MIDDLE EAST TECHNICAL UNIVERSITY

Investigation of Role of Radionuclides in Cancer Treatment

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Phys 403: Nuclear Physics II - Term Project

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Abstract

In the 21^{st} century, medical applications and interdisciplinary biological approaches across all departments increased drastically. Novel technologies and ongoing developments in physics, computer science, and applied mathematics with fast computers and novel simulation programs allowed the development of better and safer medical tools. The GEANT project started after 1974, but a faster and more applicable, user-friendly version started near the 2000s. Moreover, electronics and instrumentation with automation in the industry increased, became more accessible, and real-life experiments became faster. The project aims to discuss novel nuclear medicine tools and medical physics applications, radionuclides, cancer, and physics behind with a hint of development history. Furthermore, Some applications are shown with Iodine-131, with the novel GEANT4-DNA tool, its applications, and how we determine the material and their usage is put. Radionuclides, used in cancer treatment from their first discovery to novel usages, were discussed. The paper's prominence of nuclear medicine and radionuclides indicates a great future for medical science and nuclear physics.

Contents

1 Introduction

After the discovery of nuclear physics and the advancement of electronic technologies on par with medical advancement, particles and nuclear physics started to get used in the medical field for different properties of the atom and subatomic particles. Humanity has never benefited from nuclear scientific advancement before medical and electronic development. With novel technologies, MDs can observe internal tissues and anomalies without even giving slight radiation to the patient, such as in MRI. On par with non-invasive technologies, the invasive treatment also further developed with the help of radioactive particles. PET scanning and cancer treatment are each area that benefited the most from the nuclear technologies and physics behind them. This paper discusses the following;

1. The history of radionuclides
2. Radionuclide discoveries
3. The development of cancer treatment based on radionuclides
4. Radionuclide Physical Properties
5. Physical Principles of Radiation Therapy
6. Toolkits and Programs to develop nuclear medical treatment by Medical Physicists
7. Sample GEANT4 & GEANT4-DNA plots
8. Discussion on the importance of Medical Physics & Nuclear Physics

This paper also mainly follows $iodine - 131$, which is the most commonly used radionuclide in cancer treatment, and the simulation will be based on iodine. The paper follows its scope on investigating the role of radionuclides in cancer treatment while covering some of the physics without entering too much mathematical detail.

2 Radionuclides

In 1896, Henri Becquerel discovered naturally occurring radioactivity; later on, Frederic Joliot and Irene Joliot-Curie continued the research and discovered artificial radioactivity in 1934[1]. Most known natural radionuclides are produced through one of four decay chains; in each, radionuclides are fed by a long-lived and heavy parent *radionuclide*[1]. Vastly, the known radionuclides, on the other hand, are human-made and artificially produced through processes of nuclear activation that use the bombardment of a stable nuclide with a suitable energetic particle to induce a nuclear $transformation$[1]. Various particles or electromagnetic radiation generated by various machines are used for this purpose, main neutrons of nuclear reactors for neutron activation and protons from cyclotrons for proton *activation*[1]. When the origin of the radioactive nuclides(radionuclides) is considered, they are divided into two categories:

1. Naturally-occurring
2. Human-made or artificially produced.

2.1 Naturally Occurring *Radionuclides*[5]

There is no core difference in a physical manner between the two categories of radioactivity; the division is mainly historical and related to the sequence of radioactivity-related *discoveries*[1]. Henri Becquerel discovered natural radioactivity in 1896 when he noticed that uranium spontaneously produced unseeable, penetrating radiation that affected photographic plates he *put*[1]. Near a half-century later, in 1934, Irene Joliot-Cure and Frederic Joliot discovered artificial radioactivity with a series of experiments in which they bombarded boron samples with naturally occurring α-particles and produced nitrogen that was unstable and emitted positrons through β^+ *decay*[1]. There exist such rare long-lived light radionuclides as $carbon - 14$, which are produced by cosmic proton *radiation*[1]. Cosmic rays are highly energetic particles originating from outer space and striking the Earth's atmosphere. Majority of the cosmic rays (87 %) are protons, some 12 % are *alpha*-particles (helium ions), and about 1 % are energetic electrons. On the other hand, those of one of four radioactive series given as:

1. $Thorium$ series originates with $thorium - 232$
2. $Actinium$ series originates with $uranium - 235$
3. $Neptunium$ series originates with $neptunium - 237$
4. $Uranium$ series originates with $uranium - 238$

Name of series	Rule	Parent	First Decay	N_α	Found in nature	Half-life (10^9))	Stable end-product
Thorium	4n	$^{232}_{90}$Th	$^{228}_{88}$Ra + α	6	YES	14.05	$^{208}_{82}$Pb
Actinium	4n+3	$^{235}_{92}$U	$^{231}_{90}$Th + α	7	YES	0.704	$^{207}_{82}$Pb
Neptunium	4n+1	$^{237}_{93}$Np	$^{233}_{91}$Pa + α	7	NO	2.114*10^{-3}	$^{209}_{83}$Bi
Uranium	4n+2	$^{238}_{92}$U	$^{234}_{90}$Th + α	8	YES	4.47	$^{206}_{82}$Pb

Table 1: The four naturally occurring radioactive series, N_α for the number of steps in the decay chain required to reach the stable nucleus.

These series all begin with very heavy and long-lived parents that have half-lives of the order of the age of the earth. The n represents the atomic mass number of the series, by that for one element to be in a series of $Thorium - 232$, then it should have $4n$ atomic mass number. These series are assumed to come from collapsing stars, which led to the creation of all heavy radioactive elements, which are all approximately in equal proportions; however, they differ in half-life, which led to today's variation of abundance of radioactive heavy elements. $Neptunium - 237$ considerably has a shorter half-life than the other three. Therefore it does not occur naturally because the earth's formation was nearly 5 billion years ago. The other three series are still found in nature and serve as the parent of their series. Cosmic ray protons continually produce small amounts of radioactive materials. As mentioned above, $carbon - 14$, which decays with a half-life of 5730 years, is used for finding a once-living object's date of origin and is called carbon dating. There exist notable lighter-than-lead radioactive elements on earth, one of which is $potassium - 40$ (^{238}U), with a half-life that is near 1 billion years. It can be found in many foods, mostly in bananas. Therefore, it accounts for the largest portion of the naturally-occurring load of radiation for humans through ingestion. These four series also provide the source to short-lived daughters, which would be extinct if such parent elements didn't replenish their source with their long decay time.

2.2 Human-made(Artificial) *Radionuclides*[1]

Human-made (Artificial) radionuclides are created by bombarding stable nuclides or very long-lived radionuclides with energetic particles or energetic X-rays, which are produced by different kind of machinery. This process is called as radioactivation or nuclear activation. Founders of the artificial radionuclides (Joliot-Curie) found over 3000 different artificial radionuclides by synthesis. Therefore, the current list of known nuclides contains 280 stable nuclides and over 3000 radionuclides. Near 200 radionuclides are currently

used in industry and medicine, the vast majority produced by radioactivation. The most common way of radioactivation is bombarding stable target nuclei with neutrons produced in nuclear reactors or by protons produced in cyclotrons. In the literature, three main radioactivation procedures are given as follows:

1. Nuclear activation that is induced with thermal or fast neutrons from a nuclear reactor, which is *neutroncapture* or *neutronactivation*.
2. Nuclear activation induced via protons or heavier ions as deuterons, which is called *protonactivation* or *protoncapture*
3. Nuclear activation with high-energy x-rays from a linear accelerator, called as *nuclearphotoactivation*

Additionally, short-lived radionuclides, which are used in nuclear medicine, can be obtained from the so-called *radionuclidegenerators* which contain a relatively long-lived parent that decays to the short-lived daughter that can be chemically extracted from the parent stored in a *radionuclidegenerators*. In medicine, the most common source of radionuclides is nuclear reactors, either produced by neutron activation or fission-chemical separation.

2.3 Radionuclides in the Environment

More than 60 radionuclides can be found in the environment, and some pose a health hazard to human beings. These radionuclides are grouped into four different categories as follows:

1. *Primordial* - originates way before the creation of the Earth
2. *Secondary* - originates via decay of primordial radionuclides
3. *Cosmogenic* - Cosmic radiation produce after hitting the Earth
4. $Artificial$ - Radioactivation based products of radionuclides

These radionuclides follow several pathways to enter our environments:

1. *Atmospheric* - Can enter due to human activity, radioactive decay, cosmogenic reactions
2. $Water$ - can occur due to erosion, seepage, leaching, mining, and depositing in the water
3. $Food-Chain$ - radionuclides in water and air can enter the food chain.

Later on, these radionuclides enter the human body via three different paths:

1. $Ingestion$
2. $Inhalation$
3. $Through-Skin$

2.4 General Look on Nuclear *Activation*[1]

Several types of nuclear activation are known. They can be said as neutron activation, proton activation, and nuclear photoactivation. In medical physics, neutron activation is important in the radionuclide production that is used for external beam radiotherapy, brachytherapy, and molecular imaging; proton activation is important in positron emitter production, which is used in PET scanning; and nuclear photoactivation is important from a radiation protection point-of-view, to protect the staff that maintains and controls the radiotherapy machinery after activation and prevents a potential radiation hazard. All three activation processes discussed are inherently different. Yet, they have several features that govern the physics behind the processes, such as cross-section, target thickness, Q value, and threshold.

3 Properties of *Radionuclides*[1]

The development of nuclear physics allowing artificial radionuclides production, led to the vast usage of radionuclides in industry and medicine. These radionuclides have several unique properties, such as half-life, decay mode, decay constant, and energies of the emitted radiation. Each follows one of the four decay chains, and their radiation has different types, such as β^-, α, etc. Here these properties will be discussed in more detail.

3.1 Half-life, Decay Modes, Decay Constant, Energy of Emitted Radiation, Types of Radiation and their range, Decay *chain*[2]

The following equations show the therapeutic radionuclides' half-life, decay modes, decay constant, emitted radiation energies, types of radiation, their range, and decay chain.

Radionuclide: Cobalt-60 (Co-60)
Half-life: 5.27 years
Decay Modes:

- β- Decay: Co-60 $\rightarrow$ Ni-60 + e^- + $\overline{\nu_e}$
- Electron Capture: Co-60 + e^- $\rightarrow$ Ni-60 + ν_e

Decay Constant: λ = ln(2) / Half-life = ln(2) / 5.27 years
Energy of Emitted Radiation:

- β- Decay: Maximum energy of β- particles = 0.31 MeV
- Electron Capture: Capture energy = 1.17 MeV (prompt gamma) and 1.33 MeV (delayed gamma)

Types of Radiation: β^- particles, gamma rays
Range of Radiation: β^- particles: a few centimeters in tissue

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Radionuclide: Iodine-131 (I-131)
Half-life: 8.02 days
Decay Modes:

- β- Decay: I-131 $\rightarrow$ Xe-131 + e^- + $\overline{\nu_e}$
- Electron Capture: I-131 + e^- $\rightarrow$ Xe-131 + ν_e

Decay Constant: λ = ln(2) / Half-life = ln(2) / 8.02 days
Energy of Emitted Radiation:

- β- Decay: Maximum energy of β- particles = 0.606 MeV
- Gamma Decay: Emission of gamma rays at various energies (e.g., 364 keV, 637 keV, 723 keV)

Types of Radiation: β^- particles, gamma rays
Range of Radiation: β^- particles: a few millimeters in tissue

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Radionuclide: Yttrium-90 (Y-90)
Half-life: 2.67 days
Decay Modes:

- β- Decay: Y-90 $\rightarrow$ Zr-90 + e^- + $\overline{\nu_e}$

Decay Constant: λ = ln(2) / Half-life = ln(2) / 2.67 days
Energy of Emitted Radiation:

- Maximum energy of β- particles = 2.28 MeV

Types of Radiation: β^- particles
Range of Radiation: Several millimeters to a few centimeters in tissue

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Radionuclide: Technetium-99m (Tc-99m)
Half-life: 6.01 hours
Decay Modes:

- Isomeric Transition: Tc-99m $\rightarrow$ Tc-99 + γ

Decay Constant: λ = ln(2) / Half-life = ln(2) / 6.01 hours
Energy of Emitted Radiation: Emission of gamma rays at various energies (e.g., 140 keV, 364 keV)
Types of Radiation: Gamma rays
Range of Radiation: Varies depending on the energy of the gamma rays

3.2 Biological Effects of Radionuclides used in Medical Physics

1. **DNA Damage:** Ionizing radiation damages cell DNA directly or indirectly, which leads to various DNA lesions, including single-strand breaks, double-strand breaks, and DNA cross-links.
2. **Cell Death:** Radiation-induced DNA damage may trigger cell death through various mechanisms, some of them are apoptosis, necrosis, and mitotic catastrophe. The extent and type of cell death depend on radiation dose, dose rate, and cell type.

3. **Tumor Control:** In brachytherapy, the goal is to deliver a therapeutic radiation dose to the tumor while minimizing damage to surrounding healthy tissues. The radionuclide's biological effects are critical in achieving tumor control by damaging tumor cells and impairing their ability to populate and survive.

4. **Normal Tissue Toxicity:** Even with the most effort, healthy tissues are not spared; some radiation is inevitably delivered to surrounding healthy tissues. Radionuclides can result in acute and chronic biological effects as toxicities in these tissues, which lead to side effects such as inflammation, fibrosis, and organ failure or impairment.

5. **Radiobiological Models:** Assessing the radionuclide's biological effects and optimizing treatment plans, radiobiological models are used. These models consider factors such as radiation dose, dose rate, tissue repair capacity, and the inherent radiosensitivity of varying cell types.

4 Physical Principles of Radiation $Therapy^{[1]}$

The usage of radiation to treat cancer dates way back to the days when the destructive effects of radiation were first realized in which DNA is damaged; radiation disables the ability of an affected cell to reproduce. Therefore, it can remove highly active cancerous or unwanted tissue. Today, radiation therapy is used as a standard procedure, which is used in conjunction with other treatments that are specially designed to treat cancer, such as (surgery and chemotherapy). Radiation therapy overrides some concerns about minimizing the negative effects of radiation exposure, which damages and destroys healthy tissue while increasing the possibility of inducing new cancer in irradiated areas. The medical physicist is concerned that most cancers and tumors are less oxygenated and often less prone to radiation than normal tissue. Drugs can alleviate this by reducing oxygen to all tissues in the affected area, fractionating the dose, or using high LET(Linear Energy Transfer) radiation for which the oxygen-enhancement ratio is low. In radiation therapy, different types of radiation are used. Most of the treatments employ photon or β emitters. because they are cheaper and readily available than alternatives that will need neutron sources or charged particles; however, neutron and charged particles are still used in some novel areas.

4.1 Radiation Interactions with matter

There are different types of radiation interactions with matter, and they can be stated as:

1. Interactions of Charged Particles with Matter
2. Interactions of Photons with Matter
3. Interactions of Neutrons with Matter

Since all can be discussed in extreme detail, one should not lose their main focus; therefore, all interactions will be discussed in a summarizing manner.

4.1.1 Charged Particle Interactions

A charged particle is a particle that is surrounded by its Coulomb electric field, which interacts with orbital electrons and the nucleus of all atoms it encounters as it penetrates the matter. Charged particle interactions with the absorber's orbital electrons lead to collision loss, and interactions with the nuclei of the absorber result in radiation loss. The energy transfer from the charged particle to the matter in these atomic interactions can be considered small. Hence the particle undergoes much interaction before its kinetic energy is spent. Energy levels of these interactions are observed via a

parameter called stopping power, which defines the charged particle's gradual energy loss. In contrast, the particle penetrates the absorbing medium. There exist two classes of stopping power, *collision stopping power*, which is the result of charged particle interaction with the electrons on the orbit of the absorber; the latter is *radiation stopping power* which results from the interaction of the charged particle with the absorber's nuclei. In addition to the stopping powers, mean ionization potential, energy transfer, range, and radiation yield are also important. The energetically charged particle emission from radioactive material was first discovered in 1896, gathering interest on the origin of the particle emission and how these particles are slowed down as they traverse the matter. With the experiments of Hans Geiger, Ernest Marsden, and Ernest Rutherford in 1908 with α-particle, the stopping power theory played a significant role in understanding energy transfer. In 1913 Niels Bohr developed the classical stopping power theory; later on, Hans Bethe applying quantum mechanics, found the relativistic theory of stopping power in the 1930s, which is later again stated by Ugo Fano in the 1960s. Recent developments show accuracy development and secondary adjustments. There are three categories of interactions depending on the size of the classical impact parameter b of the charged particle trajectory compared to the classical atomic radius, a, of the absorber in which the charged particle has the interaction. The charged particle experiences the three categories based on the Coulomb interactions with the nuclei and the electrons orbiting the absorbers atom. These categories can be defined as:

1. Coulomb force interaction of the charged particle with the external nuclear field of the absorber atom for $b \ll a$ (Bremsstrahlung production)

2. Coulomb force interaction of the charged particle with the orbital electron of the absorber atom for $b \approx a$ (hard collision)

3. Coulomb force interaction of the charged particle with the orbital electron of the absorber atom for $b \gg a$ (soft collision).

Radiation, hard, and soft collisions are shown in the figure below, with b the impact parameter of the particle trajectory and an atomic radius of the absorber atom.

4.1.2 Photon Interactions

Photons can interact with absorbing media when photon energy exceeds the ionization energy of the absorber atom. These photons belong to the category of indirectly ionizing radiation, and they deposit energy in the absorbing medium through a two-step process:

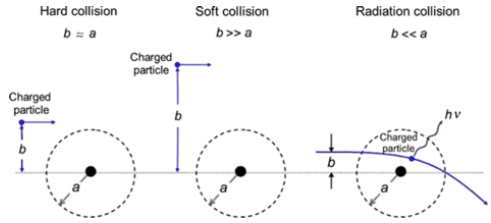


Figure 1: Three different types of collision of a charged particle with an atom

1. Energy is transferred to an energetic light-charged particle
2. Energy is deposited in the absorbing medium by the charged particle

The energy transferred in these steps to the charged particles from the interacting photon generally exceeds the energy subsequently deposited in the absorbing medium by the charged particles because the energy that can be transferred might be radiated from the charged particles in the form of photons. Some of the photon interactions are not used in medical physics but help with understanding phenomenology better; however, to understand the ones in use, it would be beneficial to discuss them since they have an essential role in imaging, radiotherapy, and radiation dosimetry. Photons depending on their energy levels and the atomic number of the absorber, photons can interact with the absorber wholly, with the nucleus of an absorber atom, or with an orbital electron of the absorber atom. After the interaction, we deal with two possible outcomes:

1. Photon disappeared
2. Photon is scattered

For photon interactions, when photons penetrate an absorbing medium, they may experience various interactions with the medium's atoms. These interactions deal with the absorbing medium's nuclei or the absorbent medium's orbital electrons.

1. Interactions with the nuclei may be direct photon-nucleus interactions (photon disintegration) or interactions between the photon and the electrostatic field of the nucleus (pair production)
2. The photon-orbital electron interaction is characterized as interactions of photon and either a loosely bound electron, $E_B \ll h\nu$, (Thomson scattering, Compton effect, triplet production) or a tightly bound electron, $E_B \leq h\nu$, (photoelectric effect, Rayleigh scattering)

For to design the total absorber thickness x, a photon beam of energy $h\nu$ strikes to a detector and produces a measured intensity of I_0. When an

absorber of thickness l is placed into the path of the photon beam, measured intensity decreases to I_1, which can be expressed as,

$$I_1 = RI_0 \tag{1}$$
$$I_2 = RI_1 = R^2 \cdot I_0 \tag{2}$$
$$I_n = I(x) = R^n \cdot I_0 = R^{(x/l)} \cdot I_0 \tag{3}$$
$$\tag{4}$$

or

$$\ln\left(\frac{I(x)}{I_0}\right) = x\frac{\ln R}{l} = -\mu x \tag{5}$$

lastly, we will end up with the following, where, as a consequence of R < 1, we define the attenuation coefficient μ as in the equation below,

$$I(x) = I_0 \cdot e^{-\mu x} \tag{6}$$

4.1.3 Neutron Interactions

Neutrons, as can be observed from their neutrality, are indirectly ionizing radiation, exhibiting a quasi-exponential penetration into an absorber and depositing energy in the absorber through a two-step process:

1. Energy transfer to heavy charged particles
2. Energy deposition in the absorber through Coulomb interactions of these charged particles with atoms of the absorber

While penetrating matter, neutrons undergo elastic and inelastic scattering and trigger nuclear reactions, such as neutron capture, spallation (target bombarding by high-energy particles), and fission. Two distinct categories of neutrons are of direct importance in medical physics: *thermal neutrons* used in boron-neutron capture therapy (BNCT) and fast neutrons used in external beam radiotherapy. Indirectly, thermal neutrons help produce radionuclide sources used in external beam radiotherapy, brachytherapy, and nuclear medicine imaging. A nuclear reactor and two types of thermal neutron interaction are used for this purpose:

1. Suitable target material neutron activation
2. Fission reaction induced by thermal neutrons in fissile target materials

There exist seven types of neutrons with respect to their E_K; they are;

1. Ultracold neutrons with $E_K < 2 \cdot 10^{-7} eV$
2. Very cold neutrons with $2 \cdot 10^{-7} eV \leq E_K \leq 5 \cdot 10^{-5} eV$

3. Cold neutrons with $5 \cdot 10^{-5} eV \leq E_K \leq 0.025$ eV
4. *Thermal neutrons* with $E_K \approx 0.025$ eV
5. *Epithermal neutrons* 1 eV $< E_K <$ 1 keV
6. Intermediate neutrons with 1 keV $< E_K <$ 0.1 MeV
7. *Fast neutrons* with $E_K >$ 0.1 MeV

Neutron interactions can be stated as with the Nuclei of the Absorber:

1. Elastic scattering
2. Inelastic Scattering
3. Neutron Capture
4. Nuclear spallation
5. Nuclear fission

The probability (cross-section) for these different interaction types varies with the kinetic energy of the neutron and the physical properties of the nuclei of the absorber.

4.2 Dose Calculation

The dose calculation given in the paper is a basic dose calculation formulation without entering into detailed derivations and cross-sections. However, one can read more from the references for more mathematical rigor derivation. Here the absorbed dose (D) can be calculated using the following equation:

$$D = \frac{E}{m} \tag{7}$$

where E is the energy deposited in the target tissue and m is the mass of the target tissue. The equivalent dose (H) can be calculated as:

$$H = D \times Q \tag{8}$$

where Q is the quality factor that considers the biological effectiveness of different types of radiation. The effective dose (E) takes into consideration the radiation weighting factors for different organs or tissues and is calculated as follows:

$$E = \sum_i H_{T_i} \times W_{T_i} \tag{9}$$

where H_{T_i} is the equivalent dose in tissue T_i and W_{T_i} is the tissue weighting factor. The total effective dose (E_{total}) can be obtained by summing the

effective doses from different organs or tissues. One should note that a simplified representation of dose calculations is given here, as mentioned above. Therefore, there may be additional factors and considerations specific to each case.

4.3 Delivery Methods for Radionuclides in Therapy

There are several delivery methods in medical treatment with radionuclides; we have an intravenous injection in brachytherapy, which means close therapy. All the methods of delivery can be given as follows;

1. Intravenous Injection (Brachytherapy)
2. Oral Administration (Imaging)
3. Inhalation
4. Implantation (brachytherapy)
5. Surface Application
6. Targeted Carriers

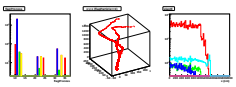
5 GEANT4/DNA Sample Medical Simulations

5.1 Design of the Simulation

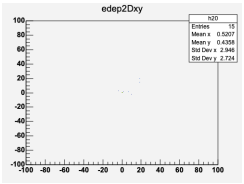
Designing a GEANT4 experiment is not an easy task; one should consider the angle of the particle gun to shoot, with which energy range it will shoot, the geometries of the absorber, material, detector, and the world's geometry. Also, the decay modes and energies should be given. These are the basic construction standards; the system does not finish with this. The coordinates of the gun and the detector are also important which particles we will shoot. There are many opportunities, and one may be required to design their material for better results.

5.2 Material Selection for tissue-like Absorbers

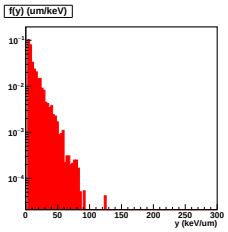
In GEANT4, there are several tissue-like materials as biological materials such as bone, muscle, and regular G4-TISSUE. Moreover, the geometry must be selected delicately to resemble the tissue one wants to deal with. To simulate a tumor, one can create another cylinder or object inside the tissue as a detector with a heavy-absorbing constant to get more realistic results. For this project, standard adjusted water with G4-Tissue is used to simulate.



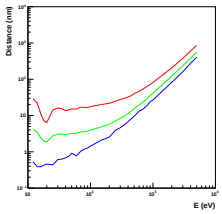
(a) tissue DNA excitation



(b) Brachytherapy Iodine one Round



(c) Microdosimetry sample



(d) Dosimetry range

Figure 2: GEANT4 and GEANT4-DNA images for microdosimetry, DNA excitation, brachytherapy, dosimetry range

6 Analysis of Results

From the results observed in the [11] & [12] experiments made by the researchers, radionuclides show promising results for the future medical applications, also with the observations conducted with 100 keV protons and 0 eV neutron in a) and b), we can see in c) that 50MeV helium ion and a 20 keV helium ion in human tissue used in a standard world. the geometry of the world is a 1mm side cube made with tissue due to being able to show intravenous injection simulation. The results show the kinetic energy loss along each step and step length, gives us some idea how did they conducted the experiments and how much energy is spent in which step in a G4-tissue.

7 Discussion and Conclusion

It was rather hard for me to comment on the GEANT4 monte carlo plots because the real DNA damage geometry did not work out; it gave errors in compiling. The plots given in the simulation are related to the range of the radionuclide, microdosimetry, and particle in tissue and how it moves with 1000 iterations with 100 keV, from the survey of books and literature review of the GEANT4 documentary and articles. Novel radionuclide treatments are promising, and doses after calibration now give promising values, indicating that the threats previously thought of as an obstacle to the treatment with nuclear materials are now seen as the primary way of treatment in cancer and imaging. To conclude, one can state that the future of imaging and treatment techniques will be treatments with nuclear medicine with nanometer radiation shields to protect healthy tissue.

8 References

References

[1] E. B. Podgorsak, "Production of Radionuclides," in *Radiation Physics for Medical Physicists*, 3rd ed., K. Becker, Springer-Nature International Publishing Switzerland, 2016, pp. 523–527 doi:10.1007/978-3-319-25382-4-12.

[2] E. B. Podgorsak, "Interactions of Charged Particles with Matter," in *Radiation Physics for Medical Physicists*, 3rd ed., K. Becker, Springer-Nature International Publishing Switzerland, 2016, pp. 229–232 doi:10.1007/978-3-319-25382-4-12.

[3] E. B. Podgorsak, "Interactions of Photons with Matter," in *Radiation Physics for Medical Physicists*, 3rd ed., K. Becker, Springer-Nature International Publishing Switzerland, 2016, pp. 277–280 doi:10.1007/978-3-319-25382-4-12.

[4] E. B. Podgorsak, "Interactions of Neutrons with Matter," in *Radiation Physics for Medical Physicists*, 3rd ed., K. Becker, Springer-Nature International Publishing Switzerland, 2016, pp. 429–431 doi:10.1007/978-3-319-25382-4-12.

[5] J. Lilley, "Nuclear Medicine," in *Nuclear Physics: Principles and Applications*, 1st ed., J. Wiley, Ed., Chichester, West Sussex: John Wiley and Sons, 2001, pp. 253–258.

[6] Na, "Brachytherapy advanced example," https://www.ge.infn.it/geant4/examples/hadrontherapy/ (accessed May 27, 2023).

[7] U. Themes, "Interaction of charged particles with matter," Radiology Key, https://radiologykey.com/interaction-of-charged-particles-with-matter/ (accessed May 27, 2023).

[8] "Radiation studies - CDC: Properties of Radioactive Isotopes," Centers for Disease Control and Prevention, https://www.cdc.gov/nceh/radiation/isotopes.html (accessed May 27, 2023).

[9] "Radioisotopes in Medicine," Radioisotopes in Medicine — Nuclear Medicine - World Nuclear Association, https://world-nuclear.org/information-library/non-power-nuclear-applications/radioisotopes-research/radioisotopes-in-medicine.aspx (accessed May 27, 2023).

[10] P. J. Blower, "A nuclear chocolate box: The periodic table of nuclear medicine," Dalton transactions (Cambridge, England: 2003), https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6205633/ (accessed May 27, 2023).

[11] C. H. Yeong, M. Cheng, and K. H. Ng, "Therapeutic radionuclides in nuclear medicine: Current and future prospects," Journal of Zhejiang University. Science. B, https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4201313/ (accessed May 27, 2023).

[12] S. Salih, A. Alkatheeri, W. Alomaim, and A. Elliyanti, "Radiopharmaceutical treatments for cancer therapy, radionuclides characteristics, applications, and challenges," Molecules (Basel, Switzerland), https://www.ncbi.nlm.nih.gov/pmc/articles/PMC9415873/ (accessed May 27, 2023).