RADIATION DOSE STUDY IN NUCLEAR MEDICINE USING GATE

by

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A Thesis Submitted to the Faculty of the

COLLEGE OF OPTICAL SCIENCES

In Partial Fulfillment of the Requirements
For the Degree of

MASTER OF SCIENCE

In the Graduate College

THE UNIVERSITY OF ARIZONA

2015

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ACKNOWLEDGEMENTS

DEDICATION

To my parents and the many who inspired me.

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ABSTRACT

Dose as a result of radiation exposure is the notion generally used to disclose the imparted energy in a volume of tissue to a potential biological effect. The basic unit defined by the international system of units (SI system) is the radiation absorbed dose, which is expressed as the mean imparted energy in a mass element of the tissue known as gray (Gy) or J/kg. The procedure for ascertaining the absorbed dose is complicated since it involves the radiation transport of numerous types of charged particles and coupled photon interactions. The most precise method is to perform a full 3D Monte Carlo simulation of the radiation transport.

There are various Monte Carlo toolkits that have tool compartments for dose calculations and measurements. The dose studies in this thesis were performed using the GEANT4 Application for Emission Tomography (GATE) software (Jan et al., 2011). GATE simulation toolkit has been used extensively in the medical imaging community, due to the fact that it uses the full capabilities of GEANT4. It also utilizes an easy to-learn GATE macro language, which is more accessible than learning the GEANT4/C++ programming language.

This work combines GATE with digital phantoms generated using the NCAT (NURBS-based cardiac-torso phantom) toolkit (Segars et al., 2004) to allow efficient and effective estimation of 3D radiation dose maps. The GATE simulation tool has developed into a beneficial tool for Monte Carlo simulations involving both radiotherapy and imaging experiments. This work will present an overview of absorbed dose of common radionuclides used in nuclear medicine and serve as a guide to a user who is setting up a GATE simulation for a PET and SPECT study.

CHAPTER 1

Introduction

Monte Carlo simulations use random sampling methods for representing and solving physical and mathematical problems. Monte Carlo simulations are used in a variety of applications in medical physics and have matured into a vital tool for modeling radiation transport involving electrons and photons. In medical physics, the GEANT4 simulation toolkit (Agostinelli et al. (2003)) is attracting increasing interest because of its great versatility. GEANT4 is a Monte Carlo toolkit that simulates particle interactions with matter such as electromagnetic interactions of charged particles, gamma rays and photons, particle decay processes and more. GEANT4 can play a key role in medical applications, both for imaging and radiotherapy, by accurately modeling the different physical processes and interactions between particles (including photons) and matter (tissues and/or detectors). For instance, Monte Carlo simulations are used in the design of imaging systems, optimization of acquisition protocols, as well as in the development and assessment of image reconstruction processes and associated correction algorithms (Barret et al. (2005), Rehfeld et al. (2005), Zhang et al. (2010)). The use of Monte Carlo simulations in radiotherapy allows accurate dosimetry calculations within the treatment planning stage (Verhaegen and Seuntjens (2003), Flampouri et al. (2006), Rassiah-Szegedi et al. (2007)).

Within the GEANT4 simulation there is an extensive array of physics properties for electromagnetic, hadronic and optical interactions for a sizable grouping of particles over a vast energy range. There are a lot of options with the use of GEANT4, its diverse nature allows a user to define unique geometries, model different sources and detection systems. The main drawback with the versatility of GEANT4 is its complexity. New users must spend a considerable amount of effort before they are able to make effective use of this object-oriented code written in the C++ program-

ming language. GATE Monte Carlo simulation platform (Jan et al. (2004b)) makes use of a wide range of GEANT4 functionality available through a user-friendly interface and has gained widespread use in the field of nuclear medicine for simulating PET and SPECT imaging devices. However, Monte Carlo simulations are associated with long execution times, which is one of the major concerns preventing its use in routine clinical practices for both image reconstruction and dosimetry applications.

GATE could be useful in many other dosimetry applications; it can be used for dose calculations in nuclear medicine, both for diagnostic applications (e.g. analysis of the radiation burden to patients) and for therapeutic applications (e.g. treatment planning in radio-nuclide therapy and treatment verification through emission scans). In this thesis work, we will explore the applicability of GATE in nuclear medicine.

Section 1.1 will start by introducing nuclear-medicine imaging and the tracer principle. Then we will discuss radiation, dose and common physical quantities and units encountered in radiology. A brief overview of positron emission tomography (PET) and single photon emission computed tomography (SPECT) will be introduced.

Chapter 2 will deal with nuclear chemistry basics, explaining isotopes and isotope notation. Section 2.2 will define the meaning of half-life and will lead into the different radioactive decays and types of radioactive interactions within matter.

In Chapter 3 the Monte Carlo simulation package GATE (GEANT4 Application for Tomographic Emission) was used to simulate the various types of radioisotopes used in the thesis. An introduction on the various required modules/parts to building a GATE simulation is introduced starting from Section 3.5.

Chapter 4 will demonstrate how dose is obtained from the GATE package. Chapter 5 will examine three different types of studies performed using GATE. The first simulation is the study of absorbed dosage from numerous radioisotopes administered in a water phantom. The second simulation is a comparison study of absorbed dose from a spherical source and a point source. And the third simulation is a study of dose for a realistic phantom using NCAT (NURBS-based cardiac-torso) phantom.

1.1 Nuclear Medicine

Nuclear medicine is a medical specialty that involves the use of a medicine (a pharmaceutical) that is attached to a small quantity of radioactive material (a radioisotope). This combination is called a radio-pharmaceutical, or more commonly, a *tracer* or *radiotracer* (Cherry et al. (2012)). Radiopharmaceuticals can be used to study how the human body operates, by measuring how these tracers distribute themselves within the body. For example, tumors and some organs, such as the brain, use glucose as a source of energy. FDG (fluorodeoxyglucose) is a fluorine-18-labeled (^{18}F) derivative of glucose which is used with positron emission tomography (PET) to provide a map of where glucose is metabolized in the body. FDG is broadly utilized as a part of cancer determination, cardiology, neurology and psychiatry because tumors, the brain and the heart all use glucose as a source of energy.

The clinical practice of nuclear medicine incorporates the administration of radiotracers (gamma-ray-emitting or positron-emitting radio-nuclides) into the body. Gamma rays or high-energy photons are emitted when the radio-nuclides undergoes its decay process, or when the emitted positron interacts with an electron. The energy of these gamma rays can exit the body and can be detected by a gamma-ray camera.

1.2 Radiation

1.2.1 What is Radiation?

The term *radiation* refers to "energy in transit" (Cherry et al. (2012)). Radiation is simply the process involving the release of energy. The most familiar form of radiation is visible light, like that produced by the sun or even a light bulb. Other forms of radiation include radiowaves, microwaves, ultraviolet light, x-rays and gamma rays used in medical procedures. Figure 1.1 illustrates two types of radiation, *non-ionizing radiation* and *ionizing radiation* with a wide range of energies that form the electromagnetic spectrum.
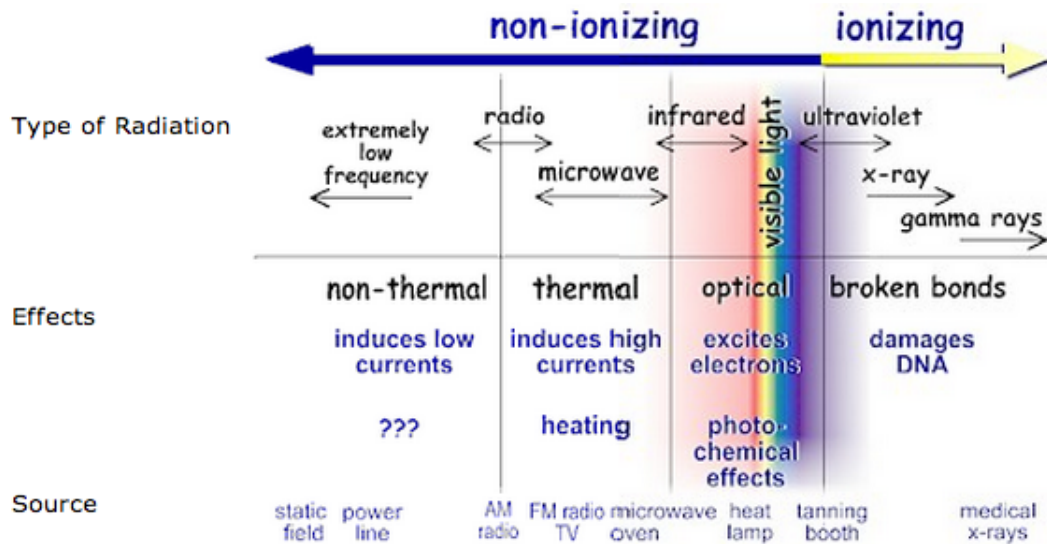
Figure 1.1: Types of Radiation in the Electromagnetic Spectrum. Image from (http://www.epa.gov/radiation/understand/index.html).

Photons of a higher frequency than the ultraviolet (UV) region of the spectrum (i.e., wave-lengths greater than 200 nm) have sufficient energy per photon to remove a bound electron from atomic shells, thereby producing ionized atoms and molecules. Ionization is the resultant procedure when a molecule or an atom gets a negative or positive charge from picking up or losing electrons respectively. Radiation in this portion of the spectrum (i.e., x-rays and gamma rays) is called *ionizing radiation*. Electromagnetic radiation with photons energies in and below the UV region (e.g., visible, infrared, terahertz, microwave and radio waves) is called *non-ionizing radiation* (Bushberg (2012)).

There are numerous types of nuclear radiation, which can accompany the decay of an atom. The following lists, which are covered in the chapters ahead, are nuclear radiations that are simulated in this thesis work.

- x-rays

- γ-rays (gamma-rays)

- β-particles (beta particles)

- positrons

- neutrons

- α-particles (alpha particles)

1.2.2 X-rays and gamma-rays

X-rays and gamma-rays are photons like visible radiation however of much higher energy, so they can penetrate and travel through materials that visible light cannot. Gamma-rays and x-rays radiations are often defined by their origin due to their overlap in energy ranges. There is no difference between x-rays and gamma-rays. X-rays are photons created when an electron changes its energy state in the cloud encompassing the atom. Gamma-rays are created by the decay of a radioactive atom when a nucleon changes its energy state inside the nucleus.

1.2.3 Beta-particles (electrons)

Beta-particles are fast-moving electrons. The only difference between a beta particle and electron is that a beta particle originates in the nucleus of an atom that undergoes a radioactive decay and an electron orbits around the nucleus. At the point when a neutron in the nucleus of an atom converts to a proton, an electron is produced. This newly produced electron is used to balance the electric charge and the energy released by that transformation. These electrons interact with the electric charges associated with atoms and they transfer their excess energy to the material through which they are traveling. This process is called bremsstrahlung. Other processes such as photoelectric effect and compton effect, which will be covered in the sections ahead are also causes of energy transfer to material.

1.2.4 Positrons

Positrons have the same mass as electrons, but have a positive electric charge. They are produced within a nucleus when a proton is converted to a neutron and

they travel through air and tissue, similar to β-particles of the same energy. Once a positron has diminished its energy to approximately the average energy of the electron in a material through which it is traveling, it will interact with an electron. This interaction will convert the pair of particles into two γ-rays that move in opposite directions. These two γ-rays have energy of 511 KeV (energy analogous to the rest mass of the electron) and are fundamental to the technique of positron emission tomography (PET) (see Section 1.3.2).

1.2.5   Neutrons

Neutrons are comparable to protons; they have the same mass and they make up the nucleus. Unlike protons, neutrons can travel long distances before its energy has been depleted.

1.2.6   Alpha-particles

When the nuclei of an unstable atom ejects alpha particles, it is releasing a form of ionizing radiation. These alpha particles consists of two protons and two neutrons holding a net charge of +2 and is generally produced in the process of alpha decay (see Section 2.3.3).

1.2.7   Energy of nuclear radiations

There are changes amongst the protons and neutrons contained in a nucleus during a nuclear process. The energy between these two particles are greater than the neclear binding between atoms (binding energy necessary to hold a nucleus together). The energy of any nuclear radiation can be related to the mass that was lost when the atom undergoes a radioactive decay process. The equation relating the energy (E) to the mass loss (m) is given by Einstein's formula

$$E = mc^2 \tag{1.1}$$

where c is the velocity of light. Einstein's formula exemplifies that mass and energy

are both different manifestation of the same thing. It shows that every amount of mass has an energy equivalent and vice versa. During a nuclear transition to a lower or higher energy level, photons can be emitted or absorbed. A photon can also be emitted when an electron and a positron are annihilated. In this case mass is converted to energy during an electron-positron annihilation process when an electron interacts with a positron. This electron-positron interaction will annihilate with the production of two gamma photons:

$$\text{e}^- + \text{e}^+ \longrightarrow \gamma_1 + \gamma_2 \tag{1.2}$$

And since energy and momentum must be conserved, the electron and positron are simply transformed into two gamma-rays in opposite direction.

During these processes, photons carrys energy and momentum. The amount of energy in a photon is given by this equation,

$$E = h\nu \tag{1.3}$$

where E is the energy of the photon; h is Planck's constant; and ν is the frequency of the photon. The momentum of a photon is calculated by combining Einstein's formula with the photon energy equation resulting to

$$P = \frac{h}{\lambda} \tag{1.4}$$

where λ is the wavelength of the photon.

1.3 Fundamental Concepts

1.3.1 Quantities and units

There are different characteristics of an x-ray beam or gamma radiation that can be utilized to express the physical amount of radiation. The primary objective of this section is to show the various radiation quantities and units. A listing of these physical quantities and units encountered in radiology is shown in Table 1.1. The

table is a useful reference for the conversion of one system of units to another. These concepts will be further discussed in chapter 4. Other useful conversion calculators are found online.[1]

Table 1.1: Radiation units and conversion factors.

Quantity	Conventional Unit	SI Unit	Conversions
Exposure	roentgen (R)	coulomb/kg of air (C/kg)	1 C/kg = 3876 R
			1 R = 258 uC/kg
Dose	rad (R)	gray (Gy)	1 Gy = 1 J/kg
Equivalent Dose	rem	sievert (Sv)	1 Sv = 1 J/kg
Radioactivity	curie (Ci)	becquerel (Bq)	1 mCi = 37 MBq

1.3.2   Background of PET/SPECT

There are two primary imaging modalities that are used in nuclear imaging: *single photon emission computed tomography* (SPECT) and *positron emission tomography* (PET). In both procedures radioactive substances are being used and the image acquisition takes place by the use of gamma-ray detectors. These images provide projection data needed for reconstructing cross-sectional images using different reconstruction techniques.

SPECT imaging uses radionuclides that decay and produce gamma-ray emissions. These emissions are imaged using a gamma-ray detector placed parallel to the patient or object. The images obtained are called the two-dimensional (2D) image projections; which are recorded from different angles around the patient. A reconstruction algorithm is then used on the multiple projections, yielding a three-dimensional (3D) dataset. During SPECT data acquisition, a collimator is needed to form the projection images. A collimator in SPECT is usually made of high Z (atomic number) materials such as thick lead, and it is used to form an image by selecting the direction along which gamma-rays propagate.

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[1]http://www.radprocalculator.com/Conversion.aspx

PET imaging makes use of radionuclides that decay by positron emission which annihilate with an electron and generate two collinear gamma-rays. These two gamma-rays can be detected coincidently using a ring of gamma-ray detectors (Barrett and Myers (2004)). Collecting these coincident data in an orbit around the patient forms tomographic data. In PET the collimator is not needed, unlike SPECT. Instead one counts just the events that take place in pairs and uses them for image reconstruction.

1.3.3 Current practice of Nuclear Medicine

Nuclear medicine is utilized for a wide assortment of analytic tests. There were approximately 100 different diagnostic imaging methods accessible in 2006 (Cherry et al. (2012)).These techniques use various radiolabeled mixes, cover all the critical organs in the body and give an extensive variety of measures of biologic capacities. Table 1.2 lists a few essential clinical methodologies in nuclear medicine.

Table 1.2: Selected clinical nuclear medicine procedures.

MDP, methyl diphosphonate; MAG3, mercapto-acetyl-triglycine; DTPA, diethylentriaminepenta-acetic acid; HMPA, hexamethylproyleneamin oxime; ECD, ethly-cystine-dimer; SPECT, single photon emission tomography; PET, positron emission tomography. Note: Planar imaging refers to nuclear medicine scans that are two-dimensional (2D) images. Table from (Cherry et al. (2012)).

Radiopharmaceutical	Imaging	Measurement	Example of Clinical Use
^{99m}Tc$-$MDP	Planar	Bone metabolism	Metastatic spread of cancer, osteomyelitis vs. cellulitis
^{99m}Tc$-$sestamibi(Cardiolite)	SPECT or planar	Myocardial perfusion	Coronary artery disease
^{99m}Tc$-$tetrofosmin(Myoview) ^{201}TI$-$thallouschloride			
^{99m}Tc$-$MAG$_3$ ^{99m}Tc$-$DTPA	Planar	Renal function	Kidney disease
^{99m}Tc$-$HMPAO(Ceretec)	SPECT	Cerebral blood flow	Neurologic disorders
^{99m}Tc$-$ECD	SPECT	Cerebral blood flow	Neurologic disorders
^{123}I$-$sodiumiodide ^{131}I$-$sodiumiodide	Planar	Thyroid function	Thyroid disorders Thyroid cancer
^{67}Ga$-$galliumcitrate	Planar	Sequestered in tumors	Tumor localization
^{99m}Tc$-$macroaggregated albumin and ^{133}Xe$-$gas	Planar	Lung perfusion/ ventilation	Pulmonary embolism
^{111}In$-$labeledwhiteblood cells	Planar	Sites of infection	Detection of inflammation
^{18}F$-$fluorodeoxyglucose	PET	Glucose metabolism	Cancer, meurological disorders and myocardial diseases
^{82}Rb$-$rubidiumchloride	PET	Myocardial perfusion	Coronary artery disease

CHAPTER 2

Nuclear Physics basics

2.1   Isotope notation

Isotopes are different forms of an atom, in most respects they differ by the numbers of neutrons in the nucleus. When we describe an atom, we want to show quickly how many protons and neutrons are in the atom. Isotope notation is the way we can write a symbol for an atom, showing the number of protons, neutrons and sometimes electrons. Below is an example of an atom written in isotope notation:

$$^{24}_{12}\text{Mg}. \tag{2.1}$$

The letters represent the element symbol of the atom where Mg is Magnesium. The number 12 is the atomic number, also known as the number of protons that are in the nucleus of the atom. The number 24 is the mass number, which is the number of protons plus the number of neutrons. The number of neutrons varies with the isotope. There are three isotopes of Magnesium: Magnesium-24, which contains 12 neutrons; Magnesium-25, which contains 13 neutrons; and Magnesium-26, which contains 14 neutrons.

An element symbol is written in isotope notation because we want to determine the number of protons, neutrons and electrons that element is composed of. For the atom Magnesium-25, we have 12 protons, 13 neutrons and 10 electrons.

2.2 Nuclear half-Life

There are several radioactive decay processes where the number of protons and neutrons in an atoms nucleus change. The following

$$^{234}_{90}\text{Th} \longrightarrow {}^{234}_{91}\text{Pa} + {}^{0}_{-1}\beta \tag{2.2}$$

is an example of a nuclear process where Thorium (Th) undergoes beta decay and turns into Protactimium (Pa). When Thorium undergoes beta decay it means that one of its neutron turns into a proton. Further, it originally had 90 protons and then it receives an additional proton for a total of 91 protons. The quantity of protons an atom has is used to distinguish it from one element of an atom to another.

Nuclear half-life is the time needed for 50 percent of an atom in a radioactive sample to decay. Thorium has a half-life of 24 days, meaning if we begin with 80 grams of Th and 24 days passes, at the end of those 24 days we are left with 40 grams of Th and the other 40 grams of Th would have turned into Pa. After another 24 days, we are left with 20 grams of Th and so forth. By way of illustration Figure 2.1 shows a graph of Th going to Pa. Table 2.1 shows some common radioisotopes and their half-lives used in nuclear medicine.
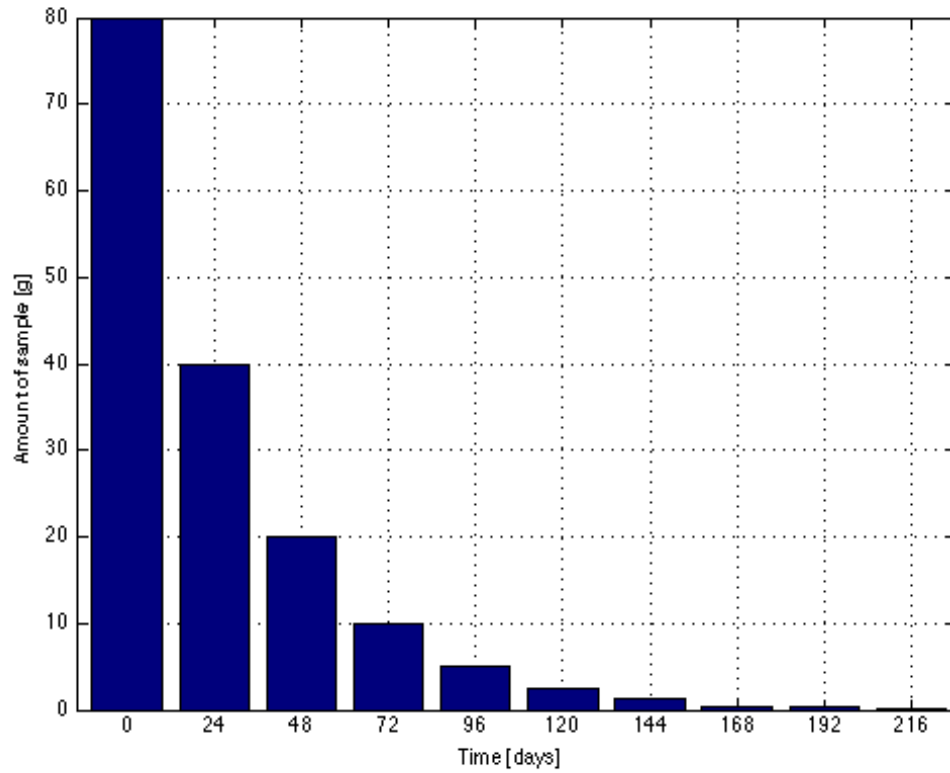
Figure 2.1: Decay of Thorium atom to Protactinum atom.

Table 2.1: Common radioisotopes and their half-life used in nuclear medicine. Table from (Johnson et al. (2012)). The subscript m in the isotope symbol name stands for metastable (an excited nucleus). For the nucleus to transition to a stable state it has to release excess energy by emitting gamma-rays.

Isotopes	Half-Lifes
$^{18}_{9}\text{F}$	109.8 min
$^{99m}_{43}\text{Tc}$	6.006 hr
$^{90}_{39}\text{Y}$	64.05 hr
$^{123}_{53}\text{I}$	13.22 hr
$^{131}_{53}\text{I}$	8.02 d
$^{111m}_{49}\text{ln}$	2.8 d

2.3 Radioactive decay

In this section the symbols used to represent the various particles encountered in nuclear reactions are identified in Table 2.2.

Table 2.2: Symbols Used in Nuclear Chemistry.

Name	Notation	Symbol
alpha particle	^4_2He or $^4_2\alpha$	α
beta particle	$^0_{-1}\text{e}$ or e^- or $^0_{-1}\beta$	β^-
gamma radiation	$^0_0\gamma$	γ
neutron	^1_0n	n
proton	^1_1H or ^1_1P	p
positron	$^0_{+1}\text{e}$ or e^+ or $^0_{+1}\beta$	β^+

2.3.1 Beta decay

Beta decay, otherwise called beta-minus decay happens in the nucleus of an atom. During beta decay, one of the neutrons in the nucleus turns into a proton and produces an electron. The electron that is created is not just any electron; it is a fast moving electron that is released from the atom. These fast moving electrons are called beta particles.

Atoms experience radioactive decay on the grounds that they are unstable. In particular, an atom that undergoes beta decay often has more neutrons in the nucleus than protons, making it unstable. By beta decaying, the atom can achieve a more stable arrangement of its protons and neutrons. This process gives off radiation in the form of beta particles or high-energy beta rays. For example,

$$^{14}_{6}\text{C} \longrightarrow {^{14}_{7}\text{N}} + {^{\ 0}_{-1}\beta} \tag{2.3}$$

represents an atom of Carbon-14 undergoing beta decay and transforming into Nitrogen-14. The number of protons determines what kind of element is left after the process.

2.3.2 Positron decay

Atoms that undergo positron decay have more protons than neutrons in the nucleus. To balance the nucleus, the atom must undergo a positron decay process in which one of the atoms proton will transform into a neutron. Therein a positron particle is created. Such as

$$^{11}_{6}\text{C} \longrightarrow {}^{11}_{5}\text{B} + {}^{0}_{+1}\beta \,, \tag{2.4}$$

where Carbon-11 is undergoing positron decay and turn into Boron-11.

2.3.3 Alpha decay

Alpha decay is a type of radioactive decay that an atom undergoes if it has a large atomic mass. During this process the atom will discharges two neutrons and two protons from its nucleus in order to reduce its atomic mass; the discharged neutrons and protons make up what is called an alpha particle. In this example,

$$^{233}_{92}\text{U} \longrightarrow {}^{229}_{90}\text{Th} + {}^{4}_{2}\alpha \tag{2.5}$$

represent Uranium-233 atom transforming into Thorium-231 atom after releasing two neutrons and protons.

2.3.4 Electron capture

Electron capture is a nuclear process that affects the number of protons and neutrons in the nucleus. During electron capture, the nucleus of an atom absorbs an orbiting electron and converts a proton into a neutron. Where the other forms of decays are releasing particles, like a beta particle or an alpha particle, electron capture is capturing an electron particle.

The captured electron comes together with a proton to produce a neutron. In this process, gamma rays are also produced. Gamma rays are high-energy waves that are produced from the atom during the process of combining an electron with

a proton to make a neutron. For instance, the example below shows an atom of Potassium-40 undergoing electron capture and turning into an Argon-40 atom.

$$^{40}_{19}\text{K} + {}^{0}_{-1}\text{e} \longrightarrow {}^{40}_{18}\text{Ar} + \gamma \qquad (2.6)$$

2.3.5 Isomeric transition

After an atom experiences radioactive decay that involves a beta emission, positron emission, or electron capture, this atom will have extra energy to be in its final stable state. In order for the nuclei of the atom to transition to a stable or ground state, it will undergo an isomeric transition by emitting the excessive energy (Sprawls (1993)).

2.3.6 Nuclear stability

The ratio of neutron/proton (N/Z) is used to determine the stability of a nuclide. As stated in Section (2.1), the number of protons is equal to the atomic number (Z). Subtracting the atomic number from the atomic mass (A) of an element will result in the number of neutrons (N) that an element has

$$A - Z = N \,. \qquad (2.7)$$

Figure 2.2 is a plot of all the stable nuclei consisting neutrons (y-axis) and protons (x-axis). This plot can determine where the radioactive decay occurs. Isotopes that have a ratio of 1:1 have smaller mass (lighter) and isotopes with a ratio of 1.5:1 have larger mass (heavier). If the ratio of these isotopes does not fall between 1:1 and 1.5:1 then they are considered unstable (Chang and Cruickshank (2005)). A more accurate plot and useful tool for determining the stability of any isotope is found on this graphical user interface (GUI) website.[1] Table 2.3 presents a listing of commonly used radionuclides for nuclear medicine.

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[1] http://employees.oneonta.edu/viningwj/sims/stability_of_isotopes_s.swf
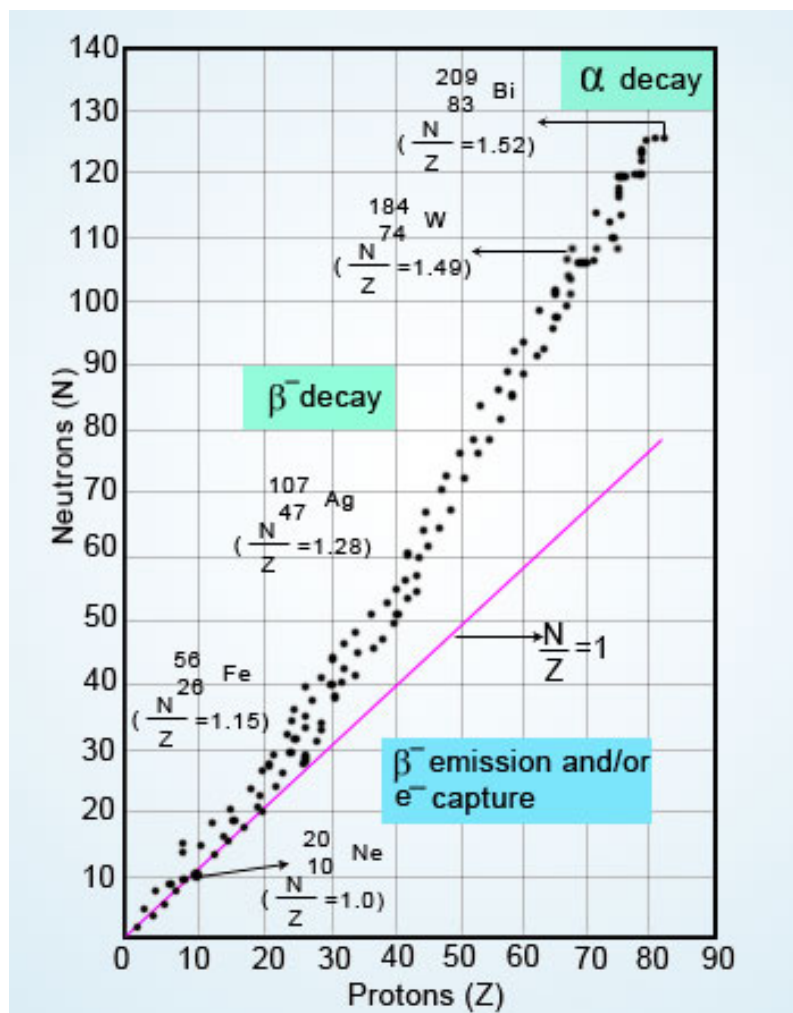
Figure 2.2: The N-Z curve is a plot of the number of neutrons(N) against the number of protons(Z). This plots shows the stability line that starts from the origin and veers above the N/Z = 1 line. Nuclides with N/Z >1 often undergo β^- decay, those with N/Z <1 undergo e^- capture or β^+ emission; nuclei with large (heavy) atomic mass that are beyond the stable band (top of curve) undergoes α decay. Image from (http://www.wwk.in/chemistry/structure-of-matter/nuclear-chemistry).

Table 2.3: Physical properties of radionuclides used in nuclear medicine studies. EC, electron capture; IT, isomeric transition. Table from (Cherry et al. (2012)).

Radionuclide	Decay Mode	Principal Photon Emissions	Half-life	Primary Use
^{11}C	β^+	511 keV	20.4 min	Imaging
^{13}N	β^+	511 keV	9.97 min	Imaging
^{15}O	β^+	511 keV	2.03 min	Imaging
^{18}F	β^+	511 keV	110 min	Imaging
^{32}P	β^-	–	14.3 d	Therapy
^{67}Ga	EC	93, 185, 300 keV	3.26 d	Imaging
^{82}Rb	β^+	511 keV	1.25 min	Imaging
^{89}Sr	β^+	–	50.5 d	Therapy
^{99m}Tc	IT	140 keV	6.02 hr	Imaging
^{111}In	EC	172,247 keV	2.83 d	Imaging
^{123}I	EC	159 keV	13.2 hr	Imaging
^{125}I	EC	27-30 keV x-rays	60.1 d	In vitro assays
^{131}I	β^-	364 keV	8.04 d	Imaging
^{153}Sm	β^-	41, 103 keV	46.7 hr	Imaging
^{186}Re	β^-	137 keV	3.8 d	Imaging
^{201}TI	EC	68-80 keV x-rays	3.04 d	Imaging

2.4 Interaction of radiation with matter

2.4.1 Types of photon interaction

Light and all other forms of electromagnetic radiations can display particle-like behavior. These light particles are called photons and they correspond to a discrete amount of energy. Photons transfer their energy to matter through interactions with atoms, nucleus and electrons. These interactions do not result in ionization specifically, but a percentage of the photon interactions bring about the ejection of orbital electrons from the atom, or the production of electron-positron pairs. (Cherry et al. (2012)).

There are several different types of photon interactions with matter. Photoelectric effect and coherent (Rayleigh) scattering are forms of photon interactions that are associated with a tightly bound electron. Photons can also interact with the

orbital cloud around the nucleus which results in pair production (see section 2.4.4) and also with a free electron that leads the Compton effect (see section 2.4.3). A tightly bound electron in the context of photon interactions, is an orbital electron with a binding energy larger that the photon energy, while a free electron is an electron with binding energy that is smaller than the photon energy.

Photons can be absorbed (photoelectric effect, pair production), scattered coherently (coherent scattering), or incoherently (compton effect) as result of interactions with a particle. Table 2.4 summarizes these interactions of photons with matter.

Table 2.4: Interactions of photons with matter.

Interactions	Effects
Photoelectric effect	Photon is absorbed and transfers all of its energy
Compton scattering	Part of the photon energy is absorbed scattered photon continues on with lower energy
Pair production	Positron-electron pair is created requires photons above 1.022 MeV
Rayleigh scattering	Photon deflected with very little energy loss only significant at low photon energies (<50 keV)

2.4.2 Photoelectric effect

The photoelectric effect happens when a photon interacts with a tightly bound orbital electron of an atom. The photon transfers its energy to the electron and if the photon has enough energy then the electron is ejected as a photoelectron, otherwise there is no interaction. The new photoelectron has mass, velocity and kinetic energy E_k given as:

$$E_k = E_0 - E_b \, . \tag{2.8}$$

The incident photon's energy is expressed as $E_0 = hv$, h is the Planck's constant and v is frequency of the photon. E_b is the closest electron shell (or K shell) binding energy of the electron. This photon interaction is depicted as a collision of the

incident photon and the orbital electron. By conservation of energy, the photon is absorbed and therefore the electron is ejected from the atom as a photoelectron with a kinetic energy as shown in Figure 2.3. These newly ejected photoelectrons must have sufficient energy from the incident photon to exceed the binding energy of that shell. Since the energy of one photon may only be absorbed by one electron then there is one photon per photoelectron ejected.
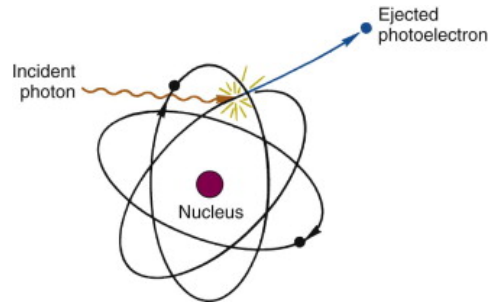
Figure 2.3: Schematic representation of photoelectric effect. The incident photon transfers its energy to a photoelectron and disappears. Image from (Cherry et al. (2012)).

2.4.3 Compton scattering

Compton scattering is a form of incoherent scattering photon and electron interaction, in which the collision is between the incident photon and an outer-shell orbital electron of an atom. In Compton scattering, the energy of the incident photon very much surpasses the binding energy of the electron in the atom as illustrated in Figure 2.4.

The difference between photoelectric effect and Compton effect is that the photon is not absorbed, it is scattered at an angle θ. θ is known as the scattering angle between the incident photon and the scattered photon. By conservation of energy, the energy of the incident photon E_0 is equal to the sum of the energy of the scattered photon E_{se} and the kinetic energy of the ejected electron E_k:

$$E_0 = E_{se} - E_k \,. \tag{2.9}$$
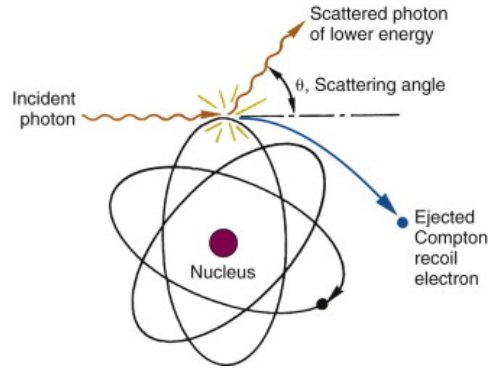
Figure 2.4: Schematic representation of Compton scattering. The incident photon transfers part of its energy to a Compton recoil electron and is scattered in another direction of travel (θ, scattering angle). Image from (Cherry et al. (2012)).

The energy of the scattered photon can be calculated from the energy of the incident photon and the angle of the scattered photon:

$$E_{se} = \frac{E_0}{1 + \frac{E_0}{511 keV}(1 - cos\theta)} . \tag{2.10}$$

The scattered photon has lower energy, lower frequency and longer wavelength according to the Planck relationship.

2.4.4   Pair production

Pair production occurs when a photon interacts with the electric field of charged particles surrounding the nucleus. This interaction leads to an electron and positron pair. Pair production can only occur when the energies of incident photons exceeds 1.02MeV (2 x 0.511-MeV) (Bushberg (2012)). 1.02MeV is the rest mass of the positron and of the electron. This energy is used to produce the positron-electron pair and the remaining goes into the kinetic energy that is shared by the pair. At the point when pair production happens, the energy of the photon is changed over into mass through Einstein's formula 1.1. See Figure 2.5.
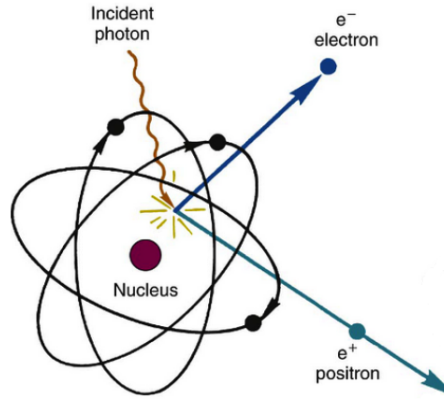
Figure 2.5: Schematic representation of pair production. Energy of incident photon is converted into an electron and a positron (total 1.022-MeV mass-energy equivalent) plus their kinetic energy. Image from (Cherry et al. (2012)).

The difference between the incident photon energy E_0 and the 1.02 MeV of energy required to create the electron pair is imparted as kinetic energy to the positron E_{e+} and the electron, E_{e-} as in Equation 2.11. When the positron has depleted its kinetic energy and is at rest, a pair of 0.511-MeV annihilation photons are emitted in opposite directions from the site:

$$E_{\gamma_1} + E_{\gamma_2} = 1.02 MeV. \tag{2.11}$$

2.4.5 Rayleigh scattering

Rayleigh scattering is a form of coherent scattering where the photon interacts with an electron bound by the electric field of the nucleus. This photon and electron interaction is elastic such as the photon loses no energy and is scattered through a small angle (Podgoršak (2005)). Rayleigh scattering is of little importance in nuclear medicine because it is not an effective process for transferring photon energy to matter.

2.4.6   Energy in matter

Photoelectric effect, Compton scattering and pair production are the most important interactions in the transfer of photon energy to matter. The exchange of energy happens ordinarily in a progression of these interactions where energy is transferred to electrons and normally secondary photons of lower energy. Figure 2.6 shows these interactions. The consequences of the results of this interaction are secondary photons and high-energy electrons. The deposition of energy in matter is a result of high-energy electrons.

Figure 2.6: Multiple interactions of a photon passing through matter. Energy is transferred to electrons in a sequence of photon-energy-degrading interactions. Image from (Cherry et al. (2012)).
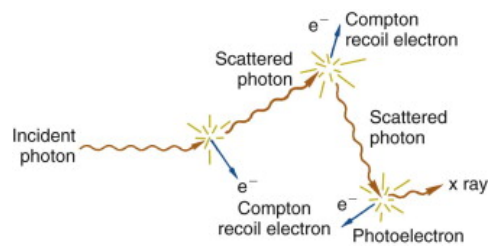
CHAPTER 3

Overview of GATE

3.1   Monte carlo simulations

Simulations are very powerful when used to investigate the influence of design parameters on the performance of a system. Simulation will always be an approximation of reality; it makes it possible to vary parameters that cannot be varied in measurements. What would be the performance if we would have no electronic noise? What would be the performance if radiation did not scatter? Questions like this cannot be answered by measurements, but can give valuable information on how the system works.

For simulating various radioisotopes sources in matter/tissues, a Monte Carlo simulation package GATE (GEANT4 Application for Tomographic Emission) was used. Monte Carlo simulations are simulations that use random numbers. Monte Carlo incorporates probability into risk analysis in order to produce distributions of possible outcome values. Numerous calculations are done each time using a different set of random values from the probability functions. The rapidness and accuracy of Monte Carlo simulations rely on the number of uncertainties and the range of input parameters identified for them.

For example, suppose there is a photon annihilation with an energy of 511 keV traveling through a certain material. There are a number of interactions this photon can have. It can Compton scatter, or it can undergo the photoelectric effect (absorption). Both types of interactions have a constant probability per distance travelled in a given material. The simulation program determines for both of the processes the (random) distance at which the interaction would occur. The interaction with the shortest distance is selected. The photon is transported the given distance and then undergoes the interaction where new particles (e.g. electrons, photons) may

be created and the properties of the photon (e.g. energy, direction) are modified.

As stated in Section 2.4, deposition of energy in matter is caused by the photoelectron from Photoelectric effect, recoil electron from Compton scattering and positron-electron pair from pair production. The radiation dose recorded by GATE is the result of these photon interactions.

3.2   What is GATE?

GATE stands for GEANT4 Application for Tomographic Emission. It harnesses the GEANT4 core functionalities into a modular manifestation of a scripted language. (Jan et al. (2004b)). GATE is an open-source (free license) simulation package developed by the OpenGATE collaboration. As stated in chapter 1, GEANT4 is used to simulate the interactions of particle as they pass through matter. GATE can be used in many other industries but OpenGATE has developed and dedicated GATE to only performing Monte Carlo simulations in medical imaging and radiotherapy. GATE is currently used for simulations involving PET, SPECT, CT and radiotherapy experiments.[1]

A disadvantage to its open-source nature is that the documentation for specialized tasks such as dose computations is limited and not regularly updated. This section describes the general steps for dose computations using GATE. It is intended to supplement the documentation provided by the OpenGate community. In this section, dose will be discussed in the context of a SPECT or PET system however, the same fundamental principles can be applied for CT as well.

3.3   Overview of GATE

GATE is the front layer to GEANT4, it uses its libraries, physics models, geometry, visualization and 3D rendering tools. The structure of GATE is built up in several different layers. The core layer encapsulates the GEANT4 kernel where time management, geometry attributes and radioactive sources are defined. (Figure 3.1). The

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[1]http://www.opengatecollaboration.org/home

application layer comes right after the core layer where the C++ classes that were defined are implemented. These classes includes creating several geometry volumes and defining their specific features and dimensions.[2]

The user layer is where the user is able to use the scripting macro language to execute a GATE simulation. This is possible since the application layer executes all proper functions, so no C++ programing is necessary. These macro scripts and/or macro commands are produced by GATE.
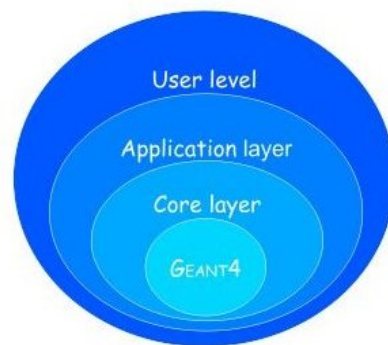
Figure 3.1: GEANT4 kernel - An application layer allows for the implementation of user classes derived from the core layer classes. Image from (`http://wiki.opengatecollaboration.org/index.php/Users_Guide_V6.2:Introduction`).

3.4 vGATE

The OpenGate collaboration created a virtual GATE known as vGATE. It is based on a 32-bit Linux distribution operating system called Ubuntu. vGATE is cross platform compatible on several different 32 or 64 bits operating systems such as Linux OS, Windows OS and Mac OS. A user can easily launch their GATE simulation using a simple command: "Gate", with no setups, configurations and compilation of C++ code. See Appendix A for a step-by-step instructions on how to setup vGATE on multiple machines(i.e. windows, mac, linux); and for building GATE locally on a linux/unix (mac, linux) machine.[3]

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[2]`http://wiki.opengatecollaboration.org/index.php/Users_Guide_V6.1:Introduction`
[3]`http://wiki.opengatecollaboration.org/index.php/New_Compilation_ProcedureV6.2`

3.5   Configuration macro files

The user layer in GATE is where all executions of simulation are scripted. Scripting commands can either be entered into GATE or written out in a macro text file directly. A collection of these commands performs a certain task or functions such as, turning on the display to visualize the geometries, creating a point source, specifying simulation run time and etc. All GATE commands are grouped in a tree like structure associated with their parent function. For example, all geometry related commands begin with the *geometry/* keyword.

Macros are ASCII text files (with **.mac** filename extensions) in which each line contains a GATE command or the character **#**, indicating that the line is a comment. Macros can be executed directly in GATE by calling the macro in the command-line window of GATE or by a parent macro. All commands and definition of components of the simulation are included in the macro file and must be in a specific order. In order to create a simulation in GATE the user must define the visualization component, volumes or geometry, physics, sources, outputs and acquisition times. Macro files are flexible in that the simulations can be modularized and executed by a master/parent macro. Each defined component of the simulation can have a separate files, which fosters reuse of macros in other simulations and organization of commands. Examples of complete macros can be found on the Appendix A.

3.6   The world

The world environment as described by GATE is a cubic box volume centered at the origin of (0 cm, 0 cm, 0 cm) in the x-axis, y-axis and z-axis of the coordinate system. The world volume is user-defined and the only volume initially present in a GATE simulation. A user can specify any size for the world volume however it must be sufficiently large to enclose all other volumes defined. All volumes in GATE can be of a tree structure, though volumes can be related/attached to another volume object. Since the world volume is the first volume and encases all other volumes

then it is known as the parent volume. Whatever volumes defined then after are known as daughters and granddaughters. Each volume has boundary dimension specified, these boundary dimensions are specified by the user and cannot exceed that of its parents.

The world can be composed of any material and these material types are defined within the GATE material database. For typical dose experimentations, the world is an air-filled cubic volume of chosen length such that all daughter and or granddaughter volumes fit within the world. Additional materials can also be constructed within GATE if it does not exist in the database. Daughter and or granddaughter volumes could be represented as a physical component of the imaging systems or objects within the world volume. For example, a detector is a standard daughter volume, or a phantom and a tumor within the phantom are examples of a granddaughter volume. See Appendix B.

3.7   Materials

GATE can simulate any material by defining their property make-up using the material database. This database is provided by the GATE software package and defines all available materials by a way of a *GateMaterials.db* text file. This easily modifiable file contains all the data needed by GATE to accurately attach the nuclear properties from the GEANT4 information sets to a material created, such as elements and materials that are utilized to create the physical properties of different sorts of molecules, atoms and compounds. The material database defines air as a gas that is composed of nitrogen, oxygen, argon and carbon elements and these elements are defined using the periodic table. A volume in the GATE simulation world must have a material type associated to it, otherwise air is assigned by default.

Elements are the fundamentals of every material utilized as a part of GATE simulations. The periodic table is utilized to characterize all elements, for example, their name, symbols, atomic number and molar mass. The database file defines some commonly used elements that are found in nature.

3.7.1 Basic materials

Materials are critical for particle interactions in GATE and they are made with a blends of different elements. A material requires four parameters for its definition; a name, density, element and their individual abundances. Elements can be characterized as a chemical compound or as a mixture. For a chemical compound the formula of that compound is defined by specifying the number of atoms. While for the mixture type the element is described by the mass fraction.

3.7.2 NCAT/XCAT phantom

Four-dimensional (4D) NURBS-based Cardiac-Torso (NCAT) is a computerized phantom that models the anatomy structure and physiology makeup of the human body. NCAT phantom is generally utilized in nuclear medicine imaging research, however it can likewise be applied to X-ray analytic methods since the phantom is utilized to characterize maps of biological activity, as well as maps of attenuation coefficient distribution (Segars et al. (2004)). The NCAT software was used to create voxel phantoms in Figure 3.2 and 3.3 with realistic variation in the size, shape and orientation of organs in a patient population. The computerized digital phantoms by NCAT are named hybrid phantoms on the grounds that they combine the authenticity of patient-based voxel phantoms with the adaptability of equation-based mathematical phantoms (Lee et al. (2007)).
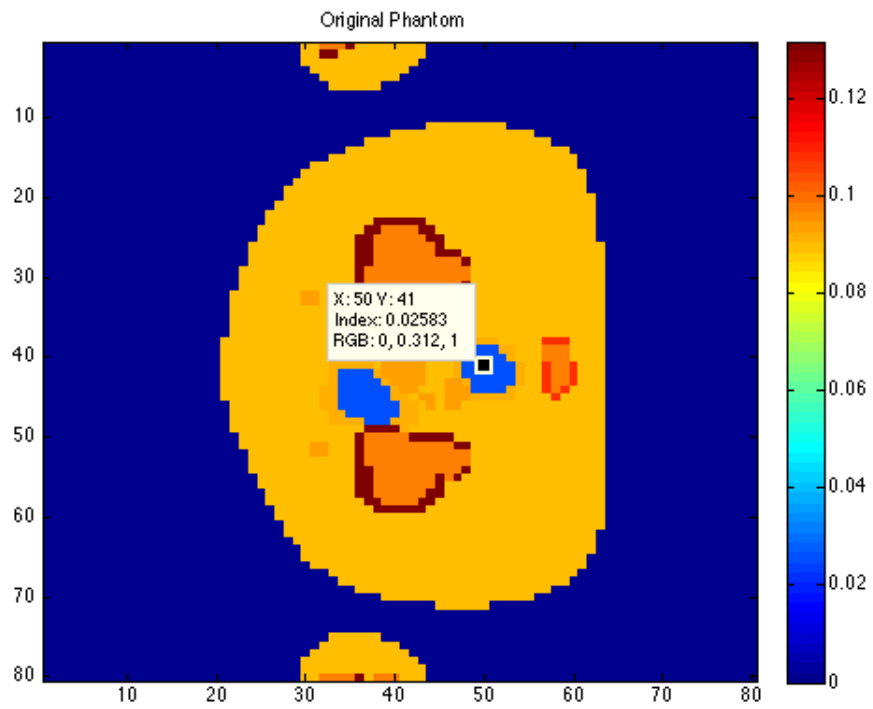
Figure 3.2: Transaxial slices of an attenuation phantom generated with NCAT.
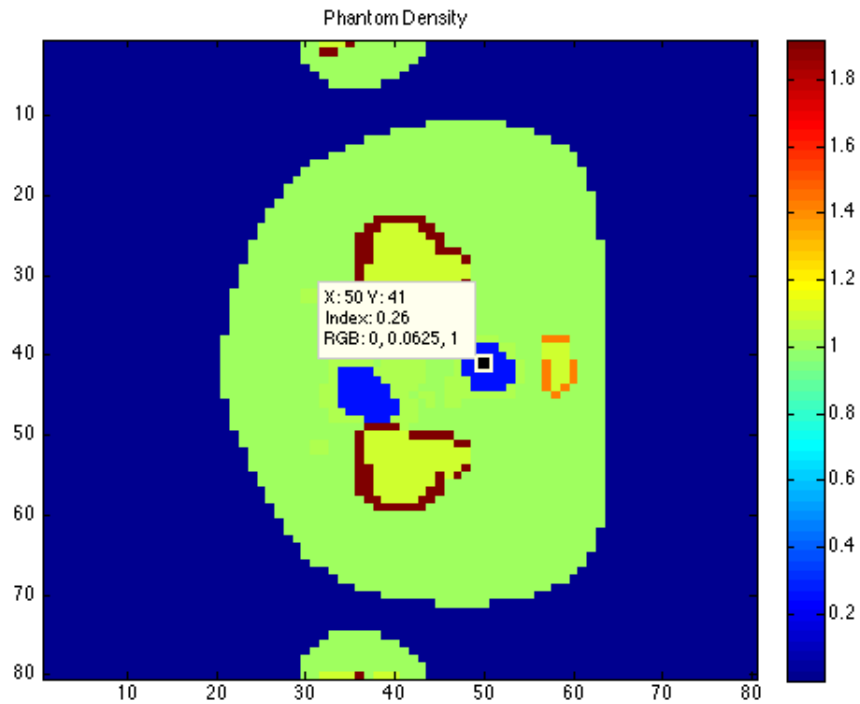
Figure 3.3: Transaxial slices of an tissue density map generated with Matlab. This will be used in the organ radiation dose computation found in Equation 4.2.

3.8   Source setup

3.8.1   General Particle Source (GPS)

GATE can model numerous source shapes and beam geometries. A critical component of a dose study is to accurately model the source spectrum. Source definition in GATE is either described as a voxelized, linacBeam, phaseSpace, or general particle source (GPS). The user must characterize the type source and its independent features, for example, the source position, orientation, angle and energy its associated with. Different types of sources can be characterized in the same GATE simulation and each one source is autonomous from another.

3.8.2 Voxelized source

GATE has been utilized to simulate substantial arrays of clinical and prototype systems. Likewise, the openGATE collaboration and other GATE users are consistently simulating these systems and developing numerous apparatuses to perform more complicated simulations. Among the appealing features of GATE, including the expansive types of geometries, moving sources, acquisition timing, is its capacity to control voxelized phantoms for credible simulation experiments.

There are two principal classifications of voxelized phantoms. The first are clinically acquired information, for example, Computerized Tomography (CT) or Emission Tomography. The second being voxelized phantoms which are typically based MRI information. In GATE, the NCAT phantom, the MOBY mouse phantom and the Zubal brain phantom are utilized as a part of various simulation studies. These phantom models are used because their geometries are described and the emission and attenuation properties can be controlled by the user. They are impeccable instruments for the investigation of various parameters of interest in realistic-like scans (Nikolas et al. (2006)). In this thesis work the NCAT torso phantom was used as the emission source.

The NCAT phantom in this work consists of 600 slices with size 350x350 pixels. Two separate files are necessary for GATE to read the NCAT phantom; the attenuation map and the emission map. First, the data format of these 3-D binary maps needs to be converted into an *Interfile* format required by the interfile reader of GATE before it is used either as a voxelized phantom or voxelized emission source. This Voxelized phantom is loaded into GATE as a material as explained in Section 3.7.2, but it also can be defined as a source as shown in Figure 3.4 and 3.5.
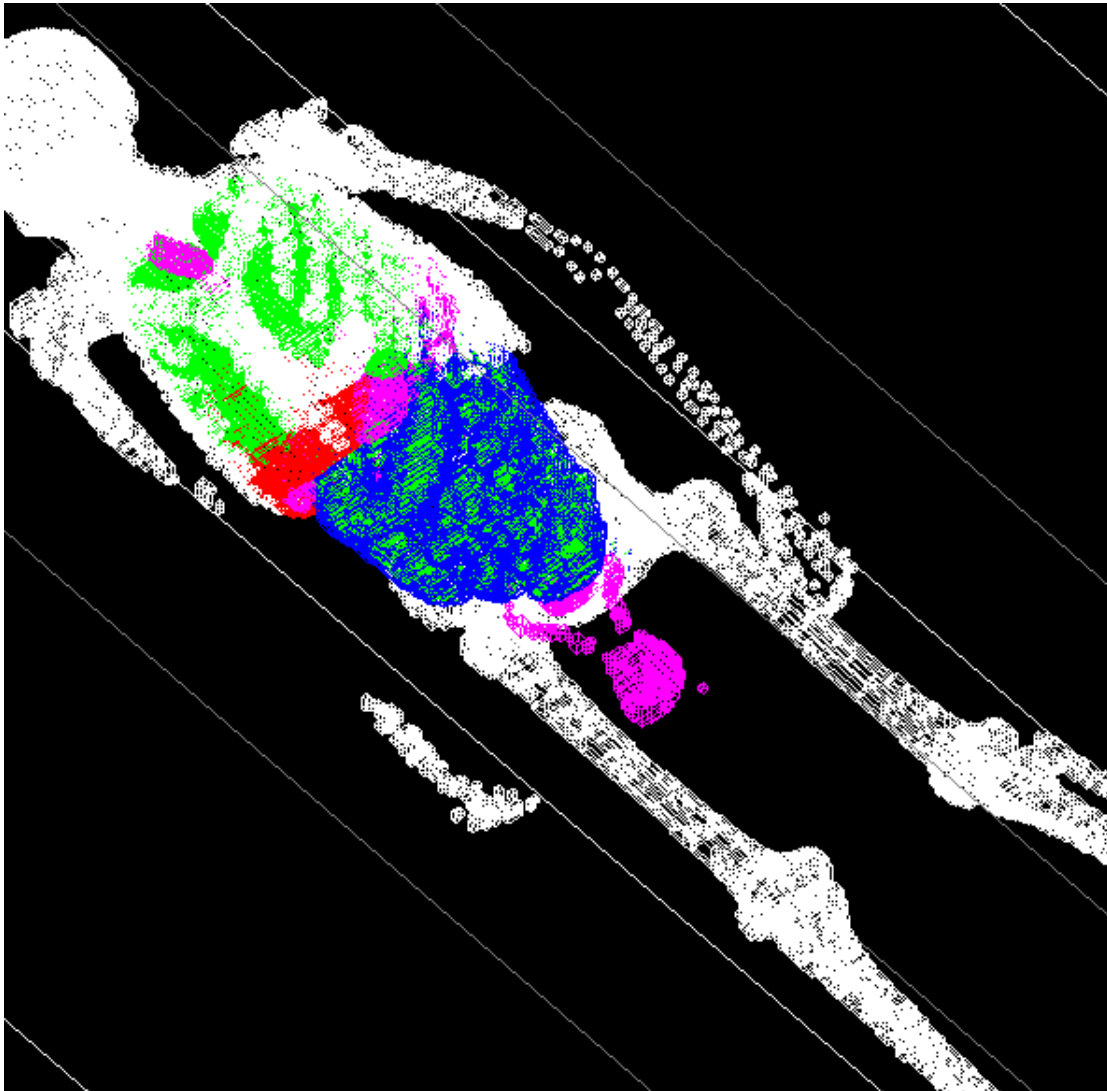
Figure 3.4: NCAT attenuation map of a phantom, converted into pixels and loaded into GATE's visualization engine.
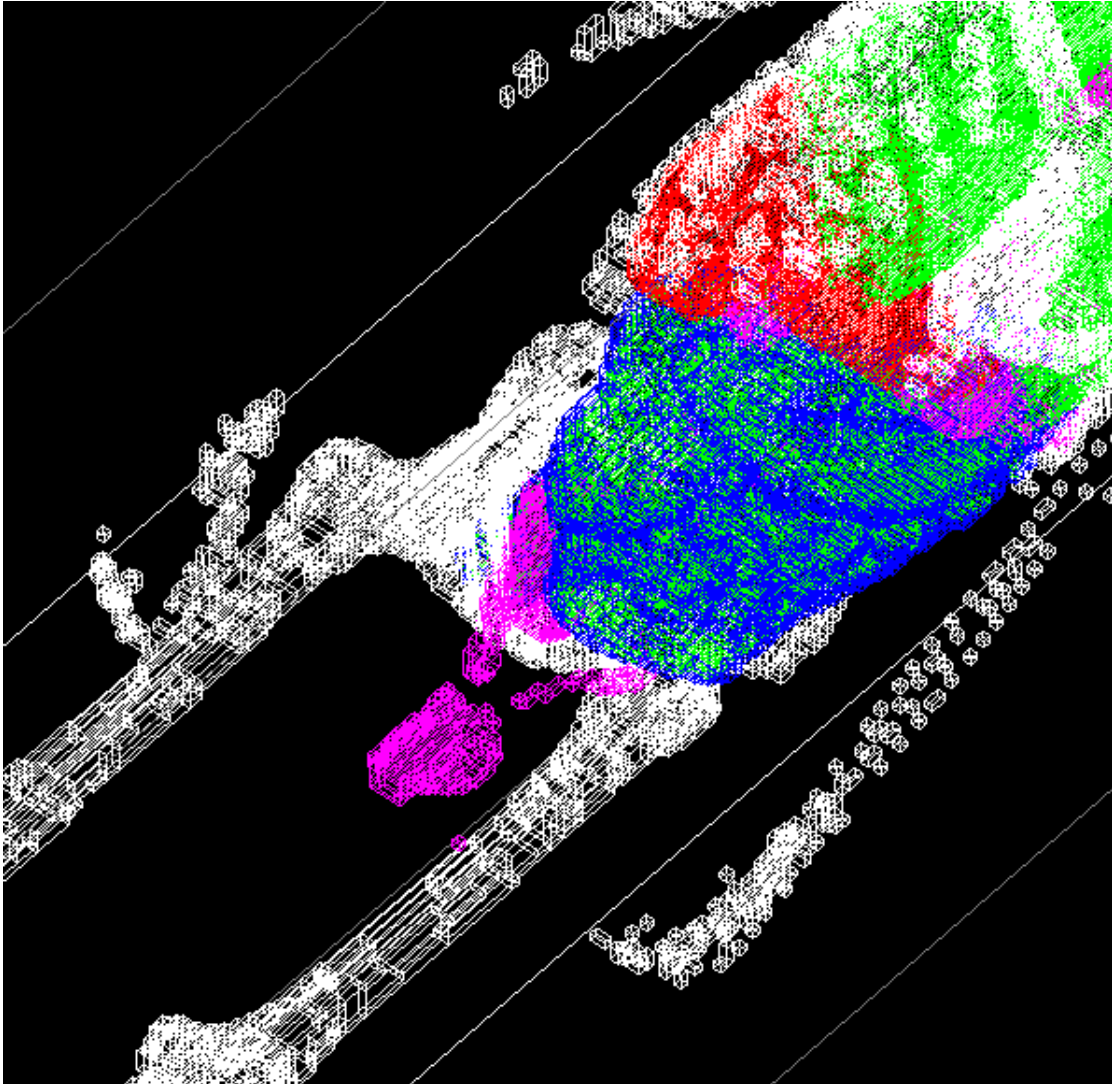
Figure 3.5: Zoomed in NCAT phantom loaded in to GATE visualization engine.

3.9   The physics

GATE models several nuclear interactions during a simulation. These interactions are considered physics models that the user must employ in their simulation study. Interactions such as, Photoelectric effect, Compton scattering, Rayleigh scattering, Electron ionization, Bremsstrahlung and Positron annihilation are modeled for a PET simulation study. GEANT4 incorporates electrons, positrons and gamma-rays

as low-energy models from the Monte Carlo code PENELOPE (PENetration and Energy LOss of Positrons and Electrons) (Sempau et al. (2003)). When modeling these effects, GATE calls the same physics libraries and functions as GEANT4. The user can choose to call the standard model or PENELOPE model for each of these processes. The PENELOPE models are an alternative to the standard models. PENELOPE models interact from 250 eV to 1 GeV while the standard model is valid for greater than 1 MeV (Allison et al. (2012)). The reason a user would choose PENELOPE is due to its affordable CPU-intensive simulation and if the user is interested in low-energy positrons. A performance penalty may arise if the physics processes being modeled are greater than 1 MeV, same results as standard models.

3.10   GATE validation

A substantial number of imaging systems have been modeled utilizing GATE. These modeled imaging systems are partly due to the OpenGATE collaboration and they are also involved in their own validation efforts. Real data acquired with PET and SPECT cameras has been vital in evaluating the accuracy of GATE. These real patient data have been used to validate simulated data for various Monte Carlo simulations. Some PET and SPECT systems that have been or are being considered for validation are listed in Table 3.1 and 3.2.

GATE has additionally been demonstrated to be adaptable for simulating different prototype imaging devices adapted towards small animal imaging. An illustration of these prototype systems are indicated in Table 3.3. It likewise outlines a portion of the features that have been depicted and validated against actual experimental measurements.

Table 3.1: Validation result summary of commercial systems already or currently considered for GATE validation in PET

PET systems	Studied FOM	References
ECAT EXACT HR+, CPS	Spatial resolution 3D sensitivity 3D count rates 3D scatter fraction	Jan et al. (2003b)
Allegro, Philips	3D count rate 3D scatter fraction	Lamare et al. (2004)
GE Advance, GE MS	Energy spectra 3D scatter fraction	Schmidtlein et al. (2006)
MicroPET 4, Concorde	Spatial resolution Sensitivity Miniature Derenzo	Jan et al. (2003a)
MicroPET Focus, Concorde	Spatial resolution Sensitivity	Jan et al. (2004a)

Table 3.2: Validation result summary of commercial systems already or currently considered for GATE validation in SPECT

SPECT systems	Studied FOM	References
IRIX, Philips	None reported	Staelens et al. (2004c)
AXIA, Philips	Spatial resolution Energy spectra Sensitivity Scatter profiles	Staelens et al. (2003)
Solstice, Philips	Sensitivity	Staelens et al. (2004b)
DST Xli, GEMS	Energy spectra Spatial resolution Sensitivity	Assié et al. (2005)

Table 3.3: Prototypes dedicated to small animal imaging modeled using GATE and features that have been studied using simulated data and summary validation results when available

Prototype systems	Studied FOM	References
Phoswich with LSO:Lu + YAP PET	Sensitivity NEC curves	Rey et al. (2003)
High-resolution, dual-head PET	Spatial resolution Sensitivity Line phantom	Chung et al. (2003)
Csl(TI) scintilation camera	Energy spectra Spatial resolution Scatter fraction Sensitivity Line phantom	Lazaro et al. (2004)
Optical-PET (OPET)	Spatial resolution Sensitivity	Rannou et al. (2004)

CHAPTER 4

Radiation Dose

4.1 Definition of dose

Energy is deposited when ionizing radiation penetrates the human body or matter. This energy absorbed from a radiative source is called radiation dose. There are three different types of dose quantities; absorbed, equivalent and effective. An absorbed dose is a measure of the energy in Joules deposited per unit mass. An equivalent dose includes a measure of biological effect of the radiation type (i.e., beta, alpha, gamma, etc) and tissue type. Equivalent dose is also known as the weighted absorbed dose. The Effective dose is a sum of each tissue/organ estimate of the Equivalent dose that is weighted for the radioactive sensitivity of the organs included. Absorbed dose and equivalent dose are identical for electrons and photons. Their relative biological effectiveness (RBE) ratio is equal to one. Dose is a subject of much interest for the field of medical imaging, fundamentally because studies have demonstrated a connection between ionizing radiation and induction of cancers in a patient (Brenner and Hall (2007)).
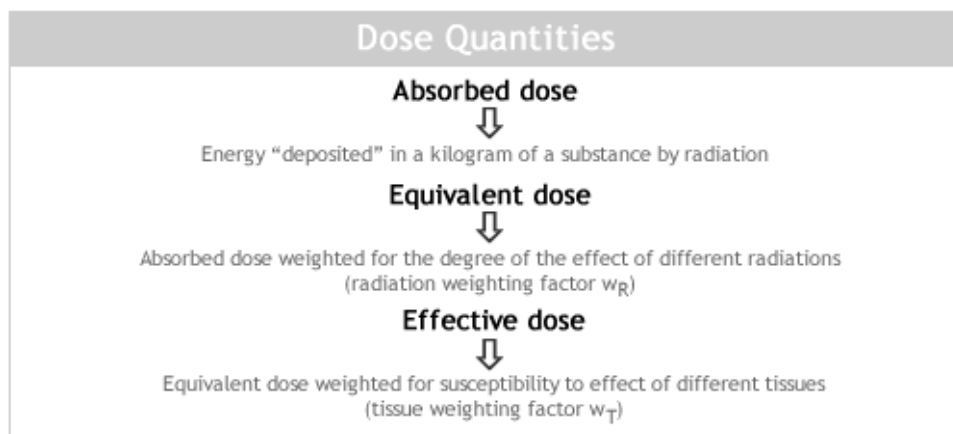
Figure 4.1: Dose quantities chart. Image from (`http://cnsc-ccsn.gc.ca/eng/readingroom/radiation/radiation_doses.cfm`).

4.2 What are the biological effects of ionizing radiation?

Any living tissue in the human body can be harmed by ionizing radiation. Radiation energy absorbed in living tissues launches physical and chemical responses that may bring about biological changes (Sai Wan (2004)). One characteristic of ionizing radiation observed in the human body is that although the energy absorbed can be low the biological impacts can be severe. The damaging effects of ionizing radiation have been known for many years. It being regularly acknowledged that high-energy tracks found by alpha, beta, gamma, x-rays radiation and atomic ions ionize cell segments along the tracks, in this manner prompting different separation channels and the formation of harmful radicals (Denifl et al. (2013)).

Analysis of the impact of ionizing radiation is normally conducted utilizing computer simulations, since some the nuclear processes are too complex to be treated analytically. A few simulation codes for radiation transport (e.g. GEANT4[1], FLUKA[2], MCNP[3]) and track structure analysis (KURBUC, PARTRAC, LEPTS, OREC, SHERBROOKE) have been produced to simulate the interaction of ionizing

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[1]`http://geant4.cern.ch/`

[2]`http://www.fluka.org/`

[3]`http://mcnp-green.lanl.gov/`

radiation with different media. (Solov'yov et al. (2012)).[4]

4.3 Absorbed dose

The absorbed dose, $D(r)$, is characterized as the mean energy, ε, deposited by ionizing radiation to a tissue of matter of mass, m, in a limited volume, V, by Equation 4.1. The SI unit of absorbed dose is J/kg and is denoted by Gray (Gy). It is utilized to characterize different radiation effects, yet it doesn't describe their biological impacts.

$$D(r) = \frac{\Delta\varepsilon(r)}{\Delta m(r)} \tag{4.1}$$

The mass-weighted average, D_T, of the absorbed dose for tissue type T is given by Equation 4.2:

$$D_T = \frac{\int_{V_T} d^3 r \, D(r)\rho(r)}{\int_{V_T} d^3 r \, \rho(r)} \tag{4.2}$$

Where r is position x, y, z of interest in tissue T, $\rho(r)$ is the density distribution for tissue T and V_T is the volume of the tissue T.

4.4 Equivalent dose

The equivalent dose H_T is defined in Equation 4.3.

$$H_T = W_R D_{T,R} \tag{4.3}$$

Where $D_{T,R}$ is the absorbed dose delivered by radiation type R, averaged over a tissue or organ T and W_R is the radiation weighting factor for radiation type R. The SI unit of equivalent dose is J/kg and is denoted by Sievert (Sv).

As stated earlier, not all types of ionizing radiation cause the same biological damage from absorbed dose. To change the dose to reflect the viability of the kind of radiation in delivering biological damages, a radiation weighting factor (W_R)

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[4]http://www.hko.gov.hk/education/dbcp/rad_health/eng/r4.htm

was created by the International Commission on Radiation Protection (ICRP) as a component of a general framework for radiation protection. Table 4.1 lists these weighting factors. For radiations principally used in medical imaging (x-rays and gamma rays) and beta particles, $W_R = 1$ (Sprawls (1993)).

Table 4.1: Radiation weighting factors (W_R) for various types of radiation. Table from (Wrixon (2008)).

Type of Radiation	Radiation Weighting Factors (W_R)
X-rays, gamma rays, beta particles and electrons	1
Protons	2
Neutrons (energy dependent)	2.5 - 20
Alpha particles and other multiple-charged particles	20

4.5   Effective dose

The effective dose, E, represents the health risks to the patient of energy being absorbed by the distinctive tissues inside the patient. The effective dose is characterized as the summation of tissue equivalent doses, each one multiplied by the proper tissue weighting factor W_T (ICRP, 2007), to show the combination of diverse doses to a few distinctive tissues in Equation 4.4. Table 4.2 lists tissue weighting factors recommend by ICRP.

$$E = \sum W_T H_T \qquad (4.4)$$

4.6   Dose Collection in GATE

4.6.1   Dose actors

In GATE, to accurately measure absorbed dose, dose actors are attached to the loaded phantom. Actors are tools that interact with the simulation. These actors

Table 4.2: Tissue weighting factors assigned by the International Commission on Radiological Protection (ICRP). Table from (Wrixon (2008)).

Organ/Tissue	W_T	% Of Total
Breast	0.12	
Bone marrow	0.12	
Colon	0.12	72
Lung	0.12	
Stomach	0.12	
Remainder	0.12	
Gonads	0.08	8
Bladder	0.04	
Esophagus	0.04	16
Liver	0.04	
Thyroid	0.04	
Bone surface	0.01	
Brain	0.01	4
Salivary gland	0.01	
Skin	0.01	
Total	**1.0**	**100**

record data during the experiment, such as absorbed dose, energy deposited, particles created in a given volume, in order to log data for output. Typically the shape and size of these actors are the same as the voxels of the phantom, but can be redefined if necessary. This dose actor outputs a 3D dose map in units of Gy and energy deposited in units of MeV.

4.7 Absorbed-Dose calculation

This section describes the general steps to dose computations using GATE. Radiation dose will be discussed in the context of a PET system; however, the same fundamental principles can be applied for SPECT, X-ray CT, etc. An example containing some useful GATE commands for running a dose computation is included in Appendix A. By a way of illustration, these general dose step computations sim-

ulates an example of absorbed dose in ^{18}FDG PET imaging depicted in Appendix D.

4.7.1 Defining a scanner geometry

The first command to be entered in GATE is the visualization, which can be enabled or disabled, followed by the location of the material database file. The world volume is sized to be sufficiently substantial to incorporate the whole simulation geometry. As shown in Figure 4.2: All volumes are linked together in a tree structure and each branch represents a volume in this example. The enclosing world geometry is set to a 10x10x10 cubic [cm] composed in air and centered at the origin. Then a daughter world of size 5x5x5 cubic [cm] of water cube is then centered in the worlds center and is displayed in cyan wireframe.

4.7.2 Defining the phantom geometry

The volume to be scanned or volume of interest is the tumor phantom. The tumor phantom is a cubic centimeter size volume sphere that is attached to the wireframe water cube, shown in red coloring in Figure 4.2. This sphere is a mixture of elements that is defined as a muscle tissue type, which is defined from the material database file. Note that other tissues/organs defined in the material database file can be used.

4.7.3 Setting up the physics processes

GATE uses the GEANT4 models for physical processes. A range of processes was chosen to model the effects of physical process during a PET study. Among those chosen were, Photoelectric effect, Compton scattering, Rayleigh scattering, Electron ionization, Bremsstrahlung and Positron annihilation. See Appendix A.

4.7.4 Initialization

The initialization process is a single line command that initializes the simulation. It triggers the initial calculations needed for the geometries, physics processes and
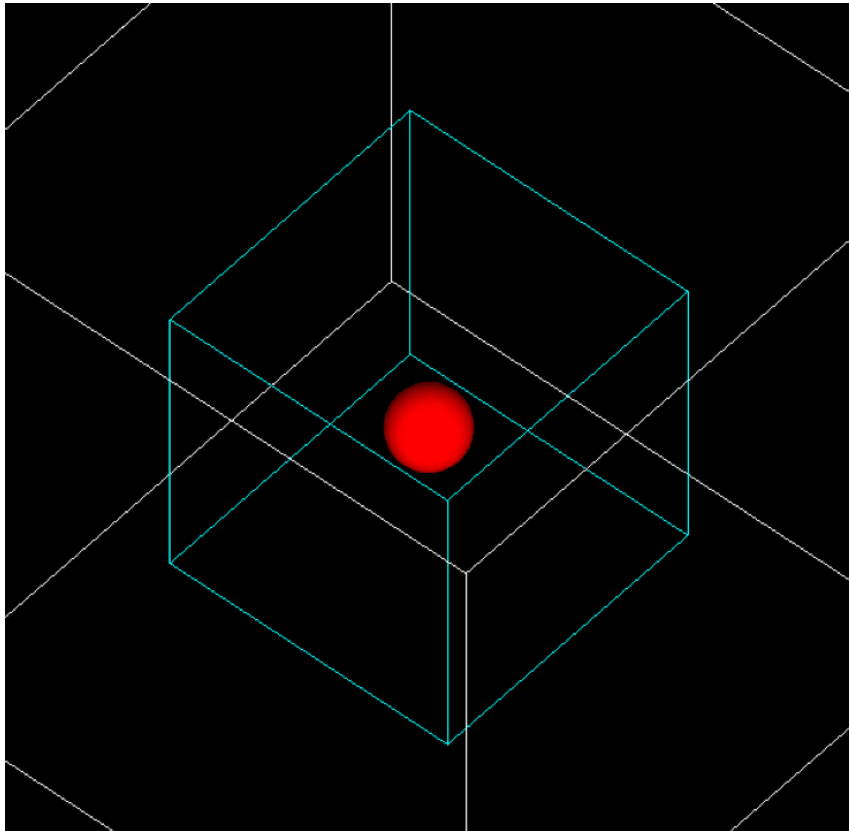
Figure 4.2: Example GATE world with a spherical tumor. The outer most white wireframe is the enclosing world, the cyan color is the water cube and the tumor is red spherical object.

sources.

4.7.5   Setting-up the source

The source is represented by a uniform distribution of 20 mCi (millicurie) of ^{18}FDG activity into the tumor volume. Positrons are emitted by the tumor phantom. ^{18}FDG was not currently available as an energy type in GATE so ^{18}F was used instead and all the characteristics of the source are set accordingly, i.e., half-life, shape, type, etc. See Appendix A.

4.7.6 Defining data output

In order to output data in GATE, dose actors need to be defined as stated in Section 4.6.1. For this dose study a dose actor was used to output a 3D dose map in units of Gy and energy deposited was also generated as a 3D map with units of MeV. Additional actors where added to produce more outputs. For example, energy spectrum actor, which creates the initial kinetic energy emitted and a histogram of the energy deposited.

4.7.7 Initializing and ending an acquisition

The final step of the GATE set up is the definition of the beginning and the end of the acquisition. The commands *setTimeStart*, *setTimeStop* and *setTimeSlice* are used to define the number of runs to make and the duration. A brute force method (Appendix D) time duration of two hours was used. This experiment is set to simulate one second of dose collection. One second in simulation world is equivalent to ten minutes in real time for this experiment. Thus, having to run the simulation for 7200 seconds would have resulted to 1200 hours/50 days of run time. To reduce long simulation run time scaling of the output data was applied.

4.7.8 Absorbed dose and time scaling

After the GATE simulation has been executed for a short period of time, a dose map file is generated. Equation 4.5 is then used to calculate the initial average absorbed dose over the entire tumor volume for that period of time. This results in $D_0 = 3.4181$ [Gy].

$$D_0 = \frac{\sum_{i=1}^{N} d_i}{N} \tag{4.5}$$

Where d_i is dose per voxel and N is the number of voxels.

Equation 4.6 is used to calculate total absorbed dose for all time (t = ∞), where τ

is the decay constant and t is the half-life of the isotope used.

$$D(\infty) = \int_0^\infty D_0 e^{-\frac{t}{\tau}} dt \tag{4.6}$$

$$D(\infty) = D_0 \tau \tag{4.7}$$

$$\tau = \frac{t}{ln(2)} \tag{4.8}$$

The brute force method in Appendix D for a 20 mCi activity uptake resulted to 2.1 Gy absorbed dose, while the GATE method resulted to 2.2 Gy.

CHAPTER 5

Case Studies/Discussions

5.1 Study 1 - Absorbed dose results

The GATE simulation was used to calculate the absorbed dose for several radioiso-
topes listed in Table 5.2. This experiment consisted of a $1cm^3$ spheric tumor filled
uniformly with those radioisotopes (See Figure 5.1). Outside the tumor is a cold
(non-radioactive) water bath. We pick this size in light of the fact that tumors differ
in shapes and sizes. The results presented in Table 5.2 are total absorbed dose. In
other words, a short time period was considered in which an initial dose per unit
time was obtained, then was analytically integrated over time from zero to infinity
with an exponential decay corresponding just to the physical half-life. Recall that
the exponential time constant τ is the half-life divided by 0.693 ($ln(2)$) (Equation
4.8) and the analytical integral only shows that the dose for infinite time is the
initial dose per unit time multiplied by τ (Equation 4.7).

In GATE, the best way to define a radiotracer source is through a method called
Isotope source. The isotope method can depict any radiotracer by characterizing
its attributes, for example, nuclear number (Z), nuclear weight (A), ionic charge
in units of energy (Q) and its excitation energy in keV (E) as shown in Table 5.1.
It also models the radioactive decay scheme and de-excitation of that atom. This
method is the slowest, yet is the most realistic approach.

Table 5.1: Radiotracer source type definition for common isotopes in GATE

Isotopes	Atomic number (Z)	Atomic weight (A)	Excitation energy in keV (E)
^{18}F	9	18	0
^{90}Y	39	90	0
^{111m}In	49	111	537
^{123}I	53	123	0
^{131}I	53	131	0
^{99m}Tc	43	99	143

Absorbed dose was collected on the tumor by several radioisotopes, as shown in Figure 5.1 and 5.2. After the collection of these absorbed dose in Table 5.2, it was unclear why ^{99m}Tc delivered more dose than ^{18}F. ^{99m}Tc has 3 times the half-life by 1/10th the electron yield per decay, plus a lower electron energy (120 keV vs. 250 keV average position energy in ^{18}F). After performing similar calculations found in Appendix D for the ^{99m}Tc, the radiotracer source method for the ^{99m}Tc source was inaccurate in the current GATE simulation version. A newer version of GEANT4 is addressing this issue. Using the energy and probability of electrons detailed for the radionuclide data in (Johnson et al. (2012)), an alternative method was used to model each individual electron as a source, which yielded a lower dose calculation than ^{18}F as shown in Table 5.3.
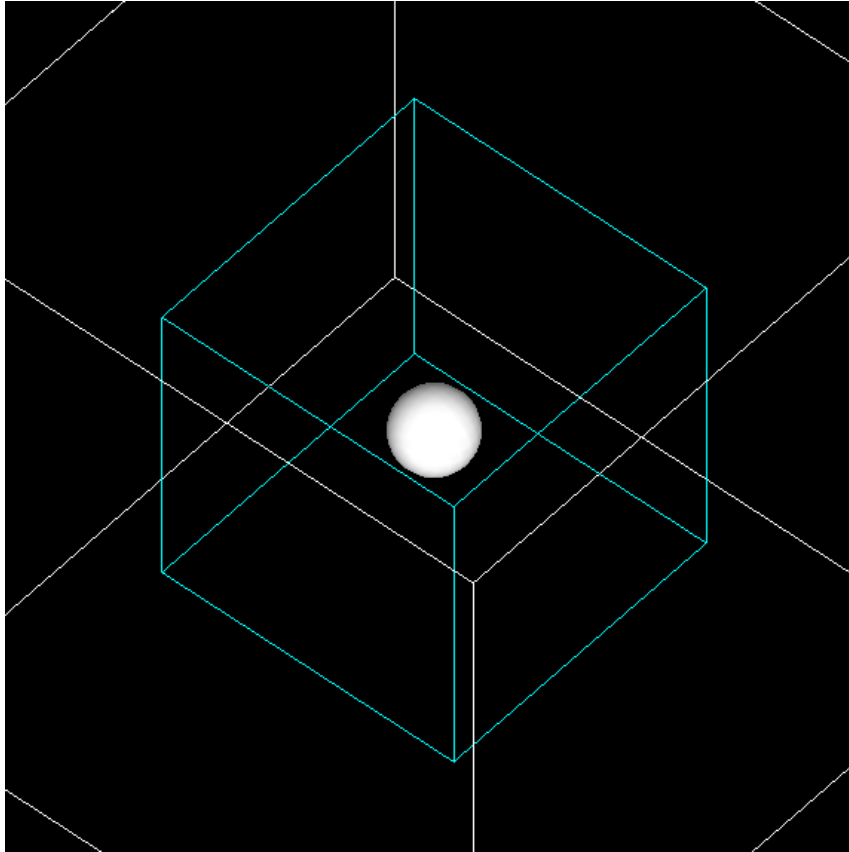
Figure 5.1: Spherical tumor enclosed by a water cube after radiotracer was administered. The most outer white wireframe is the enclosing world, the cyan color is the water cube and the tumor is the white spherical object.
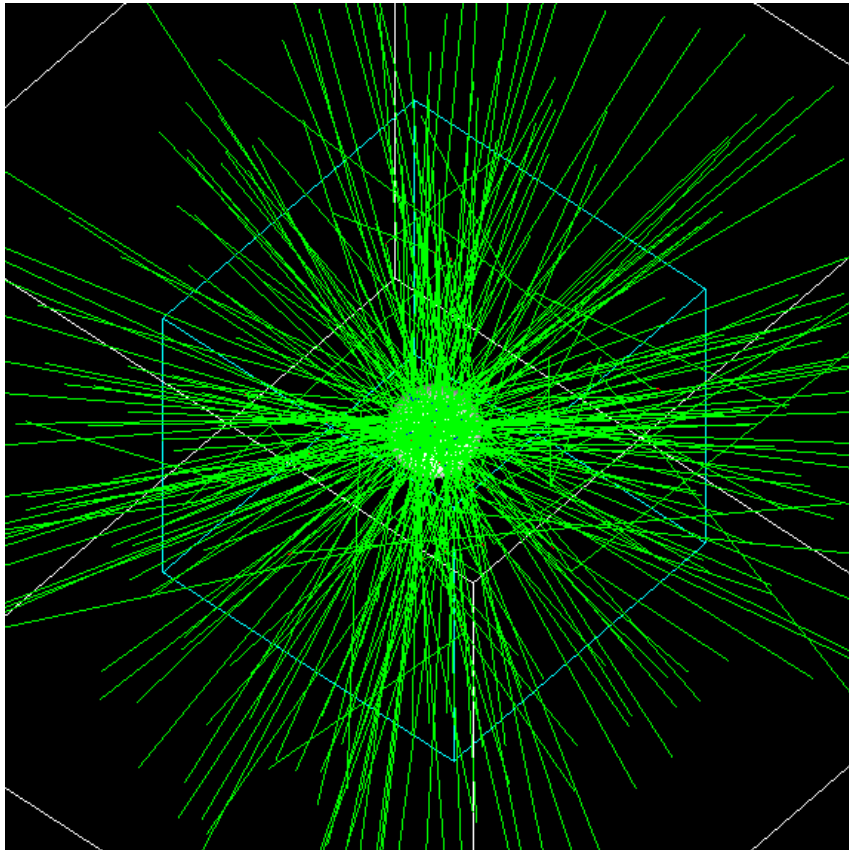
Figure 5.2: Spherical tumor enclosed by a water cube, after radiotracer was administered. Where the most outer white wireframe is the enclosing world; the cyan color is the water cube; and the tumor is white spherical object.
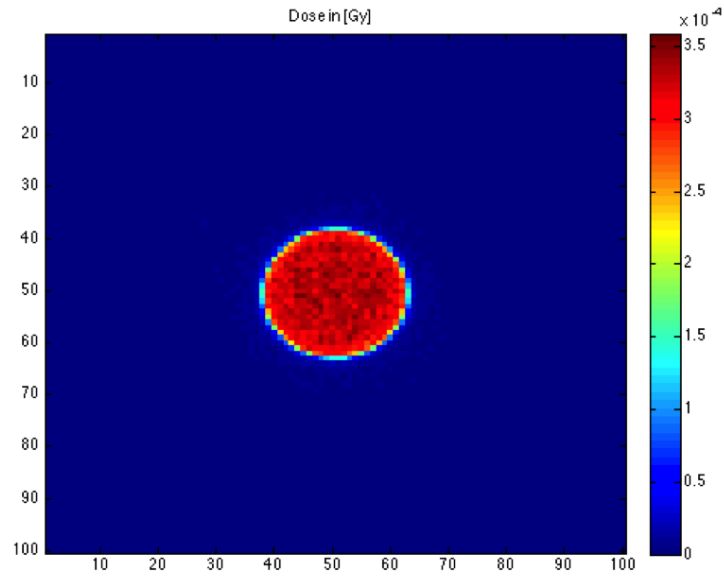
Figure 5.3: Transverse slice of absorbed dose for the spherical tumor.

Table 5.2: Calculated Dose for common isotopes using GATE

Isotopes	Emission Type	Energy [keV]	Halflife	Activity [mCi]	Dose [Gy]
^{18}F	Positron	249.8	109.8 min	1	10.75
^{90}Y	Beta	934.8	64.05 hr	1	1213.25
^{111m}In	Gamma	536.95	7.7 min	1	178.64
^{123}I	Gamma	159	13.22 hr	1	7.63
^{131}I	Beta	191.58	8.02 d	1	952.55
^{99m}Tc	Gamma	140.5	6.006 hr	1	15.22

Table 5.3: Comparison of Dose using isotope source and electron sources in GATE

Isotopes	Source Type	Energy [keV]	Halflife	Activity [mCi]	Dose [Gy]	
^{131}I	Radiotracer	-	8.02 d	1	952.55	
^{131}I	e-	191	8.02 d	1	1034.90	
^{99m}Tc	Radiotracer	-	6.006 hr	1	15.22	
^{99m}Tc		1.6	6.006 hr	0.74	0.3373	
^{99m}Tc		2.1		0.25	0.1460	
^{99m}Tc		2.2		0.1	0.0616	3.71
^{99m}Tc	e-	15.5		0.02	0.0880	
^{99m}Tc		119		0.088	2.57	
^{99m}Tc		137		0.014	0.5216	

5.2   Study 2 - 131-Iodine study

In this study a spherical source and a point source (single small voxel) of ^{131}I in a water phantom were considered and the surrounding dose distribution was computed. Dose maps were generated for both spherical source and for point source of ^{131}I, using $1cm^3$ cube of water with 0.1 mm voxels and a diameter of 1cm for the spherical case. A point source of ^{131}I was simulated in this water cube. Figure 5.4 shows the center slice of the dose map obtained, which shows a sharp peak. Figure 5.5 shows the enhance contrast image of the same center slice and that the voxel containing the point source is higher than the surrounding tissue. Same procedures were performed for the spherical case in Figure 5.6 and Figure 5.7.
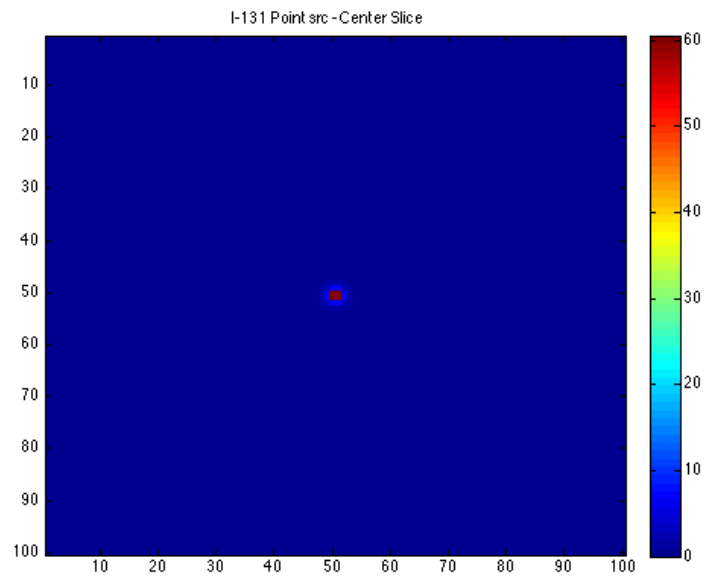
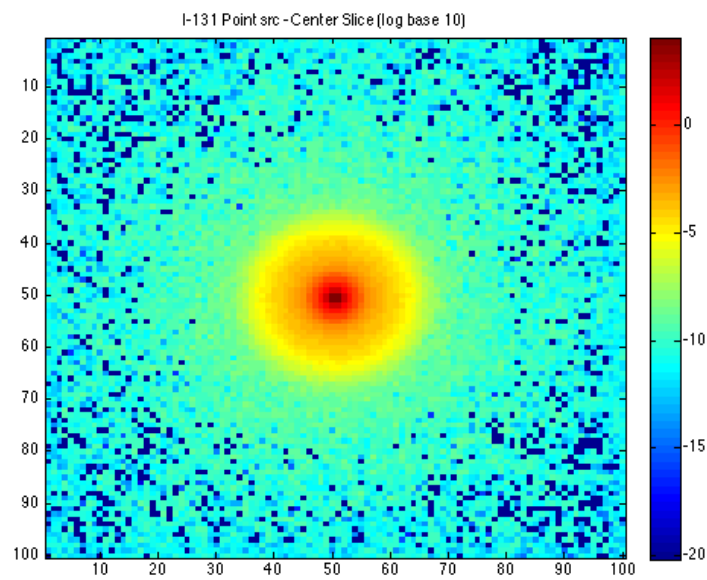Figure 5.4: Transaxial slice of ^{131}I dose map (point source).

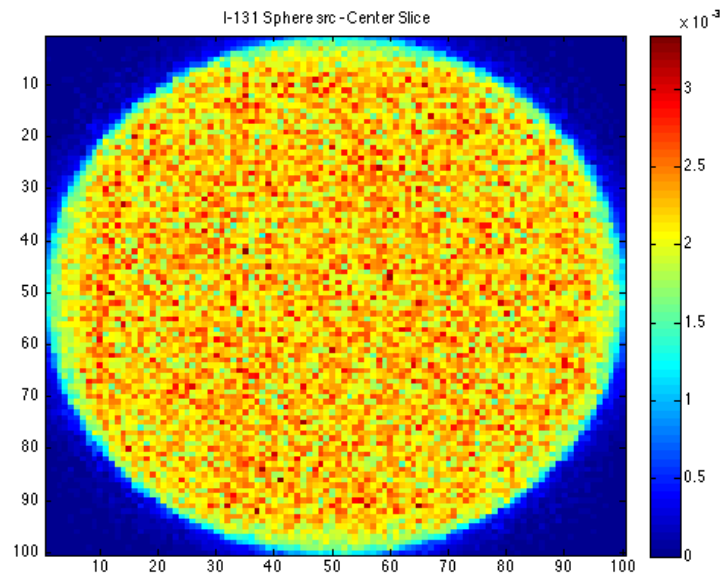Figure 5.5: Transaxial slice of ^{131}I dose map (point source).

Figure 5.6: Transaxial slice of ^{131}I dose map (spherical source).
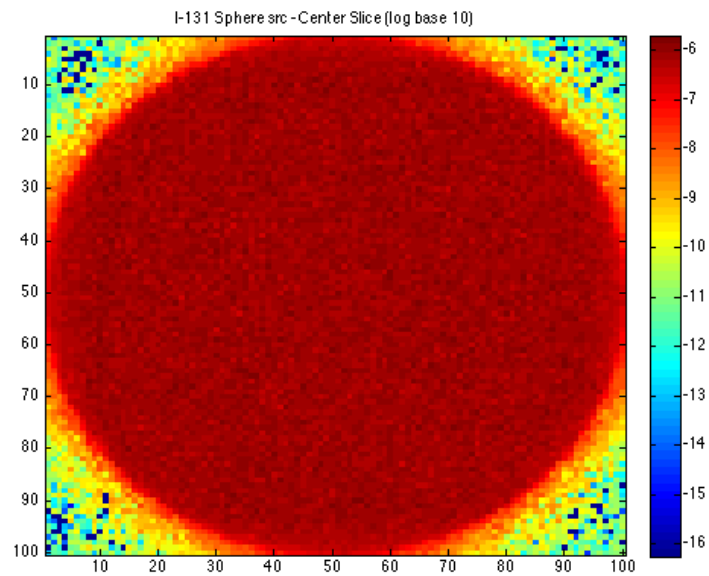

Figure 5.7: Transaxial slice of ^{131}I dose map (spherical source).

The total absorbed dose was calculated for both scenarios. Total absorbed dose

in this case means the initial dose in J/kg in the water cube, scaled over the ^{131}I half-life. See Equations 4.7 to 4.8. Both the point source and the spherical source contained the same total activity of 1 mCi. The results show that the point source delivered dose of 60 Gy, while the sphere resulted in around 2-3 mGy.

5.3   Study 3 - NCAT study using 18-Fluorine

There are two possible ways to read in voxelized sources within GATE. One can choose to read an ASCII file, or an InterFile image. The InterFile image was chosen because any digital phantom, or patient data stored in InterFile format can be read as an emission distribution. The NCAT torso phantom was used as the emission source for this study as mentioned in Section 3.8.2. This software package was used to create voxel phantoms with realistic variation in the size, shape and orientation of organs in a patient. Each execution of the NCAT creates an activity phantom and an attenuation phantom. In this study the organs that were modeled in the activity phantom were the heart, liver, lungs, kidney, spleen and background. The background was composed of the remaining organs that were within the field of view of the imaging system. The attenuation phantom contained the default organs output by NCAT. In Computed Tomography (CT) the object is the attenuation map, so a conversion of the attenuation map to the interfile format is required by GATE.

In GATE, this voxelized phantom or patient dataset is used to define the source in order to simulate realistic acquisitions. This study was set up by administering 1 mCi of ^{18}F radiotracer into the heart, kidney and heart plus kidney and the results are shown in Table 5.4. Figures 5.8 through 5.10 show GATE using the kidney and heart organ as an emission source, while Figures 5.11 and 5.12 shows the transaxial slice of the GATE 3-D dose map.

Table 5.4: Calculated organ dose for 1 mCi of ^{18}F radiotracer in heart and kidney organs. Where *(+)* means, 97% of the activity was administered in that organ while 3% was evenly distributed through out the body.

Organs	Activity of ^{18}F [mCi]	Organ Absorbed Dose [Gy]
Heart	1	0.5464
Heart (+)	1	0.8845
Kidney	1	0.8650
Kidney (+)	1	1.1918
Heart + Kidney	1	1.4110
Heart + Kidney (+)	1	1.7905

GATE was used to compute the total absorbed dose and dose maps for this realistic patient situation while using the NCAT phantoms. The values in the output file of the dose actor (Section 4.6.1) is the 3-D absorbed dose map by each voxel, reported in units of Gy $= J/kg$. The next step is to compute the absorbed organ dose (Equation 4.2), which, by definition accounts for the volume of the voxel through the tissue density as shown in Figure 3.3.
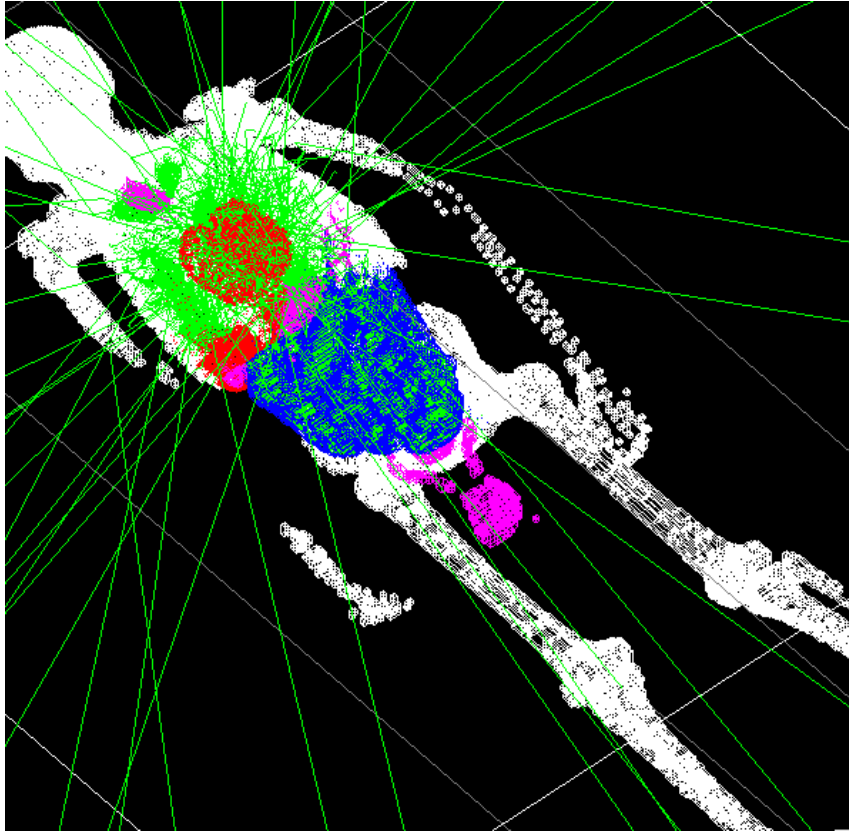
Figure 5.8: GATE visualization showing activity admitted to only the heart organ.

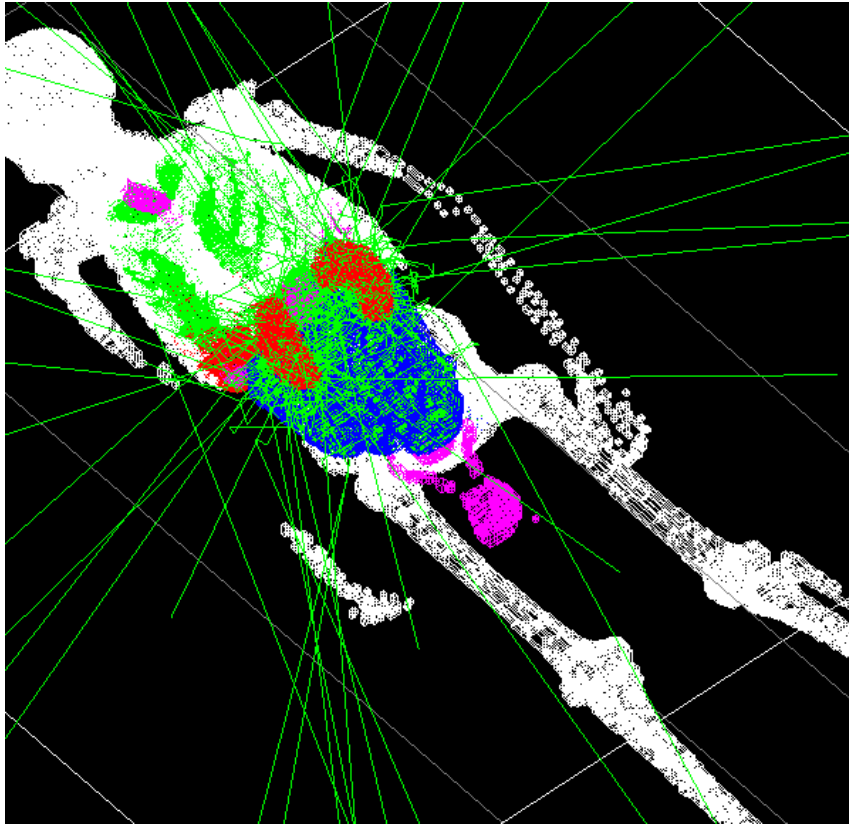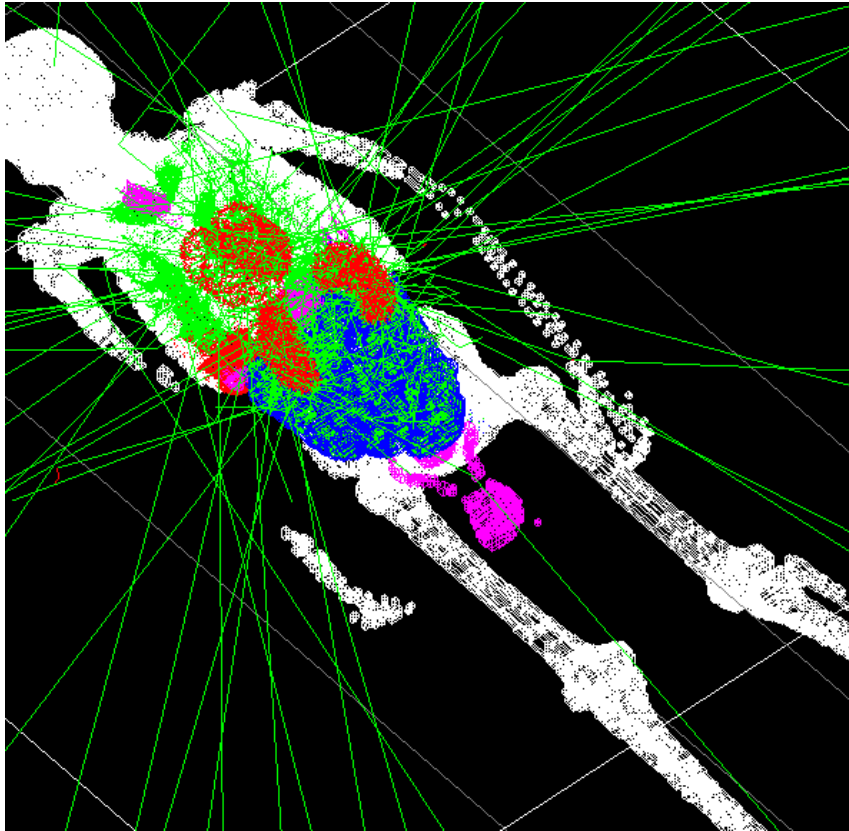Figure 5.9: GATE visualization showing activity admitted to only kidney organ.

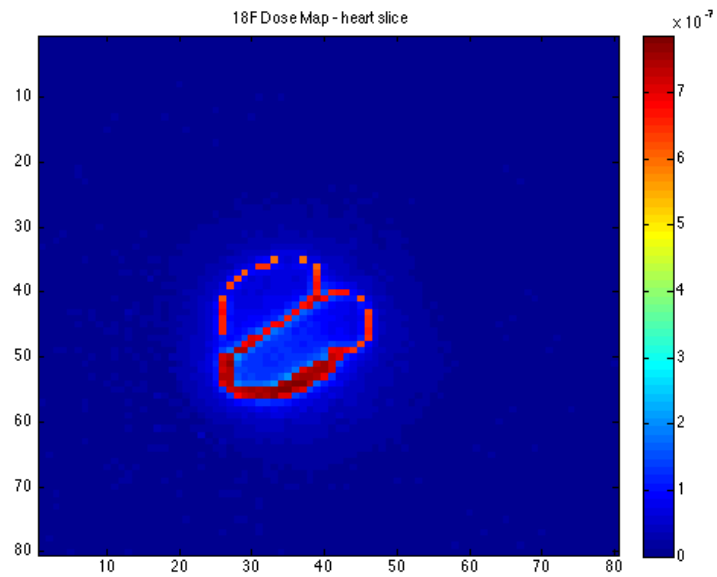Figure 5.10: GATE visualization showing activity admitted to both the heart and kidney organs.

Figure 5.11: Transaxial slice of the GATE 3-D dose map output for showing activity admitted to heart organs.
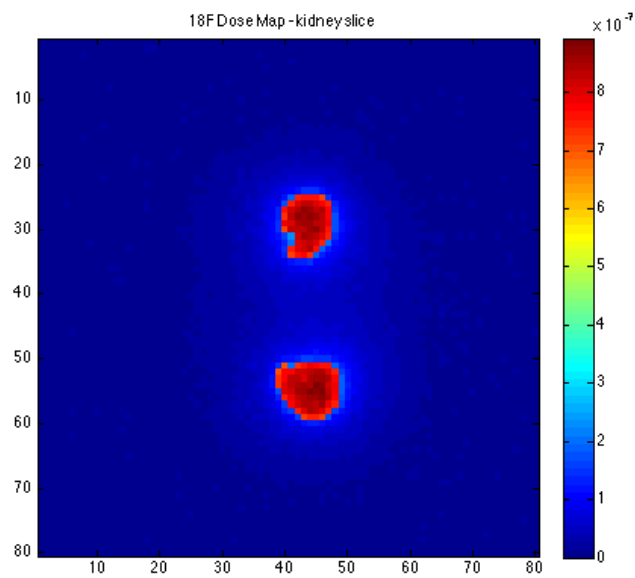

Figure 5.12: Transaxial slice of the GATE 3-D dose map output for showing activity admitted to kidney organs.

CHAPTER 6

Conclusion

6.1 Recap

The GATE Monte Carlo simulation package is an excellent toolset for simulating PET and SPECT imaging devices by making GEANT4 physics science models accessible through an easy to understand interface. In this thesis work, we have used this open-source GATE Monte Carlo simulation platform to evaluate dose distributions computed with common radioisotpes. The main interest of a slower and detailed Monte Carlo simulation, such as GATE, is its versatility. It can be utilized as a reference Monte Carlo code for validation purposes, it permits consolidated imaging, dosage simulations and radiotherapy simulations utilizing different particles, for example, carbon particles and so forth.

GATE is a relevant tool for Monte Carlo simulations in Emission Tomography. GATE is similarly fitting for studying detector designs and how they impact image quality in designs that incorporate movements. GATE enables Monte Carlo simulations of various types of radiotracer and generates radiation dose maps. Comparison of these simulated results and measurements (measured) of absorbed dose shows that the optical physics models of GEANT4/GATE enable accurate prediction of the absorbed dose, provided that all necessary input parameters are supplied.

Unlike transmission imaging where dose is a function of exposure time, the dose in emission imaging depends solely on the amount of radiotracer uptake in the patient (Barrett and Myers (2004)). Thus, when running a GATE simulation to compute dose in PET/SPECT it seems that one would need to run the simulation for enough time to model twice the half-life of the radiotracer. Alternately, one might run the simulation for less than this amount of time and then compute the scale factor to get the dose to the full life of the radiotracer. This approach was

performed in the studies referenced in Chapter 5. In the event that neither of those options is feasible, then it would be necessary to report dose along with the time associated with that dose and the half-life of the radiotracer.

Radiotracers can be used to deliver dose to tumors for performance radiation therapy. A medical physicists main task is to deliver the correct amount of dose to the correct tumor location. Therefore, quality assurance, as well as, patient exposure to radiation is of primary importance, especially in regard to the delivery system and the treatment planning system such as, radiation therapy, proton, electron and so on.

This thesis work is the first study demonstrating the capabilities of GATE to evaluate a radiotracer agent for dosimetry studies. The GATE toolset can subsequently add to the assessment, benchmarking and advancements of treatment planning system (TPS). It is a favorable simulation tool for imaging studies, such as PET and SPECT, or for the examination of new imaging modalities like the detection of radiations (gamma-rays or nuclear particle). The GATE tool can predict various research studies in the field of nuclear medicine.

6.2 Future work

A significant downside of GATE is the computing/processing time expected to run the simulations, a potential remedy for computation of GATE can be in view of the utilization of PC clusters and/or Graphics Processing Units (GPUs). Recognizing other approaches to accelerate the GATE Monte Carlo simulation is crucial to making measurements processing tractable particularly on account of a radiotracer, which must be tracked over its lifetime. In this thesis study the use of macro based scripts for simulating several different radioisotopes were used, creating a collections of these sample scripts as basis for future work should be considered.

APPENDIX A

Sample first script for vGATE

In section 4.3 a method for computing absorbed dose maps using the GEANT4 application for tomographic emission (GATE) software was presented. This appendix contains a GATE script that uses dose actors attached to a spherical tumor in a cube of water to produce the dose map for 1 mCi of $^{18}F,^{90}Y,^{111m}In,^{123}I,^{131}I,^{99m}Tc$ radiotracers.

```
#=====================================
# Vis
#=====================================
/vis/disable
#/control/execute visu.mac



#=====================================
# Materials
#=====================================
/gate/geometry/setMaterialDatabase materialFiles/
    GateMaterials.db



#=====================================
# World
#=====================================
/gate/world/geometry/setXLength 10 cm
```

```
/gate/world/geometry/setYLength 10 cm
/gate/world/geometry/setZLength 10 cm
/gate/world/setMaterial            Air


# Daughter World − Water Cube
/gate/world/daughters/name                    waterCube
/gate/world/daughters/insert                  box
/gate/waterCube/placement/setTranslation 0 0 0 cm
/gate/waterCube/geometry/setXLength      5 cm
/gate/waterCube/geometry/setYLength      5 cm
/gate/waterCube/geometry/setZLength      5 cm
/gate/waterCube/setMaterial              Water
/gate/waterCube/vis/setColor             cyan
/gate/waterCube/vis/forceWireframe


# Daughter World − Tumor Sphere
/gate/waterCube/daughters/name           tumor
/gate/waterCube/daughters/insert         sphere
/gate/tumor/placement/setTranslation 0 0 0 cm
/gate/tumor/geometry/setRmin         0. cm
/gate/tumor/geometry/setRmax         0.5 cm
/gate/tumor/setMaterial              Muscle
/gate/tumor/vis/setColor             red
/gate/tumor/vis/forceSolid




#=======================================================
# Physics Process
```

```
#==================================================
/gate/physics/addProcess
    PhotoElectric
/gate/physics/processes/PhotoElectric/setModel
    StandardModel

/gate/physics/addProcess
    Compton
/gate/physics/processes/Compton/setModel
    StandardModel

/gate/physics/addProcess
    RayleighScattering
/gate/physics/processes/RayleighScattering/setModel
    PenelopeModel

/gate/physics/addProcess
    GammaConversion
/gate/physics/processes/GammaConversion/setModel
    StandardModel

/gate/physics/addProcess
    IonIonisation

/gate/physics/addProcess
    ElectronIonisation
/gate/physics/processes/ElectronIonisation/setModel
    StandardModel e-
```

```
/gate/physics/processes/ElectronIonisation/setModel
    StandardModel e+

/gate/physics/addProcess
    Bremsstrahlung
/gate/physics/processes/Bremsstrahlung/setModel
    StandardModel e−
/gate/physics/processes/Bremsstrahlung/setModel
    StandardModel e+

/gate/physics/addProcess
    PositronAnnihilation

/gate/physics/addProcess
    eMultipleScattering
/gate/physics/processes/eMultipleScattering/
    setGeometricalStepLimiterType e− distanceToBoundary
/gate/physics/processes/eMultipleScattering/
    setGeometricalStepLimiterType e+ distanceToBoundary

#for ion source
/gate/physics/addProcess
    RadioactiveDecay

/gate/physics/processList
    Enabled
/gate/physics/processList
    Initialized
```

```
#=================================================
# Output
#=================================================
# ————————————————————————————————————————
# the following actor stores 3D distributions of
# dose/edep/uncertainty/nbHit into files (hdr image file
    format)

/gate/actor/addActor                          DoseActor dose
/gate/actor/dose/save                         output/dose.bin
/gate/actor/dose/attachTo                     tumor
/gate/actor/dose/stepHitType                  random
/gate/actor/dose/setPosition                  0 0 0 cm
/gate/actor/dose/setSize                      5 5 5 cm
/gate/actor/dose/setVoxelSize                 0.05 0.05 0.05 cm
/gate/actor/dose/enableEdep                   true
/gate/actor/dose/enableUncertaintyEdep        false
/gate/actor/dose/enableDose                   true
/gate/actor/dose/enableSquaredDose            false
/gate/actor/dose/enableUncertaintyDose        false
/gate/actor/dose/enableNumberOfHits           false


# ————————————————————————————————————————
# the following actor creates four histograms:
# (1) the initial kinetic energy of each track (
    energySpectrum)
```

```
# (2) the energy deposition per event (edepHisto)
# (3) the energy deposition per track (edepTrackHisto)
# (4) the energy loss per track (eLossHisto).
# These histograms are stored in a (root file).


# /gate/actor/addActor
                                        EnergySpectrumActor
    engSpectrum
# /gate/actor/engSpectrum/save
                                output/energySpectrum.root
# /gate/actor/engSpectrum/energySpectrum/setEmin
            0 MeV
# /gate/actor/engSpectrum/energySpectrum/setEmax
            1 MeV
# /gate/actor/engSpectrum/energySpectrum/setNumberOfBins
    10
# /gate/actor/engSpectrum/energyLossHisto/setEmin
            0 MeV
# /gate/actor/engSpectrum/energyLossHisto/setEmax
            1.5 MeV
# /gate/actor/engSpectrum/energyLossHisto/setNumberOfBins
    10


# ————————————————————————————————————
# the following actor stores in a 3D image the position
# where particles are produced and where particles are
    stopped. (hdr image file format)
```

```
# /gate/actor/addActor
    ProductionAndStoppingActor partLoc
# /gate/actor/partLoc/save          output/
    particleLocation.bin
# /gate/actor/partLoc/attachTo       tumor
# /gate/actor/partLoc/stepHitType    random
# #/gate/actor/partLoc/setResolution 10 10 100
# /gate/actor/partLoc/setVoxelSize   0.05 0.05 0.05 cm
# /gate/actor/partLoc/stepHitType     post


# ————————————————————————————————————————
# the following actor creates a root file and stores the
    number of
# secondaries in function of the particle type. (root
    file)


#/gate/actor/addActor            SecondaryProductionActor
    partLoc2
#/gate/actor/partLoc2/save       output/
    numSecondaryParticles.root
#/gate/actor/partLoc2/attachTo   tumor




#==========================================================
# Initialize
#==========================================================
/gate/run/initialize
```

```
#=======================================================
# Source − Fluorine (18−F)
#=======================================================
/gate/source/addSource                          sourceF18
/gate/source/sourceF18/gps/type                 Volume
/gate/source/sourceF18/gps/shape                Sphere
/gate/source/sourceF18/gps/radius               0.5 cm

/gate/source/sourceF18/gps/particle             ion
/gate/source/sourceF18/gps/ion                  9 18 0 0
/gate/source/sourceF18/setForcedUnstableFlag    true
/gate/source/sourceF18/setForcedHalfLife        6586 s
/gate/source/sourceF18/gps/energytype           Mono
/gate/source/sourceF18/gps/monoenergy           0. MeV
/gate/source/sourceF18/setActivity              37000000 Bq
   #1mCi (1 mili curries)

/gate/source/sourceF18/gps/angtype              iso
/gate/source/sourceF18/gps/centre               0 0 0 cm
/gate/source/sourceF18/attachTo                 tumor
/gate/source/sourceF18/dump                     1
/gate/source/list

#=======================================================
# Verbose
#=======================================================
```

```
#  /gate/verbose  Physic      1
#  /gate/verbose  Cuts        0
#  /gate/verbose  SD          0
#  /gate/verbose  Actions     0
#  /gate/verbose  Actor       0
#  /gate/verbose  Step        0
#  /gate/verbose  Error       1
#  /gate/verbose  Warning     0
#  /gate/verbose  Output      0
#  /gate/verbose  Beam        0
#  /gate/verbose  Volume      0
#  /gate/verbose  Image       0
#  /gate/verbose  Geometry    0
#  /gate/source/verbose       2


#  /gate/output/verbose       2




#=======================================================
#  Start
#=======================================================
#  /gate/application/setTimeSlice     1  ms
#  /gate/application/setTimeStart     0  s
#  /gate/application/setTimeStop      1  ms
#  /gate/application/startDAQ

/gate/random/setEngineName       MersenneTwister
/gate/random/setEngineSeed       247984241
```

```
/gate/application/setTimeSlice  1 s
/gate/application/setTimeStart  0 s
/gate/application/setTimeStop   1 s
/gate/application/startDAQ
```

APPENDIX B

vGate step-by-step installation walkthrough

B.1 vGate Description

Virtual GATE, also known as vGATE, is a virtual machine running an Ubuntu 32-bit operating system; it was made using the free software Virtual Box. This virtual machine can be run on any machine running Linux, Windows or MacOS running in 32 or 64 bits, provided that the Virtual Box program is installed and ready for use.

With vGATE you can launch your first GATE simulation via macro scripts in just a few steps. No need to install anything, no need to configure anything, and no time spent to understand compilation. A full Linux environment is totally set up to be able to use GATE just by launching a simple command: "Gate".

B.2 How to get vGATE

There are two ways to get GATE:

1. OpenGate collaboration website

   If you are a registered user on the OpenGate collaboration website,[1] log in and go to "Download source". You will then be able to download the virtual machine. Be aware that the file you will download is very large (between 1 and 2 Gbytes). The file is a ".7z" file, in other words, it is a file that has been compressed using the program 7-zip. 7-zip is a free, open-source program that can be easily installed on any operating system). You have to decompress your file, which is a VDI (Virtual Disk Image) file. This file is to be used with the Virtual Box software.

---

[1] `http://www.opengatecollaboration.org`

2. Server machine iqserver5 and hydra2 only at the University of Arizona

If you are a user on the iqserver5 or the hydra2 machine, log in by using these addresses **iqserver.optics.arizona.edu** or **hydra2.radiology.arizona.edu**. A copy of vGate was downloaded and placed on the paths in iqserver5 machine: **/Volumes/G-RAID/Users/kaguwa/research/vgate** and on hydra2: **/home/kaguwa/research/vgate**. Once in either one of those directories, one can either choose to copy the full uncompressed file **vGATE_v2.1.vdi** or the compressed file **vgate_v2_1_vdi_7z_20873.7z** and use the 7-zip program to uncompress it. Note that the necessary file is at 8 Gbytes of uncompressed versus compressed at 2 Gbytes.

B.3 How to use vGATE

1. Install Virtual Box

   (a) Since vGate machine has been built using the Virtual Box software, you will have to install this software on your host machine first. Go to the Virtual Box website[2] and download their software.

2. Install vGate

   (a) Launch Virtual Box and click on "New" to create a new virtual machine. (See Figure B.1)

   (b) Click on "Next" and give a name to your machine. (See Figure B.2)

   (c) Choose 'Linux' as Operating System and 'Ubuntu' as Version. If you are asked to, precise 32 bits system. Click on "Next". (See Figure B.2)

   (d) Select the amount of RAM that you want to give to the virtual machine (at least 1Gigabyte if possible, the higher the better). Click on "Next". (See Figure B.3)
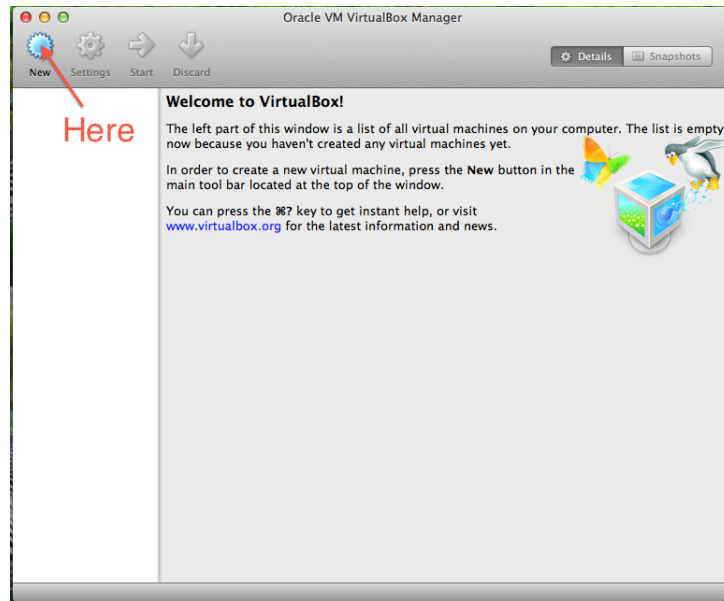

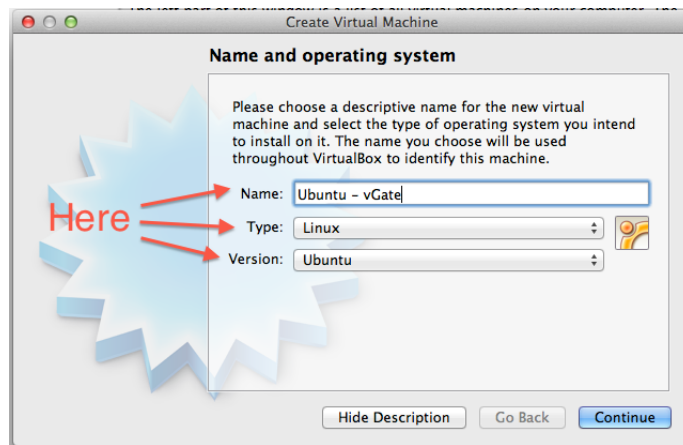[2]https://www.virtualbox.org

Figure B.1: vGate installation step A

Figure B.2: vGate installation step B and C

(e) Select "Use existing hard disk" and then go in the menu on the right, click on "Hard drive" then "Add" and find the VDI file that you have just downloaded. Click on "Next". (See Figure B.4)

(f) Click on "Finish" and you can change settings of your virtual machine and start it. (See Figure B.5)

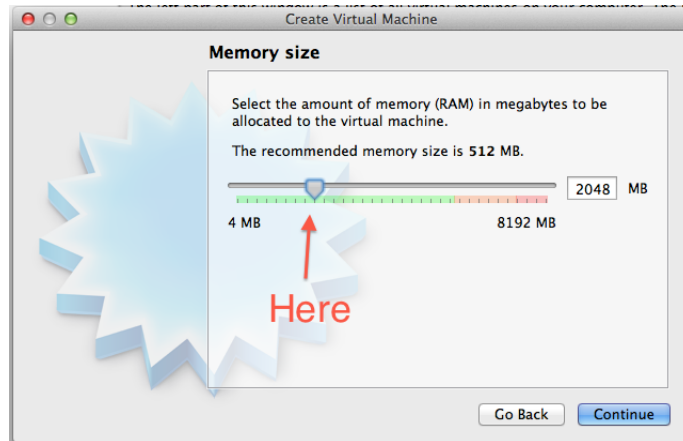(g) The only user in the machine is named "gate" and its associated password

Figure B.3: vGate installation step D
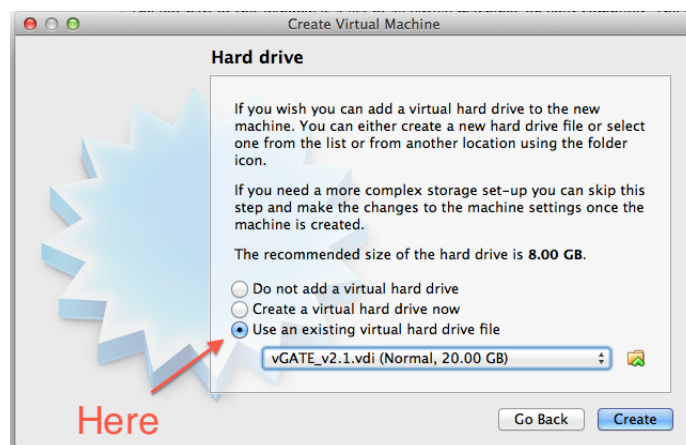
Figure B.4: vGate installation step E

is "virtual". (See Figure B.6)

(h) NOTE: You have to use the **on-screen keyboard** and not the actual physical keyboard. By default the keyboard keys are in french, so one needs to pull up the on screen keyboard and type in the password. Once logged in just change the keyboard language to English instead of french. (See Figure B.7)
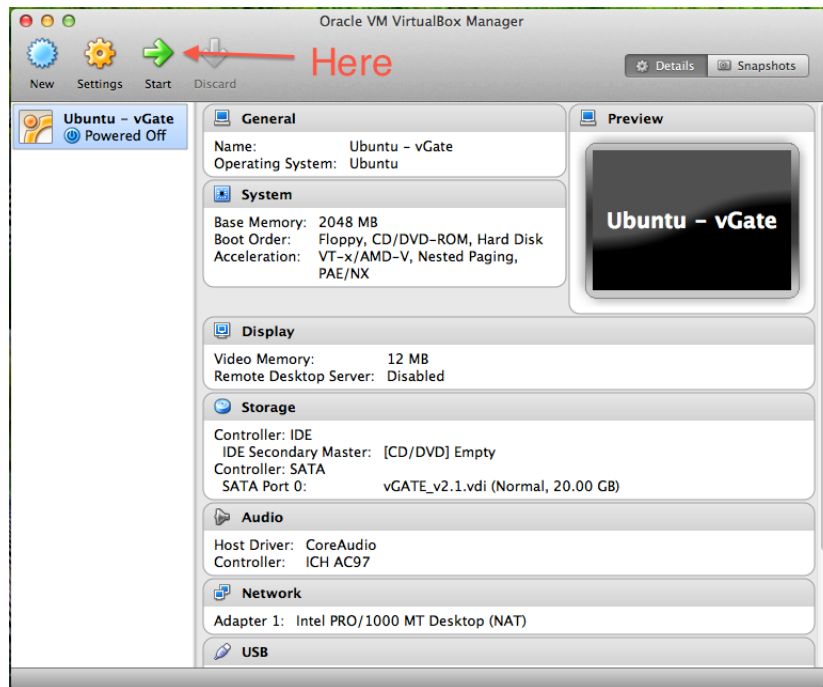
(i) That's it!

Figure B.5: vGate installation step F

B.4 How to get my keyboard properly working

1. Go into the "System" menu, then in "Preferences" and finally in "Keyboard". (See Figures B.8 and B.9)

2. Go in the "Layout" tab and choose the appropriate layout corresponding to your keyboard. (See Figure B.10 through B.12)

B.5 How to run your first GATE simulation in vGate

1. A copy of an example of a GATE macro files from Appendix A and Appendix C is placed on iqserver5 machine with path: **/Volumes/G-RAID/Users/kaguwa/research/vgate** and on hydra2 with path: **/home-/kaguwa/research/vgate**

2. Copy **example_macro.tgz** from either of these paths unto your vGate area. Either via, ftp or setting up a shared directory between the host and the guest
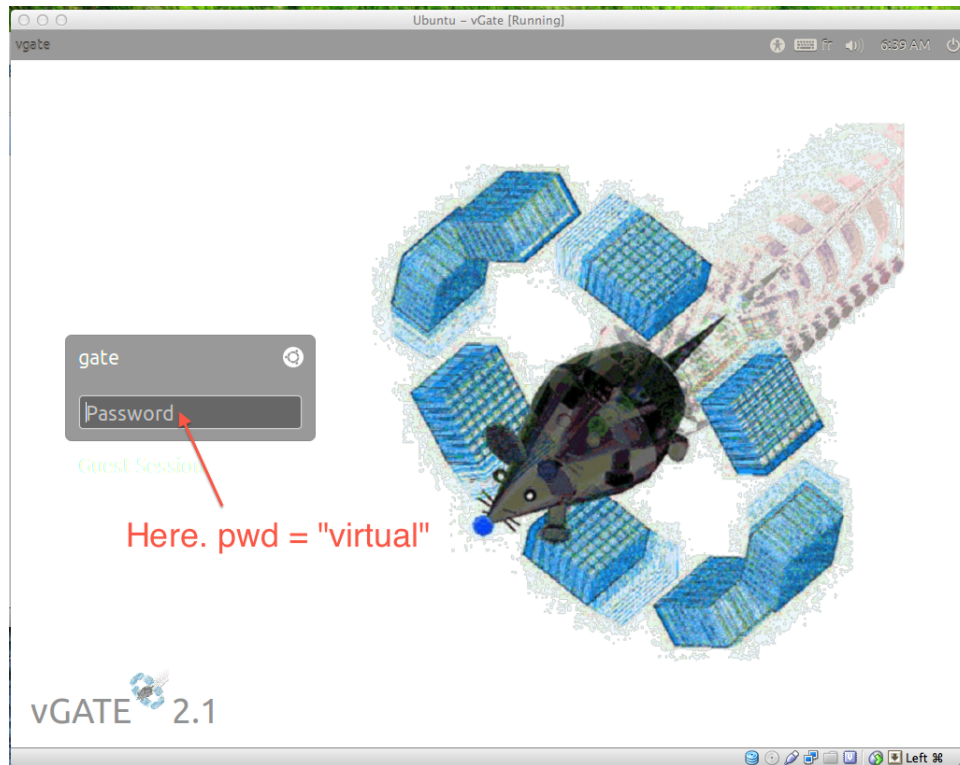
Figure B.6: vGate installation step G

machine explained in tutorial website[3] or send your files via email.

3. Open up the terminal application (See Figure B.13), locate the file and "un tar" it using this command **tar -zxvf example_macro.tgx**

4. Change directory into the **example_macro**

5. Launch GATE using this simple command **Gate example_F18_ion.mac** (See Figure B.14)

6. That's it!

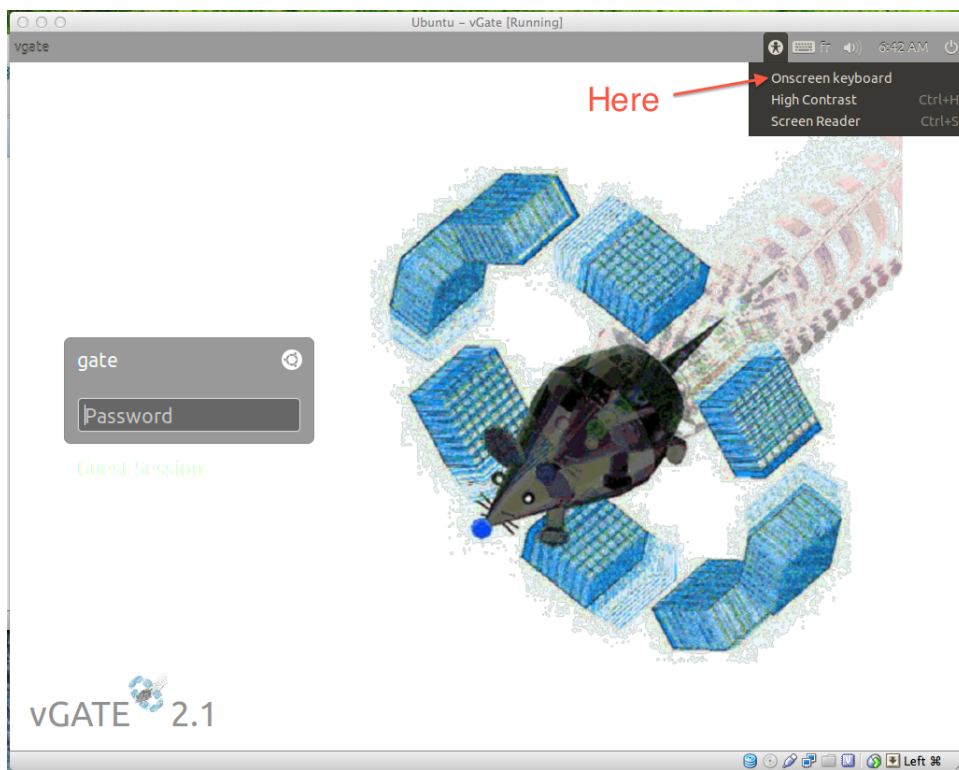[3]http://www.virtualbox.org/manual/ch04.html
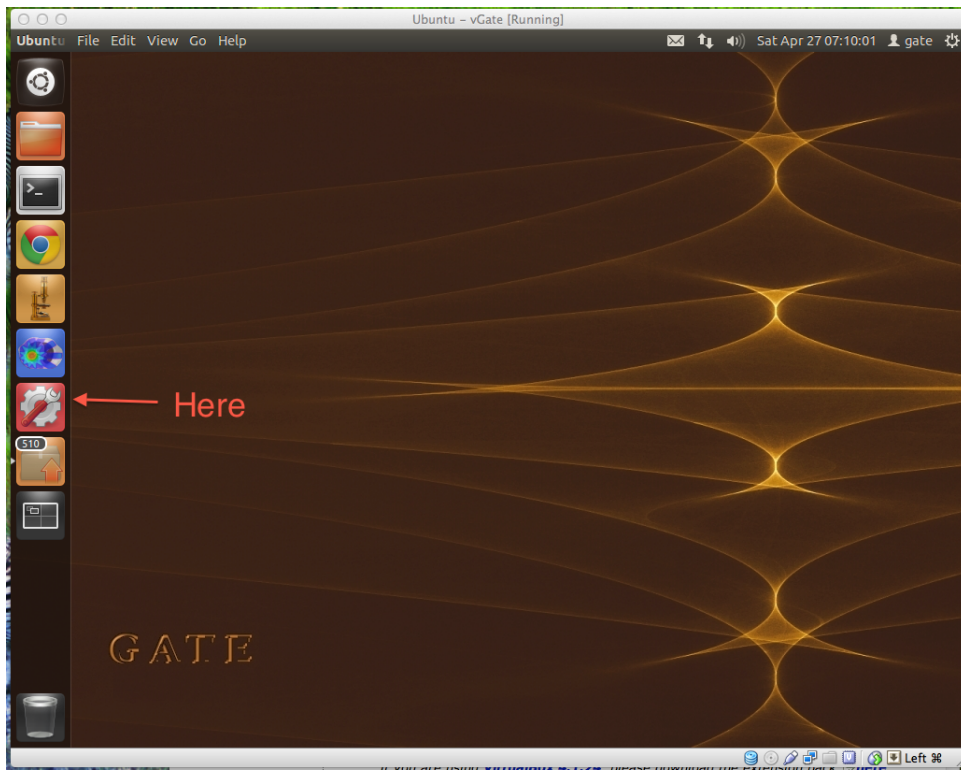
Figure B.7: vGate installation step H

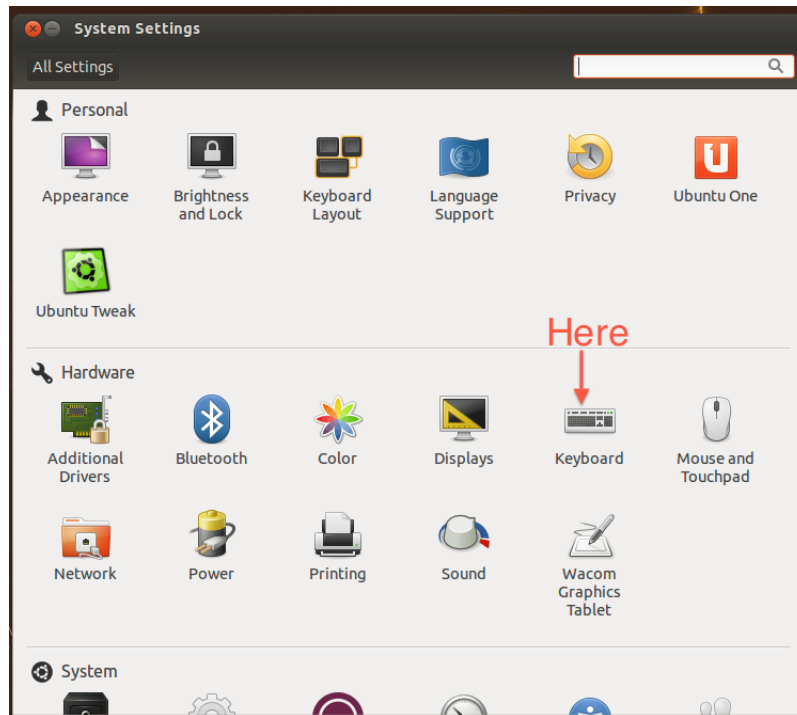Figure B.8: vGate keyboard fix step 1

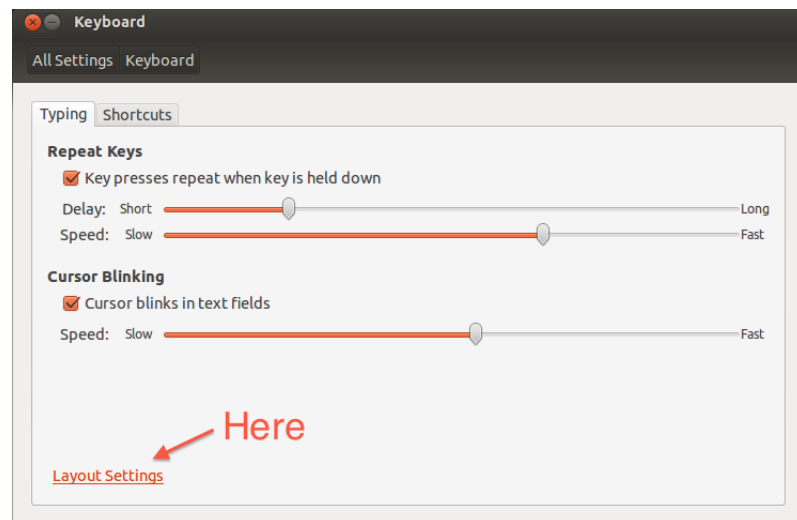Figure B.9: vGate keyboard fix step 2

Figure B.10: vGate keyboard fix step 3

Figure B.11: vGate keyboard fix step 4
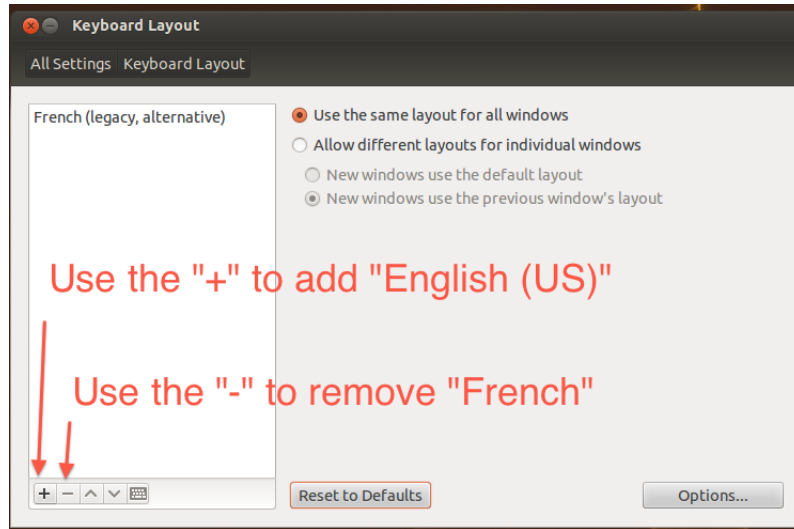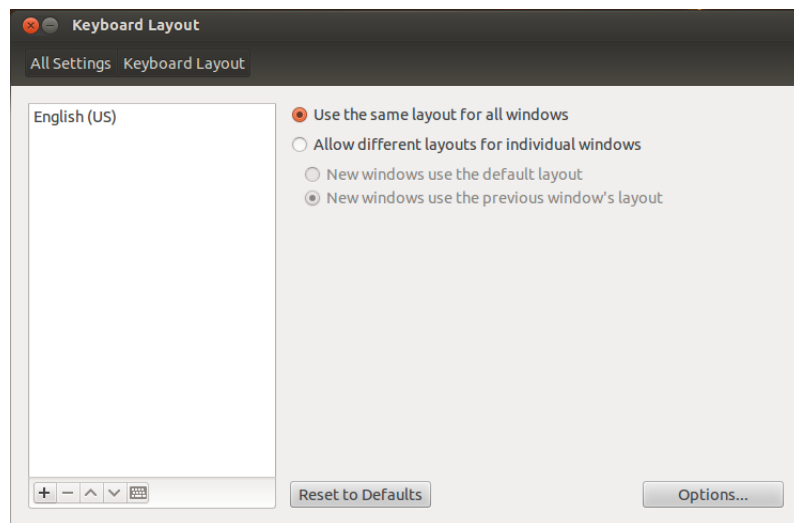

Figure B.12: vGate keyboard fix step 5

Figure B.13: Run vGate step 1
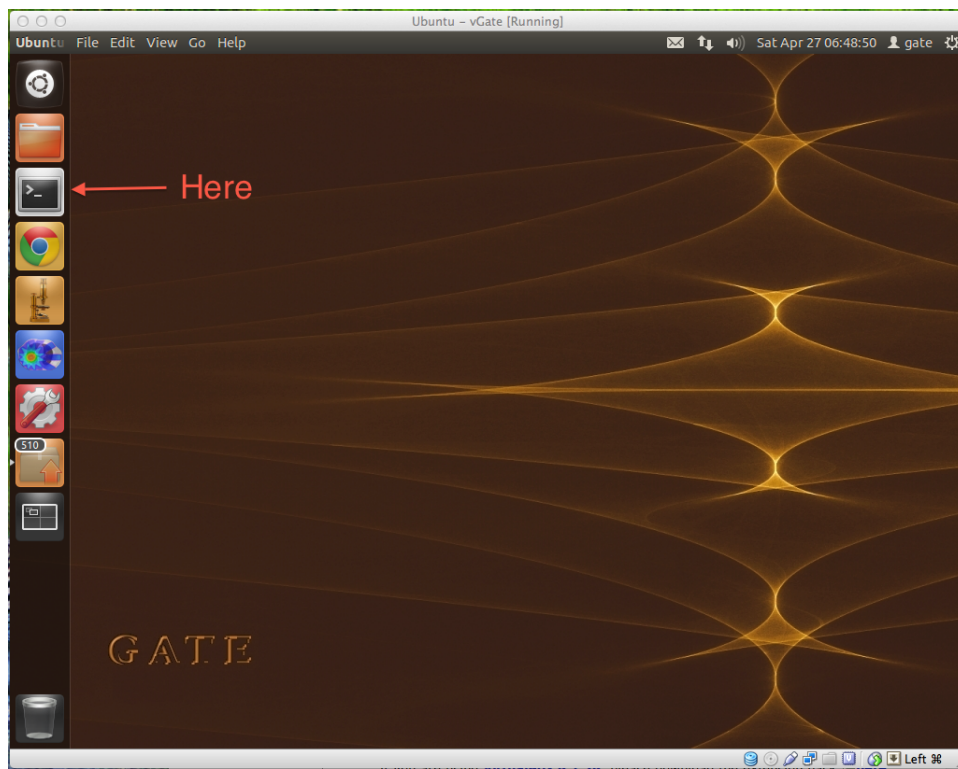

Figure B.14: Run vGate step 2

APPENDIX C

Main GATE script for Absorbed Dose

As in Appendix A, this appendix also contains a GATE script that uses dose actors attached to a digital phantom to produce the dose map for 1 mCi ^{18}F radiotracer.

C.1   Main macro file

```
# Configuration
/control/execute  myConfig.mac


# Vis
# /vis/disable
/control/execute  myVis.mac


# Materials
/gate/geometry/setMaterialDatabase  ../GateMaterials.db


# World
/gate/world/geometry/setXLength  100  cm
/gate/world/geometry/setYLength  100  cm
/gate/world/geometry/setZLength  350  cm
/gate/world/setMaterial          Air


# Daughter  World − Voxel  Phantom
/gate/world/daughters/name
                                 voxelphantom
```

```
/gate/world/daughters/insert
                                    compressedMatrix
/gate/voxelphantom/geometry/insertReader
                            interfile
/gate/voxelphantom/interfileReader/insertTranslator
                range
/gate/voxelphantom/interfileReader/rangeTranslator/
    readTable    {ncat_data}/ncat_atn_range_new.dat
/gate/voxelphantom/interfileReader/rangeTranslator/
    describe        1
/gate/voxelphantom/interfileReader/readFile
                        {ncat_data}/ncat_atn_phantom.h33
/gate/voxelphantom/placement/setTranslation
                    0. 0. 0. cm
/gate/voxelphantom/placement/setRotationAxis
                    1 0 0
/gate/voxelphantom/placement/setRotationAngle
                    0 deg
/gate/voxelphantom/attachVoxelPhantomSD

# Attach the phantom SD and the output module (dose in
    cGy)
# /gate/voxelphantom/addOutput
                                    doseOutput
# /gate/output/doseOutput/saveUncertainty
                    false
# /gate/output/doseOutput/setFileName
                        {out_path}/
```

```
    dose_ncat_F18_ion_1mCi_phantom.bin
# /gate/voxelphantom/verbose 2

# Physics Process
/control/execute myPhysics.mac

# Output
/gate/actor/addActor                      DoseActor dose
/gate/actor/dose/save                     {out_path}/
    dose_ncat_F18_ion_1mCi_test.bin
/gate/actor/dose/attachTo                 voxelphantom
/gate/actor/dose/stepHitType              random
# /gate/actor/dose/setSize                  80 80 80 cm
/gate/actor/dose/setPosition              0 0 0 cm
/gate/actor/dose/setVoxelSize             0.6 0.6 0.6 cm
/gate/actor/dose/enableEdep               true
/gate/actor/dose/enableUncertaintyEdep    false
/gate/actor/dose/enableDose               true
/gate/actor/dose/enableSquaredDose        false

# Initialize
/gate/run/initialize

# Source − Voxel − F18 ion
/gate/source/addSource

    voxelSource voxel
```

```
/gate/source/voxelSource/reader/insert
                                    interfile
/gate/source/voxelSource/interfileReader/translator/
    insert               range
/gate/source/voxelSource/interfileReader/rangeTranslator/
    readTable     {ncat_data}/ncat_act_range.dat
/gate/source/voxelSource/interfileReader/rangeTranslator/
    describe        1
/gate/source/voxelSource/interfileReader/readFile
                         {ncat_data}/ncat_atn_phantom.h33
/gate/source/voxelSource/setPosition
                                    -240.0  -240.0  -1050.0
    mm
# The default position of the voxellized source is in the
    1^{st}
# quarter. So the voxellized source has to be shifted
    over half its
# dimension (dimension = dimImgXYZ * dimVoxXYZ)in the
    negative direction on each axis

# /gate/source/addSource
    voxelSource
# /gate/source/voxelSource/gps/type                Volume
# /gate/source/voxelSource/gps/shape               Sphere
# /gate/source/voxelSource/gps/radius              {
    source_radius}

/gate/source/voxelSource/gps/particle            ion
```

```
/gate/source/voxelSource/gps/ion                    {F18_ion}
/gate/source/voxelSource/setForcedUnstableFlag  true
/gate/source/voxelSource/setForcedHalfLife      {
    F18_halflife}
/gate/source/voxelSource/gps/energytype         Mono
/gate/source/voxelSource/gps/monoenergy         0. MeV
# /gate/source/voxelSource/setActivity            {one_mCi
    }
#
/gate/source/voxelSource/gps/angtype            iso
/gate/source/voxelSource/gps/centre             0 0 0 cm
/gate/source/voxelSource/attachTo
    voxelphantom
# /gate/source/voxelSource/gps/confine            NULL
/gate/source/voxelSource/dump                   1
/gate/source/list


# Start
/control/execute myStart.mac
```

C.2   Sub macro file: myConfig.mac

```
/control/alias  F18_ion      9   18   0   0
/control/alias  Tc99m_ion   43  99   0   143
/control/alias  Y90_ion     39  90   0   0
/control/alias  I123_ion    53  123  0   0
/control/alias  I131_ion    53  131  0   0
/control/alias  In111m_ion  49  111  0   537
```

```
/control/alias  F18_halflife       6586  s
/control/alias  Tc99m_halflife     21621  s
/control/alias  Y90_halflife       230591  s
/control/alias  I123_halflife      47592  s
/control/alias  I131_halflife      692902  s
/control/alias  In111m_halflife    241920  s


#  /control/alias  one_mCi         37000000  Bq
/control/alias  one_mCi         0.001  Ci
/control/alias  pt74_mCi        0.00074  Ci
/control/alias  pt25_mCi        0.00025  Ci
/control/alias  pt1_mCi         0.0001  Ci
/control/alias  pt02_mCi        0.00002  Ci
/control/alias  pt088_mCi       0.000088  Ci
/control/alias  pt014_mCi       0.000014  Ci



/control/alias  source_radius    0.5  cm
/control/alias  tumor_radius     0.62053  cm


/control/alias  out_path     /Users/kratos/gate/workDir/
    output

#  /control/alias  ncat_data   /Users/kratos/xcat/output
#  /control/alias  ncat_data   /Users/kratos/xcat/
    output_sphere
```

```
/control/alias ncat_data    /Users/kratos/xcat/
   output_fullSample
# /control/alias ncat_data    /Users/kratos/xcat/
   output_50x50x50pt6
# /control/alias ncat_data    /Users/kratos/gate/workDir/
   ncat_data
```

C.3   Sub macro file: myVis.mac

```
#         V I S U A L I S A T I O N
/vis/open OGLSX
/vis/viewer/reset

# define the zoom factor
/vis/viewer/zoom 5.5

# Set the viewing angle
#/vis/viewer/set/viewpointThetaPhi 45 45
/vis/viewer/set/viewpointThetaPhi 60 −60
#/vis/viewer/set/viewpointThetaPhi 70 20
#/vis/viewer/set/viewpointThetaPhi 120 30
#/vis/viewer/set/viewpointThetaPhi 240 −60
#/vis/viewer/set/viewpointThetaPhi −90 90

# Set the drawing style
#/vis/viewer/set/style surface

# Tell the viewer to draw the volumes
```

```
/vis/drawVolume



# The trajectories for each run should be drawn together
# don't store trajectories = 0; store trajectories = 1
/tracking/storeTrajectory 0
#/tracking/storeTrajectory 1


/vis/scene/add/trajectories

# Requests viewer to refresh hits, tracks, etc., at end
   of event.
# Or to accumulate drawings. Detector remains or is
   redrawn.
/vis/scene/endOfEventAction accumulate
#/vis/scene/endOfEventAction accumulate 10


/vis/viewer/flush
/tracking/verbose 0
/vis/viewer/update
```

C.4   Sub macro file: myPhysics.mac

```
#==================================================
# Physics Process
#==================================================
```

```
/gate/physics/addProcess
    PhotoElectric
/gate/physics/processes/PhotoElectric/setModel
    StandardModel

/gate/physics/addProcess                    Compton
/gate/physics/processes/Compton/setModel  StandardModel

/gate/physics/addProcess
    RayleighScattering
/gate/physics/processes/RayleighScattering/setModel
    PenelopeModel

/gate/physics/addProcess
    GammaConversion
/gate/physics/processes/GammaConversion/setModel
    StandardModel

/gate/physics/addProcess
    IonIonisation

/gate/physics/addProcess
    ElectronIonisation
/gate/physics/processes/ElectronIonisation/setModel
    StandardModel e−
/gate/physics/processes/ElectronIonisation/setModel
    StandardModel e+
```

```
/gate/physics/addProcess
    Bremsstrahlung
/gate/physics/processes/Bremsstrahlung/setModel
    StandardModel  e−
/gate/physics/processes/Bremsstrahlung/setModel
    StandardModel  e+


/gate/physics/addProcess  PositronAnnihilation


/gate/physics/addProcess
    eMultipleScattering
/gate/physics/processes/eMultipleScattering/
    setGeometricalStepLimiterType  e− distanceToBoundary
/gate/physics/processes/eMultipleScattering/
    setGeometricalStepLimiterType  e+ distanceToBoundary

#for  ion  source
/gate/physics/addProcess  RadioactiveDecay


/gate/physics/processList  Enabled
/gate/physics/processList  Initialized
```

C.5   Sub macro file: myStart.mac

```
#==================================================
#  Start
#==================================================
#  /gate/application/setTimeSlice      1  ms
```

```
#  /gate/application/setTimeStart       0  s
#  /gate/application/setTimeStop        1  ms
#  /gate/application/startDAQ


/gate/random/setEngineName        MersenneTwister
/gate/random/setEngineSeed        247984241
/gate/application/setTimeSlice  0.01  s
/gate/application/setTimeStart  0  ms
/gate/application/setTimeStop   0.01  s
/gate/application/startDAQ
```

APPENDIX D

Brute force absorbed dose calculation

Figure D.1: Example of a Brute Force Absorbed Dose Calculation Method. Image slide from H.H Barrett presentation slide.

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