2r 14 5r 6
2r 14 81r 4 10r 14 6r 6 14 83r 4 9r 14 93r 4 7r 14 6 1r 14 92r 4
3r 14 9164r 4 2r 14 97r 4 8r 14 92r 4 10r 14 90r 4 12r 14 89r 4
12r 14 89r 4 12r 14 89r 4 12 4 11r 14 88r 4 12 4 11r 14 88r 4
5r 9 2r 4 4r 14 88r 4 5r 9 2r 4 3r 14 89r 4 5r 9 2r 4 2r 14
6r 6 1r 14 81r 4 10r 14 6r 6 1r 14 82r 4 9r 14 7r 6 14 84r 4
7r 14 6 1r 14 92r 4 3r 14 9163r 4 5r 14 94r 4 9r 14 92r 4 10r 14
90r 4 12r 14 89r 4 12r 14 89r 4 13r 14 88r 4 12 4 11r 14 88r 4
12 4 11r 14 88r 4 5r 9 2r 4 4r 14 88r 4 5r 9 2r 4 4r 14 88r 4
5r 9 1r 4 3r 14 5r 6 2r 14 81r 4 10r 14 5r 6 14 84r 4 9r 14
6r 6 14 85r 4 7r 14 6 1r 14 91r 4 5r 14 9162r 4 6r 14 94r 4
9r 14 91r 4 11r 14 90r 4 12r 14 88r 4 13r 14 88r 4 13r 14 88r 4
12 4 11r 14 88r 4 12 4 11r 14 88r 4 5r 9 1r 4 5r 14 88r 4 5r 9
2r 4 3r 14 89r 4 6r 9 4 3r 14 5r 6 1r 14 82r 4 10r 14 5r 6 1r 14
83r 4 9r 14 5r 6 1r 14 85r 4 7r 14 6 1r 14 92r 4 3r 14 9165r 4
4r 14 95r 4 7r 14 92r 4 11r 14 89r 4 13r 14 88r 4 14r 14 87r 4
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86r 4 4r 14 4r 6 14 9159r 4 4r 14 95r 4 7r 14 92r 4 11r 14 89r 4
13r 14 88r 4 14r 14 87r 4 14r 14 87r 4 12 4 12r 14 86r 4 1r 12
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86r 4 7r 13 4 6r 14 86r 4 7r 13 4 4r 14 88r 4 11r 14 5r 6 1r 14
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2r 6 14 93r 4 14 9063r 4 7r 14 93r 4 9r 14 91r 4 11r 14 89r 4
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4 13r 14 85r 4 16r 14 85r 4 7r 13 4 6r 14 86r 4 6r 13 1r 4 5r 14
88r 4 12r 14 2r 6 2r 14 83r 4 11r 14 90r 4 10r 14 92r 4 6r 14
2r 6 14 93r 4 14 9063r 4 7r 14 93r 4 9r 14 91r 4 11r 14 89r 4
13r 14 87r 4 15r 14 86r 4 15r 14 86r 4 12 4 13r 14 86r 4 12
4 13r 14 85r 4 16r 14 85r 4 15r 14 86r 4 6r 13 1r 4 5r 14 88r 4
6r 13 4 4r 14 2r 6 2r 14 83r 4 11r 14 90r 4 10r 6 14 2r 6 14
87r 4 6r 14 2r 6 1r 14 92r 4 14 9063r 4 7r 14 93r 4 9r 14 91r 4
11r 14 89r 4 13r 14 87r 4 15r 14 86r 4 15r 14 86r 4 12 4 13r 14
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11r 14 90r 4 10r 14 92r 4 6r 14 2r 6 14 93r 4 14 9063r 4 7r 14
93r 4 9r 14 91r 4 11r 14 89r 4 13r 14 87r 4 15r 14 86r 4 15r 14
86r 4 12 4 13r 14 86r 4 12 4 2r 13 2r 4 7r 14 85r 4 5r 13 2r 4
7r 14 85r 4 15r 14 86r 4 7r 13 1r 4 4r 14 88r 4 6r 13 1r 4 3r 14
3r 6 1r 14 83r 4 6r 13 4 3r 14 90r 4 10r 14 92r 4 6r 14 3r 6
14 92r 4 14 9063r 4 7r 14 93r 4 9r 14 91r 4 11r 14 89r 4 13r 14
87r 4 15r 14 86r 4 15r 14 86r 4 15r 14 86r 4 12 4 2r 13 2r 4
7r 14 85r 4 5r 13 2r 4 7r 14 85r 4 15r 14 86r 4 7r 13 1r 4 4r 14
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86r 4 10r 14 6 14 1r 6 14 87r 4 6r 14 97r 4 14 9064r 4 7r 14
92r 4 11r 14 89r 4 13r 14 87r 4 15r 14 86r 4 15r 14 85r 4 16r 14
85r 4 16r 14 85r 4 12 4 2r 13 2r 4 8r 14 85r 4 12 4 2r 13 2r 4
7r 14 86r 4 13r 14 88r 4 6r 13 4 4r 14 89r 4 5r 13 2r 4 2r 14
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88r 4 13r 14 87r 4 14r 14 86r 4 16r 14 85r 4 5r 13 1r 4 8r 14

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89r 4 7r 14 1r 6 2r 14 9158r 4 5r 14 94r 4 9r 14 91r 4 11r 14
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6r 13 1r 4 1r 14 92r 4 9r 14 6 14 90r 4 6r 14 3r 6 14 9160r 4
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91r 4 4r 14 3r 6 1r 14 9157r 4 7r 14 93r 4 10r 14 90r 4 12r 14
88r 4 13r 14 87r 4 15r 14 86r 4 15r 14 85r 4 6r 13 1r 4 7r 14
85r 4 5r 13 4 13 4 7r 14 85r 4 12 4 3r 13 1r 4 8r 14 85r 4 5r 13
4 9r 14 85r 4 6r 13 2r 4 4r 14 87r 4 6r 13 2r 4 3r 14 88r 4
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14 9056r 4 7r 14 93r 4 9r 14 91r 4 11r 14 89r 4 13r 14 87r 4
14r 14 87r 4 15r 14 85r 4 6r 13 1r 4 7r 14 85r 4 6r 13 1r 4
7r 14 85r 4 12 4 2r 13 1r 4 8r 14 86r 4 4r 13 4 9r 14 86r 4
5r 13 2r 4 4r 14 88r 4 5r 13 2r 4 3r 14 89r 4 6r 13 4 3r 14
91r 4 8r 14 94r 4 6r 14 1r 6 1r 14 9158r 4 7r 14 93r 4 9r 14
91r 4 11r 14 89r 4 13r 14 87r 4 14r 14 87r 4 6r 13 4 7r 14 85r 4
6r 13 2r 4 6r 14 85r 4 7r 13 4 7r 14 85r 4 12 4 2r 13 1r 4 8r 14
86r 4 12 4 2r 13 2r 4 7r 14 86r 4 5r 13 2r 4 4r 14 88r 4 5r 13
2r 4 3r 14 89r 4 11r 14 91r 4 8r 14 94r 4 6r 14 9162r 4 7r 14
93r 4 9r 14 91r 4 11r 14 89r 4 13r 14 87r 4 14r 14 87r 4 6r 13
4 7r 14 85r 4 7r 13 1r 4 6r 14 85r 4 4r 13 4 1r 13 4 7r 14 85r 12
4 3r 13 1r 4 8r 14 86r 12 4 3r 13 4 13 4 7r 14 86r 4 5r 13 2r 4
4r 14 88r 4 5r 13 2r 4 3r 14 89r 4 11r 14 91r 4 8r 14 94r 4
6r 14 9163r 4 5r 14 93r 4 10r 14 91r 4 12r 14 88r 4 14r 14 86r 4
15r 14 85r 4 8r 13 4 7r 14 84r 4 7r 13 1r 4 7r 14 84r 4 5r 13
4 10r 14 84r 12 4 3r 13 1r 4 9r 14 85r 4 5r 13 1r 4 7r 14 86r 4
5r 13 2r 4 5r 14 87r 4 5r 13 2r 4 5r 14 87r 4 12r 14 90r 4 10r 14
92r 4 7r 14 96r 4 14 9064r 4 5r 14 93r 4 10r 14 91r 4 12r 14
88r 4 14r 14 86r 4 15r 14 85r 4 8r 13 4 7r 14 84r 4 7r 13 1r 4
7r 14 84r 4 17r 14 84r 4 12 4 2r 13 2r 4 8r 14 85r 4 4r 13 2r 4

7r 14 86r 4 5r 13 2r 4 5r 14 87r 4 6r 13 4 6r 14 87r 4 12r 14
90r 4 10r 14 92r 4 7r 14 96r 4 14 9065r 4 5r 14 94r 4 9r 14
90r 4 13r 14 87r 4 15r 14 85r 4 16r 14 84r 4 8r 13 1r 4 7r 14
83r 4 8r 13 1r 4 6r 14 84r 4 17r 14 84r 4 12 4 3r 13 1r 4 8r 14
85r 4 5r 13 1r 4 8r 14 85r 4 5r 13 2r 4 6r 14 86r 4 6r 13 4
6r 14 87r 4 13r 14 89r 4 10r 14 92r 4 6r 14 9164r 4 4r 14 95r 4
9r 14 90r 4 12r 14 88r 4 14r 14 86r 4 16r 14 85r 4 7r 13 1r 4
6r 14 84r 4 8r 13 1r 4 2r 10 1r 4 1r 14 84r 4 14r 10 4 1r 14
84r 4 12 4 3r 13 1r 4 8r 14 85r 4 5r 13 1r 4 7r 14 86r 4 5r 13
2r 4 5r 14 87r 4 6r 13 4 6r 14 87r 4 12r 14 90r 4 10r 14 92r 4
6r 14 9266r 4 7r 14 92r 4 12r 14 88r 4 13r 14 87r 4 15r 14 85r 4
7r 13 1r 4 4r 11 4 14 85r 4 7r 13 1r 4 2r 10 1r 4 11 4 14 84r 4
13r 10 4 1r 14 84r 4 12 4 3r 13 1r 4 8r 14 85r 4 5r 13 2r 4
6r 14 86r 4 5r 13 2r 4 5r 14 88r 4 12r 14 89r 4 12r 14 90r 4
9r 14 93r 4 6r 14 9265r 4 7r 14 92r 4 12r 14 88r 4 13r 14 87r 4
15r 14 85r 4 8r 13 1r 4 3r 11 4 14 85r 4 8r 13 1r 4 1r 10 1r 4
11 4 14 84r 4 12r 10 1r 4 1r 14 84r 4 1r 12 4 2r 13 1r 4 8r 14
85r 4 5r 13 2r 4 6r 14 86r 4 5r 13 2r 4 5r 14 88r 4 12r 14 89r 4
12r 14 90r 4 9r 14 93r 4 6r 14 9266r 4 6r 14 92r 4 11r 14 89r 4
13r 14 87r 4 8r 13 4 5r 14 86r 4 7r 13 1r 4 1r 10 1r 11 4 14
85r 4 9r 13 4 1r 10 1r 4 11 14 85r 4 16r 14 85r 12 4 3r 13 1r 4
8r 14 86r 4 4r 13 1r 4 7r 14 87r 4 13r 14 88r 4 12r 14 89r 4
12r 14 90r 4 9r 14 93r 4 5r 14 9267r 4 6r 14 92r 4 11r 14 89r 4
13r 14 87r 4 8r 13 4 5r 14 86r 4 8r 13 1r 4 2r 11 4 14 85r 4
9r 13 4 1r 10 1r 4 11 14 85r 4 13r 10 1r 4 14 85r 4 12 4 2r 13
1r 4 8r 14 86r 4 4r 13 1r 4 7r 14 87r 4 13r 14 88r 4 12r 14
89r 4 12r 14 90r 4 9r 14 93r 4 5r 14 9268r 4 3r 14 94r 4 10r 14
90r 4 11r 10 4 14 87r 4 9r 13 4 1r 10 1r 4 14 86r 4 8r 13 1r 4
1r 10 2r 4 14 85r 4 9r 13 4 2r 10 1r 11 4 14 83r 4 17r 14 84r 4
12 4 2r 13 1r 4 9r 14 85r 4 4r 13 1r 4 8r 14 86r 4 14r 14 87r 4
13r 14 89r 4 11r 14 90r 4 9r 14 94r 4 4r 14 9368r 4 9r 14 90r 4
12r 14 89r 4 8r 13 1r 10 2r 4 14 86r 4 9r 13 1r 4 10 2r 14 86r 4
12r 10 2r 11 4 14 84r 4 13r 10 1r 4 14 84r 4 12 4 3r 13 4 9r 14
85r 4 4r 13 1r 4 8r 14 86r 4 14r 14 87r 4 13r 14 89r 4 11r 14
91r 4 8r 14 94r 4 4r 14 9368r 4 9r 14 90r 4 12r 14 89r 4 9r 13
10 2r 4 14 86r 4 9r 13 1r 4 10 1r 4 14 86r 4 12r 10 2r 11 4
14 84r 4 13r 10 2r 14 84r 4 12 4 14r 14 85r 4 15r 14 86r 4 14r 14
87r 4 13r 14 89r 4 11r 14 91r 4 8r 14 94r 4 4r 14 9369r 4 7r 14
92r 4 11r 14 89r 4 10r 13 10 1r 14 88r 4 10r 13 10 1r 4 14 86r 4
12r 10 1r 11 4 14 85r 4 16r 14 85r 4 15r 14 86r 4 14r 14 87r 4
13r 14 88r 4 11r 14 90r 4 10r 14 92r 4 7r 14 96r 4 2r 14 9371r 4
6r 14 92r 4 11r 14 90r 4 12r 14 88r 4 11r 10 1r 4 14 87r 4 11r 10
1r 11 1r 14 85r 4 13r 10 2r 14 85r 4 12 4 13r 14 86r 4 14r 14
87r 4 12r 14 89r 4 11r 14 91r 4 9r 14 93r 4 6r 14 96r 4 1r 14
9373r 4 4r 14 94r 4 9r 14 91r 4 12r 14 88r 4 14r 14 87r 4 10r 10
2r 11 1r 14 86r 4 11r 10 2r 14 86r 4 12 4 12r 14 87r 4 13r 14

```
     88r 4 12r 14 90r 4 10r 14 91r 4 9r 14 93r 4 5r 14 9472r 4 6r 14
     93r 4 10r 14 90r 4 10r 10 4 14 88r 4 10r 10 1r 11 1r 14 86r 4
     11r 10 2r 4 14 86r 4 12r 10 1r 4 14 86r 4 12 4 12r 14 87r 4
     14r 14 87r 4 13r 14 89r 4 11r 14 90r 4 10r 14 92r 4 6r 14 98r 4
     14 9372r 4 4r 14 95r 4 9r 14 91r 4 9r 10 4 14 88r 4 11r 10 1r 4
     14 86r 4 12r 10 1r 11 14 86r 4 12r 10 1r 4 14 86r 4 12 4 12r 14
     87r 4 14r 14 88r 4 12r 14 89r 4 11r 14 90r 4 10r 14 93r 4 4r 14
     9473r 4 4r 14 95r 4 8r 14 91r 4 10r 10 11 14 89r 4 10r 10 1r 14
     88r 4 11r 10 1r 14 88r 4 13r 14 88r 4 13r 14 88r 4 12r 14 89r 4
     12r 14 89r 4 11r 14 91r 4 8r 14 94r 4 4r 14 9473r 4 3r 14 96r 4
     8r 14 92r 4 10r 14 90r 4 9r 10 1r 4 14 88r 4 11r 10 1r 14 88r 4
     12r 10 14 88r 4 12 4 11r 14 88r 4 12r 14 89r 4 12r 14 89r 4
     10r 14 92r 4 8r 14 95r 4 3r 14 9575r 4 6r 14 93r 4 9r 14 92r 4
     8r 10 4 14 90r 4 9r 10 1r 14 90r 4 10r 10 4 14 89r 4 11r 14
     90r 4 11r 14 90r 4 10r 14 91r 4 9r 14 93r 4 6r 14 9677r 4 5r 14
     94r 4 9r 14 91r 4 11r 14 89r 4 10r 10 1r 14 89r 4 11r 10 14
     89r 4 12 4 10r 14 89r 4 11r 14 90r 4 10r 14 92r 4 8r 14 95r 4
     5r 14 9679r 4 2r 14 96r 4 7r 14 92r 4 10r 14 91r 4 8r 10 1r 14
     91r 4 10r 14 90r 12 4 9r 14 91r 4 9r 14 92r 4 8r 14 94r 4 6r 14
     96r 4 4r 14 9780r 4 6r 14 94r 4 7r 10 14 92r 4 8r 10 1r 14 91r 4
     10r 14 90r 4 10r 14 91r 4 9r 14 92r 4 8r 14 94r 4 6r 14 97r 4
     3r 14 9781r 4 5r 14 94r 4 8r 14 92r 4 8r 10 14 92r 4 9r 14 92r 4
     8r 14 93r 12 4 7r 14 93r 4 7r 14 95r 4 5r 14 98r 4 1r 14 9783r 4
     3r 14 96r 4 7r 14 93r 4 7r 10 14 93r 4 7r 10 14 92r 12 4 7r 14
     93r 4 7r 14 94r 4 7r 14 96r 4 3r 14 9884r 4 3r 14 96r 4 7r 14
     94r 4 6r 10 14 93r 4 7r 10 14 93r 12 4 7r 14 93r 4 7r 14 95r 4
     5r 14 99r 4 14 9886r 4 2r 14 97r 4 5r 14 95r 4 7r 14 93r 4 8r 14
     93r 4 12 4 6r 14 94r 4 6r 14 96r 4 4r 14 10088r 4 5r 14 95r 4
     6r 14 95r 4 6r 14 95r 12 4 5r 14 95r 4 6r 14 96r 4 3r 14 10091r 4
     2r 14 97r 4 5r 14 95r 4 6r 14 95r 12 4 5r 14 95r 4 5r 14 98r 4
     2r 14 10193r 4 3r 14 97r 4 4r 14 97r 4 4r 14 98r 4 2r 14
     1151489r
c
c Cell Containing Lattice
c
   997    0     -1111   fill = 996    imp:p 1 imp:e 1
c

c +++++++++++++++++++++++++++++++++++++++++++++++++++++++
c
c    Surfaces
c
c +++++++++++++++++++++++++++++++++++++++++++++++++++++++
c
  999 so  20     $ 20cm universe sphere
c
```

```
c Box for Filling Universes
c
  1111  rpp   0.000     3.0387060     0.000   3.0387060    0.000  3.0210048
  3333  rpp   0.000     0.0295020     0.000   0.0295020    0.000  0.0059004
  4444  rpp  -0.001     0.0300000    -0.001   0.0300000   -0.001  0.0060000
c

c ++++++++++++++++++++++++++++++++++++++++++++++++++++++++
c
c     All the materials  where calculated by organic elemental analysis
c
c ++++++++++++++++++++++++++++++++++++++++++++++++++++++++
c ------------------------------------
c Air
c ------------------------------------
m1
             7000    -0.755
             8000    -0.232
            18000    -0.013
c ------------------------------------
c Muscle
c ------------------------------------
m2
             1000.03e    -0.069
             6000.03e    -0.489
             7000.03e    -0.118
             8000.03e    -0.324
c ------------------------------------
c Legs
c ------------------------------------
m3
             1000.03e    -0.064
             6000.03e    -0.482
             7000.03e    -0.115
             8000.03e    -0.339
c ------------------------------------
c Crop
c ------------------------------------
m4
             1000.03e    -0.069
             6000.03e    -0.367
             7000.03e    -0.003
             8000.03e    -0.561
c ------------------------------------
c Exoskeleton
c ------------------------------------
```

```
m5
            1000.03e    -0.075
            6000.03e    -0.507
            7000.03e    -0.079
            8000.03e    -0.339
c ------------------------------------
c Rectum
c ------------------------------------
m6
            1000.03e    -0.07
            6000.03e    -0.508
            7000.03e    -0.046
            8000.03e    -0.376
c ------------------------------------
c Intestine
c ------------------------------------
m7
            1000.03e    -0.071
            6000.03e    -0.491
            7000.03e    -0.062
            8000.03e    -0.376
c ------------------------------------
c Venomsac
c ------------------------------------
m8
            1000.03e    -0.066
            6000.03e    -0.489
            7000.03e    -0.111
            8000.03e    -0.333
c ------------------------------------
c Rest
c ------------------------------------
m9
            1000.03e    -0.071
            6000.03e    -0.491
            7000.03e    -0.062
            8000.03e    -0.376
c
c +++++++++++++++++++++++++++++++++++++++++++++++++++++++
c
c       Source
c
c
c ++++++++++++++++++++++++++++++++++++++++++++++++++++++++
c
mode p e
```

```
sdef erg=0.1 par=3 eff=0.000001 X=d1 Y=d2 Z=d3 cel=d4
si1 0.001 0.0295020
sp1 0 1
si2 0.001 0.0295020
sp2 0 1
si3 0.001 0.0059004
sp3 0 1
si4 L (7<996<997) $brain source
sp4 1
*f8:e u=(1)     $antenna
*f18:e u=(2)    $head
*f28:e u=(3)    $thorax
*f38:e u=(4)    $abdomen
*f48:e u=(5)    $muscle
*f58:e u=(6)    $legs
*f68:e u=(7)    $brain
*f78:e u=(8)    $eyes
*f88:e u=(9)    $crop
*f98:e u=(10)   $rectum
*f108:e u=(11)  $venom sac
*f118:e u=(12)  $heart
*f128:e u=(13)  $Intestine
e8 0 0.000001 6.0
e18 0 0.000001 6.0
e28 0 0.000001 6.0
e38 0 0.000001 6.0
e48 0 0.000001 6.0
e58 0 0.000001 6.0
e68 0 0.000001 6.0
e78 0 0.000001 6.0
e88 0 0.000001 6.0
e98 0 0.000001 6.0
e108 0 0.000001 6.0
e118 0 0.000001 6.0
e128 0 0.000001 6.0
PRDMP 3j 2 j
nps 2000000
```

I. MATLAB FUNCTIONS

All MATLAB function and main script are included in this appendix.

a. Data extractor

```
%% ========================= Voxel Data Extractor =========================
%
% This Script is going to hepl anyone working with voxel modeling. it will
% go thorough every MCNP output file as long as you give the right path and
% some other things that need to be modified for it to do all the work for
% you.
%
%


%   Copyright 2015 Mario E. Gomez-Fernandez
clc; clear; close all;

%% ========================= Organs and Energies ==========================
% Define the name or the organs and the total number of organs that will be
% used in the voxel model function Organs has this data.
[OrgansData]=Organs();

Number_organs=size(OrgansData,1);

% Define the number of photon and electon energies that are being used

PhotonEnergies=[0.01; 0.015; 0.02; 0.03; 0.05; 0.1; 0.2; 0.5; 1.0;
    1.5; 2.0; 4.0];

ElectronEnergies=[0.1; 0.2; 0.4; 0.5; 0.7; 1.0; 1.5; 2.0; 4.0];

% load source data
[Photon_Int_Energies,Electron_Int_Energies]=Sources();



%% ==================== Extact data from the files ========================

[Photon_Data]=PhotonData(Number_organs,PhotonEnergies);

[Electron_Data]=ElectronData(Number_organs,ElectronEnergies);

%% ============================ Plot Data =================================
% Use the function graph to plot all the data extracted from MCNP. This
% plots are in a log scale since most of the values are very small.

Graph(Photon_Data,PhotonEnergies,OrgansData(:,1));

Graph(Electron_Data,ElectronEnergies,OrgansData(:,1));

%% ===================== Data Interpolation ===============================
%
```

```
Photon_Integrated_Data=InterData(Photon_Data,PhotonEnergies,...
    Photon_Int_Energies,OrgansData(:,1));

Electron_Integrated_Data=InterData(Electron_Data,ElectronEnergies,...
    Electron_Int_Energies,OrgansData(:,1));

%% ========================= Dose Calculations ============================

[P_DoseCal]=DCFcal(OrgansData(:,2), Photon_Int_Energies,...
    Photon_Integrated_Data);

[E_DoseCal]=DCFcal(OrgansData(:,2), Electron_Int_Energies,...
    Electron_Integrated_Data);
% Add all the doses together

%%
%
sources={'C-14';'Cs-137'; 'Sr-90'; 'Y-90';'Co-60';...
    'I-131';'Cl-36';'Ra-226'};
[DCF]=DCFadd(P_DoseCal,E_DoseCal,sources);
```

b. <u>Sources</u>

```
function [Photon, Electron]=Sources()

% Sources includes the sources data (Energy, yield, branching ratio)
Source_Strenght=1E6; %Bequerel
Const=1.6021e-10;

    Cs137=struc({'Cs-137';.661; 0.851; 1});
    Co601=struc({'Co-60'; 1.173; 0.999736; 1});
    Co602=struc({'Co-60';1.332; 0.999856; 1});
    I1314=struc({'I-131';.080185; 0.0262; 1});
    I1315=struc({'I-131';.284; 0.0614; 1});
    I1316=struc({'I-131';.36448; 0.817; 1});
    I1317=struc({'I-131';.636; 0.0717; 1 });
    I1318=struc({'I-131';.722; 0.01773; 1 });
    Cl361=struc({'Cl-36';.511; 1;  0.019});
    Ra226=struc({'Ra-226';.186; 0.0359; 1});


Photon = [Cs137 Co601 Co602 I1314 I1315 I1316 I1317 I1318 Cl361 Ra226]';
const=([Photon{:,2}]'.*[Photon{:,3}]'.*[Photon{:,4}]');
const=const*Source_Strenght*Const;
B=cell(size(const));

for i=1:length(const)

    B{i}=const(i);

end

Photon(:,5)=B;
```

```
    C14=struc({'C-14'; 0.052; 1; 1});
    Cs1371=struc({'Cs-137'; .171; 0.944; 1});
    Cs1372=struc({'Cs-137';.3917; 0.056; 1  });
    Sr90=struc({'Sr-90';.188; 1; 1});
    Y90=struc({'Y-90';.760; 1; 1});
    Co603=struc({'Co-60';.106; 0.99925; 1});
    I1311=struc({'I-131';.0826; 0.021; 1});
    I1312=struc({'I-131';.1113; 0.0722; 1 });
    I1313=struc({'I-131';.2021; 0.899; 1});
    Cl362=struc({'Cl-36';.2362; 1; 0.981});

Electron=[C14 Cs1371 Cs1372 Sr90 Y90 Co603 I1311 I1312 I1313 Cl362]';

const=([Electron{:,2}]'.*[Electron{:,3}]'.*[Electron{:,4}]');
const=const*Source_Strenght*Const;
B=cell(size(const));

for i=1:length(const)

    B{i}=const(i);

end

Electron(:,5)=B;


end
```

c. <u>PhotonData</u>

```
function [Photon_Data]=PhotonData(Number_organs,PhotonEnergies)


% Add the directories where your files are loctated. This is necesary
% because matlab needs to know what data is being used. This is not the
% same as going to the directory as 'dir' does
addpath('/Users/mariogomez/Documents/MATLAB/Research/MCNP/uHbee/Brain/Photon
')
addpath('/Users/mariogomez/Documents/MATLAB/Research/MCNP/uHbee/Crop/Photon'
)
addpath('/Users/mariogomez/Documents/MATLAB/Research/MCNP/uHbee/Midgut/Photo
n')
addpath('/Users/mariogomez/Documents/MATLAB/Research/MCNP/uHbee/Muscle/Photo
n')
addpath('/Users/mariogomez/Documents/MATLAB/Research/MCNP/uHbee/Rectum/Photo
n')
% -------------------------------------------------------------------------

%   Copyright 2015 Mario E. Gomez-Fernandez
% dir goes to the directory to extract the names of the files.
BrainPhotonfile=dir(...
    '/Users/mariogomez/Documents/MATLAB/Research/MCNP/uHbee/Brain/Photon');
```

```
CropPhotonfile=dir(...
    '/Users/mariogomez/Documents/MATLAB/Research/MCNP/uHbee/Crop/Photon');

MidgutPhotonfile=dir(...
    '/Users/mariogomez/Documents/MATLAB/Research/MCNP/uHbee/Midgut/Photon');

MusclePhotonfile=dir(...
    '/Users/mariogomez/Documents/MATLAB/Research/MCNP/uHbee/Muscle/Photon');

RectumPhotonfile=dir(...
    '/Users/mariogomez/Documents/MATLAB/Research/MCNP/uHbee/Rectum/Photon');

% get the file names
BrainPhotondata={BrainPhotonfile.name}';
Brain_photon=BrainPhotondata(3:end,:);

CropPhotondata={CropPhotonfile.name}';
Crop_photon=CropPhotondata(3:end,:);

MidgutPhotondata={MidgutPhotonfile.name}';
Midgut_photon=MidgutPhotondata(3:end,:);

MusclePhotondata={MusclePhotonfile.name}';
Muscle_photon=MusclePhotondata(3:end,:);

RectumPhotondata={RectumPhotonfile.name}';
Rectum_photon=RectumPhotondata(3:end,:);


% ============================== File names ==============================
% Extract the file names from the folders in the MCNP directory
% *************function -OpenFiles***************


PBrain_files=OpenFiles(Brain_photon);

PCrop_files=OpenFiles(Crop_photon);

PMidgut_files=OpenFiles(Midgut_photon);

PMuscle_files=OpenFiles(Muscle_photon);

PRectum_files=OpenFiles(Rectum_photon);

Number_Photon_files=size(PBrain_files,1);

% ================= Extact Photon data from the files ====================
% Use the Function DataExtractor to get all the data from the MCNP files
% including the error. This function will also calculate the Absorded
% fraction

[PBrain_EandE, Brainphotonafs]= DataExtractor(Number_organs,...
```

```
    Number_Photon_files,PhotonEnergies,PBrain_files);

[PCrop_EandE, Cropphotonafs]= DataExtractor(Number_organs,...
    Number_Photon_files,PhotonEnergies,PCrop_files);

[PMidgut_EandE, Midgutphotonafs]= DataExtractor(Number_organs,...
    Number_Photon_files,PhotonEnergies,PMidgut_files);

[PMuscle_EandE, Musclephotonafs]= DataExtractor(Number_organs,...
    Number_Photon_files,PhotonEnergies,PMuscle_files);

[PRectum_EandE, Rectumphotonafs]= DataExtractor(Number_organs,...
    Number_Photon_files,PhotonEnergies,PRectum_files);

% =============== Create a Structure to store all values ==================


Brain=struc({'Photon Source in Brain';Brainphotonafs;PBrain_EandE});

Crop=struc({'Photon Source in Crop';Cropphotonafs;PCrop_EandE});

Midgut=struc({'Photon Source in Midgut';Midgutphotonafs;PMidgut_EandE});

Muscle=struc({'Photon Source in Muscle';Musclephotonafs;PMuscle_EandE});

Rectum=struc({'Photon Source in Rectum';Rectumphotonafs;PRectum_EandE});

Photon_Data= [Brain,Crop,Midgut,Muscle,Rectum];

end
```

d. ElectronData

```
function [Electron_Data]=ElectronData(Number_organs,ElectronEnergies)

% Add the directories where your files are loctated. This is necesary
% because matlab needs to know what data is being used. This is not the
% same as going to the directory as 'dir' does
addpath('/Users/mariogomez/Documents/MATLAB/Research/MCNP/uHbee/Brain/Electron')
addpath('/Users/mariogomez/Documents/MATLAB/Research/MCNP/uHbee/Crop/Electron')
addpath('/Users/mariogomez/Documents/MATLAB/Research/MCNP/uHbee/Midgut/Electron'
)
addpath('/Users/mariogomez/Documents/MATLAB/Research/MCNP/uHbee/Muscle/Electron'
)
addpath('/Users/mariogomez/Documents/MATLAB/Research/MCNP/uHbee/Rectum/Electron'
)
% ---------------------------------------------------------------------------

%   Copyright 2015 Mario E. Gomez-Fernandez
% dir goes to the directory to extract the names of the files.
BrainElectronfile=dir(...
```

```
    '/Users/mariogomez/Documents/MATLAB/Research/MCNP/uHbee/Brain/Electron');

CropElectronfile=dir(...
    '/Users/mariogomez/Documents/MATLAB/Research/MCNP/uHbee/Crop/Electron');

MidgutElectronfile=dir(...
    '/Users/mariogomez/Documents/MATLAB/Research/MCNP/uHbee/Midgut/Electron');

MuscleElectronfile=dir(...
    '/Users/mariogomez/Documents/MATLAB/Research/MCNP/uHbee/Muscle/Electron');

RectumElectronfile=dir(...
    '/Users/mariogomez/Documents/MATLAB/Research/MCNP/uHbee/Rectum/Electron');

% get the file names
BraiElectrondata={BrainElectronfile.name}';
Brain_electron=BraiElectrondata(3:end,:);

CropElectrondata={CropElectronfile.name}';
Crop_electron=CropElectrondata(3:end,:);

MidgutElectrondata={MidgutElectronfile.name}';
Midgut_electron=MidgutElectrondata(3:end,:);

MuscleElectrondata={MuscleElectronfile.name}';
Muscle_electron=MuscleElectrondata(3:end,:);

RectumElectrondata={RectumElectronfile.name}';
Rectum_electron=RectumElectrondata(3:end,:);

% ============================== File names ==============================
% Open the file names from the previous step
% ************** function OpenFiles ****************


EBrain_files=OpenFiles(Brain_electron);

ECrop_files=OpenFiles(Crop_electron);

EMidgut_files=OpenFiles(Midgut_electron);

EMuscle_files=OpenFiles(Muscle_electron);

ERectum_files=OpenFiles(Rectum_electron);

Number_Electron_files=size(EBrain_files,1);


% ================ Extact Electron data from the files ===================
%
% ************** function DataExtractor ****************
% Use the Function DataExtractor to get all the data from the MCNP files
% including the error. This function will also calculate the Absorded
```

```
% fraction

[EBrain_EandE, Brainelectronafs]= DataExtractor(Number_organs,...
    Number_Electron_files,ElectronEnergies, EBrain_files);

[ECrop_EandE, Cropelectronafs]= DataExtractor(Number_organs,...
    Number_Electron_files,ElectronEnergies, ECrop_files);

[EMidgut_EandE, Midgutelectronafs]= DataExtractor(Number_organs,...
    Number_Electron_files,ElectronEnergies, EMidgut_files);

[EMuscle_EandE, Muscleelectronafs]= DataExtractor(Number_organs,...
    Number_Electron_files,ElectronEnergies, EMuscle_files);

[ERectum_EandE, Rectumelectronafs]= DataExtractor(Number_organs,...
   Number_Electron_files,ElectronEnergies, ERectum_files);

% =============== Create a Structure to store all values ==================


Brain=struc({'Electron Source in Brain';Brainelectronafs;EBrain_EandE});

Crop=struc({'Electron Source in Crop';Cropelectronafs;ECrop_EandE});

Midgut=struc({'Electron Source in Midgut';Midgutelectronafs;EMidgut_EandE});

Muscle=struc({'Electron Source in Muscle';Muscleelectronafs;EMuscle_EandE});

Rectum=struc({'Electron Source in Rectum';Rectumelectronafs;ERectum_EandE});

Electron_Data= [Brain,Crop,Midgut,Muscle,Rectum];

end
```

e. <u>Dataextractor</u>

```
function [EnergyError, AFs]=DataExtractor(Number_organs,Number_files,
Energies,organ_files)

% ==========================================================================
%
% DataExtractor is a function that will return all the results from all the
% MCNP output files of the given organ. It uses find_val to go through each
% of the files and storing only the values that are needed.
%
% ==========================================================================

%   Copyright 2015 Mario E. Gomez-Fernandez

% Create a zero matrix of Number of organs by 2 time the number of energies
% used
EnergyError=zeros(Number_organs,2*size(Energies,1));
```

```
Energies_only = zeros(Number_organs,size(Energies,1));
% Create an odd and even index to store energies and error from each of the
% output files
oddI=1:2:size(EnergyError,2); %Energy is store in the odd columns
eveI=2:2:size(EnergyError,2); %Error is store in the even columns

%Extract the energies and erros
for i=1:Number_files

    [Energy, Error]=find_val(Number_organs,organ_files(i));

    EnergyError(:,eveI(i))=Error;

    EnergyError(:,oddI(i))=Energy;

    % this for loop is to check if the error in the data is greater or
    % equal to 10%, if not, then the energy value will be zero
    for j=1:length(Error)

        if Error(j) >= 0.1

            Energies_only(j,i)= 0;

        else

            Energies_only(j,i)=Energy(j);
        end

    end


end

% Creata a zero matrix of Number of data extracted by the number of
% energies used in the problem

AFs=zeros(size(EnergyError,1),size(Energies,1));


% Grab all odd columns (contain the *F8 tally results) and divide them by
% the energy to calculate the absorbed fraction and write in a matrix

for i=1:length(Energies)

    AFs(:,i)=Energies_only(:,i)/Energies(i);


end

 end
```

f. OpenFiles

```
function[organ_files]= OpenFiles(organ)

% ==========================================================================
%
% OpenFiles opens the MCNP files and stores them as a matrix. This files
% will be used to extract information (Tallies) from the files
%
% ==========================================================================

%   Copyright 2015 Mario E. Gomez-Fernandez
% Create a matrix of zeros of the same dimensions as the input matrix
organ_files=zeros(size(organ,1),size(organ,2));

%start an index to store the data
n=1;

% Go through every single array in the input cell array and open them
for idx=1:size(organ,1)

    % Store the data in the organ_file matrix
    organ_files(n,:)=fopen(organ{idx});

    n=n+1;

end

end
```

g. find val

```
function [Energy, Error]=find_val(Number_files,filename)

% ==========================================================================

% Find_val file will get find the Energy and Error values from the MCNP
% files and store then into a vector.
% Note: DataExtractor wil organize this values later
%
% ==========================================================================

% Create two zero vectors that has the same amount of rows as the number of
% files

Energy= zeros(Number_files,1);
Error = zeros(Number_files,1);

idx = 1;

% Read the text file and look for 'total', then convernt the strings into a
% number. (18:28) and (30:35) represent the columns in the text where the
```

```
% data is present

while ~feof(filename)

    a = fgets(filename); %next line from text

    if length(a) >= 6  % if the amount of character is > than 6

        if a(1:11) == '      total'
            %store the MCNP result
            Energy(idx,1)=str2double(a(18:28));
            %store the errors
            Error(idx,1)=str2double(a(30:35));

            idx = idx + 1;
        end

    end

end
% close the file
fclose(filename);
end
```

h. Organs

```
function [OrganData]=Organs()

% this function contains information about the organs that were identified
% (segmented)
An=struc({'Antenna';6.8E-7 });
He=struc({'Head'; 2.11E-5});
Th=struc({'Thorax'; 4.95E-5});
Ab=struc({'Abdomen'; 6.72E-5});
Mu=struc({'Muscle'; 9.46E-6});
Le=struc({'Legs'; 9.19E-6});
Br=struc({'Brain'; 2.444E-6});
Ey=struc({'Eyes'; 1.51E-6});
Cr=struc({'Crop'; 1.9E-6});
Re=struc({'Rectum'; 7.07E-7});
Ve=struc({'VenumSac'; 6.93E-8});
Ht=struc({'Heart'; 6.94E-7});
Mi=struc({'Midgut'; 1.61E-6});

OrganData=[An He Th Ab Mu Le Br Ey Cr Re Ve Ht Mi]';

end
```

i. InterData

```
function [Interpolated_Data]= InterData(Data,Energies,Int_Energy,Organs)

%
```

```
==========================================================================
%
% InterData is a function that will interpolate the data based on the
% energies/sources that you will be using. It will return a matrix will
all
% the interpolated values. This script is a bit confusing if you don't
% understand structures and for loops
%
%
==========================================================================

%   Copyright 2015 Mario E. Gomez-Fernandez
Sources=length(Data(1,:));

ERange=length(Energies);

Targets=length(Organs);

% Create a structures to store all the interpolations for each source and
% each energy
Interpolated_Data=struc({});

% Create a matrix to store the data for each source
Inter=zeros(Sources,Targets);

% First for loop will use ach of the source energies
for k=1:length(Int_Energy)

    Interpolated_Data(1,k)=Int_Energy(k,1);
    Interpolated_Data(2,k)=Int_Energy(k,2);

    % Second loop will through all the avalable data of each of the MCNP
    % energies

    for j=1:ERange

        % If statement will look at the upper and lower energy based on
the
        % source energy selected in the first loop

        if Int_Energy{k,2}>=Energies(j,:) &&
Int_Energy{k,2}<=Energies(j+1,:)

            UpE=Energies(j+1,:);
            LoE=Energies(j,:);

            % Third for loop will go throug all the source locations and
            % store then in the matix Inter

            for i=1:Sources

                data=Data{2,i};

                High=data(:,j+1);
```

```
                Low=data(:,j);

                if High==0
                    Interation=0;
                elseif Low==0
                    Interation=0;
                else

                Interation=Low+((Int_Energy{k,2}-LoE)./(UpE-LoE)).*(High-
Low);
                end
                Inter(i,:)=Interation';


            end


        end

        % this Structure is the one that saves all the values for every
        % source location and source energy
        Interpolated_Data(3,k)={Inter};

    end

end
```

j. <u>Graph</u>

```
function Graph=Graph(Data,Energies, Organs)
% ==========================================================================
%
% Graph is a simple plot funciton that will look in to the scructure
% created before and select the data that needs to be plotted, and
% selecting the correct title base on the data you are using.
%
% ==========================================================================
%
% First look at how many columns are in the structure
Number_columns=size(Data,2);
cc=hsv(13);
% Look through each of the colums and grab the title of your plot and the
% data that goes with it
for j=1:Number_columns

%   Copyright 2015 Mario E. Gomez-Fernandez
    Source=Data(1,j);   % Title
    Sub=zeros();        % Create a matrix to store the values that
    Sub=Data{2,j};      % correspond to the title

    Number_rows=size(Sub,1);

    figure
```

```
        for i=1:Number_rows
            hold on
            Graph=plot(Energies,Sub(i,:),'-s', 'Color',cc(i,:));
        end
    % set the labels of the plots
    xlabel ('Energy (MeV)','FontSize',10);
    ylabel ('Absorbed Fraction (unitless)','FontSize',10);
    legend (Organs,'FontSize',12, 'Location','northeastoutside');
    title (['Absorbed Dose Fraction, ',Source],'FontSize',12);
    grid on; set(gca,'YScale','log');
    hold off
    colormap lines;
end

end
```

k. DCFcalc

```
function [AF2Dose]=DCFcal(Masses, source, IntData)


N_columns= size(IntData,2); % all energy source

AF2Dose=struc({});



Masses=[Masses{:,:}]'; %convert cells to numbers
af2dose=zeros(size(IntData{end,1},1));
% This loop will go through all the sources that are available

%   Copyright 2015 Mario E. Gomez-Fernandez
for i=1:N_columns


    %carry the source names and energies

    AF2Dose(1,i)=IntData(1,i);
    AF2Dose(2,i)=IntData(2,i);

    % temporarely store the data that will be used
    Data=IntData{3,i};


    % This for loop will look for the energies that are equal and will
    % extract the row/index were the equal value is located so that it will
    % select the correct constant to multiply
    for c=1:size(source,1)

        row=eq(AF2Dose{2,i},source{c,2});

        if row == 1
```

```
        Const= [source{c,5}];

        end
    end

    % This for look will do the Absorded franction to dose calculation here
    % you will get a set of matrices for each of the energies, so they need
    % to be added later
    for j=1:size(Data,1)

        for k=1:size(Data,2)

            af2dose(j,k)=((Data(j,k)*Const*1000)/Masses(k))*...
                (3600*Masses(k)*24/1E6);


        end

    end

    AF2Dose(3,i)={af2dose};

end


end
```

l. DCFadd

```
function [DCFs]=DCFadd(PDCFcalcs, EDCFcalcs,sources_names)


%   Copyright 2015 Mario E. Gomez-Fernandez

DCFs=struc({});

    for i=1:size(sources_names,1)


        A=zeros();        % Matrix to get an index
        B=zeros();        % Matrix to get an index
        PADD=zeros();     % Matrix to temporarely store data
        EADD=zeros();     % Matrix to temporarely store data

        DCFs(1,i)=sources_names(i);

        %look for each  of the source names in the photon category
        for c=1:size(PDCFcalcs,2)

            A(1,c)=strcmp(PDCFcalcs{1,c},sources_names{i});
```

```
        end
        % store them in a matrix
        [~,pc]=find(A==1);

        %look for each of the source name in the electron category
        for c=1:size(EDCFcalcs,2)

            B(1,c)=strcmp(EDCFcalcs{1,c},sources_names{i});

        end
        %store them in a matrix
        [~,ec]=find(B==1);

        % because we have determine their location in the structure then we
        % need to add all the matrices that have the same source
        % this for lop does it for photons
        for j=1:size(pc,2)
            if pc(j) == 0
                continue
            else
            PADD= PADD+PDCFcalcs{end,pc(j)};
            end
        end

        % This other for loop does it for electrons
        for j=1:size(ec,2)
            if ec(j) ==0
                continue
            else
            EADD=EADD+EDCFcalcs{end,ec(j)};
            end
        end
        % Add both electons and photons to get the DCF and the final
        % results, then repeat until all the sources are completed

        DCFs{2,i}= PADD+EADD;

    end

end
```