Kingdom of Saudi Arabia

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Estimating Organ Doses from Iodine-131 in Food Using Geant4 Simulations

A graduation project submitted to the Department of Physics in partial fulfillment of the requirements for the degree of Bachelor of Science in Applied Physics

by

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الشكر والإهداء

بسم الله الرحمن الرحيم الحمدالله الذي ما نجحنا وما علونا ولا تفوقنا إلا برضاه الحمدالله الذي ما اجتزنا درباً ولا تخطينا جهداً إلا بفضله وإليه ينسب الفضل

(وَاخِرُ دَعوَاهم أَنِ الحَمدُالله رَبِ العَالَمِينَ)

لم تكن الرحلة قصيرة ولا الطريق محفوفًا بالتسهيلات، لكِنني فعلتها، فالحمد لله الذي يسَر البدايات وبلَغنا النهايات بفضله

أهدي ثواب هذا البحث إلى من لا ينفصل اسمي عن اسمه إلى الرجل الذي علمني ووجهني وبذل كل ما بوسعه ولم يبخل وهو مصدر قوتي وفخري لطالما عاهدته بهذا النجاح ها أنا اتممت وعدي واهديته إليك

" والدي الحبيب "

وإلى نبراس أيامي ووهج حياتي إلى التي ظلت دعواتها تضم اسمي دائمًا إلى من افنت عمرها في سبيل تعليمي وأن أحقق طموحي قدوتي ومعلمتي وصديقة أيامي

" والدتي الحنونة "

وإلى الشموع التي تنير طريقي وإلى مُلهمي نجاحي " أخوتي "

ولا أنسى رُفقاء الروح الذين شاركوني خطوات هذا الطريق إلى من هونوا تعب الطريق إلى رُفقاء السنين ممتنة لكم

وإلى د. مها مشرفة هذا البحث التي لم تتوانى في مد يد العون لي

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ABSTRACT

The study of estimating organ doses from iodine-131 in food is very important in public health, as it helps identify health risks associated with exposure to nuclear radiation in food. The research aims to evaluate exposure levels of iodine-131 in different organs to determine which organs are most affected by this radioactive element and to provide recommendations for reducing health risks. The results showed that the stomach is the most exposed organ to iodine-131, which requires careful monitoring of iodine-131 levels in food to reduce health risks.

الملخص العربي

تكتسب دراسة تقدير جرعات الأعضاء من اليود-131 في الغذاء أهمية كبيرة في مجال الصحة العامة، حيث تساهم في تحديد المخاطر الصحية المرتبطة بالتعرض للإشعاعات النووية في الغذاء. يهدف البحث إلى تقييم مستويات التعرض لليود-131 في أعضاء مختلفة، لتحديد الأعضاء الأكثر تأثراً بهذا العنصر الإشعاعي وتقديم توصيات للحد من المخاطر الصحية. وقد أظهرت النتائج أن المعدة هي الأكثر تعرضاً لليود-131، مما يستدعي ضرورة المراقبة الدقيقة لمستويات اليود-131 في الأغذية، لتقليل المخاطر الصحية.

CHAPTER 1: INTRODUCTION

1.1 Introduction

Radiation is broadly defined as the transfer or emission of energy in the form of waves or particles through space or a material medium. Electromagnetic radiation includes radio waves, microwaves, infrared, and visible radiation, which is an essential part of our daily lives. It is naturally present in sunlight, cosmic rays, ultraviolet rays, X-rays, and gamma rays [1].

Additionally, radiation is utilized in devices we use daily, such as smartphones and medical imaging equipment [1].

Radiation has numerous beneficial applications, including medical diagnostics, communication and energy production. However, excessive exposure to radiation can be harmful to human health. Therefore, it is essential to understand the effects of radiation on human health [1].

1.2 Types of radiation

Radiation is typically classified as either ionizing or non-ionizing based on the energy of the particles, which can also include photons. Ionizing radiation has energy exceeding 10 eV, which allows it to ionize atoms and molecules and break chemical bonds. This distinction is significant duo to the increased harm that ionizing radiation can cause to living organisms. Ionizing radiation includes radioactive emissions such as alpha, beta, or gamma radiation, which consist of helium nuclei, electron or positrons, and photons, respectively [1].

Alpha particle consist of the bare nucleus of a helium atom, which is a helium nucleus without electron. These particles are emitted during a nuclear reaction known as alpha decay, typically observed in heavy nuclides like those heavier than lead (bp). The energy spectrum of alpha particle is generally within the range of 4-6 MeV, which makes them highly energetic and capable of causing significant biological effects [2].

Beta particle are beams of high-energy electrons or positrons (the electrons antiparticle). They arise during nuclear reactions referred to as beta decay. Unlike alpha particle, beta particle exhibit a continuous energy spectrum, which is derived from the energy of neutrinos that are emitted simultaneously with the beta particles during beta decay [2].

Gamma rays are electromagnetic waves emitted during nuclear transitions from one energy level to another. These energy levels are analogous to the electronic energy levels of atoms or molecules. Gamma rays, like X-rays, belong to the family of electromagnetic waves [2].

1.3 Radiation interacts with matter

The mechanisms of energy transfer vary depending on the type of radiation. Alpha and beta are charged particles that interact with matter through electrostatic forces. In contrast, gamma and X-rays are electromagnetic waves that interact via processes such as the Compton effect, the photoelectric effect, and pair production [3].

Charged particles like alpha and beta behave differently. Alpha particles are relatively large, doubly charged, and travel at slower speeds (approximately $1/20^{th}$ the speed of light). Due to their high charge, they ionize almost every molecule they encounter but lose their energy quickly, resulting in a short range. Beta particles, being much lighter and singly charged, travel at speeds close to the speed of light. Their interactions are less intense than alpha particles, but they still produce ion pairs when passing through matter. Additionally, beta particles may lose energy through a process called "bremsstrahlung "or braking radiation [3].

Gamma and X-rays, as electromagnetic waves, interact with matter differently. The photoelectric effect is one such interaction, where low energy photons (such as X-rays) are absorbed by an inner electron, giving it enough to escape the atom. This leaves a positively charged atom and a vacancy in the inner shell, which is then filled by an electron from a higher shell, releasing energy in the form of another photon [3].

The photoelectric effect is an absorption process that typically occurs with low energy photons (less than 0.1 Mev), such as X-rays. During this process, the energy of the X-rays photon is absorbed by an inner electron, usually one from the k-shell. This absorption provides the electron with enough energy to escape from the atom. As a result, the atom becomes positively charged an ion and enters an excited state duo to the vacancy left in the inner shell. Thes vacancy is quickly filled by another electron transitioning from a higher shell, which leads to the release of a photon. The frequency of this photon is determined by the energy difference between the two shells involved [3]. The Photoelectric effect is shown in Figure 1.1.

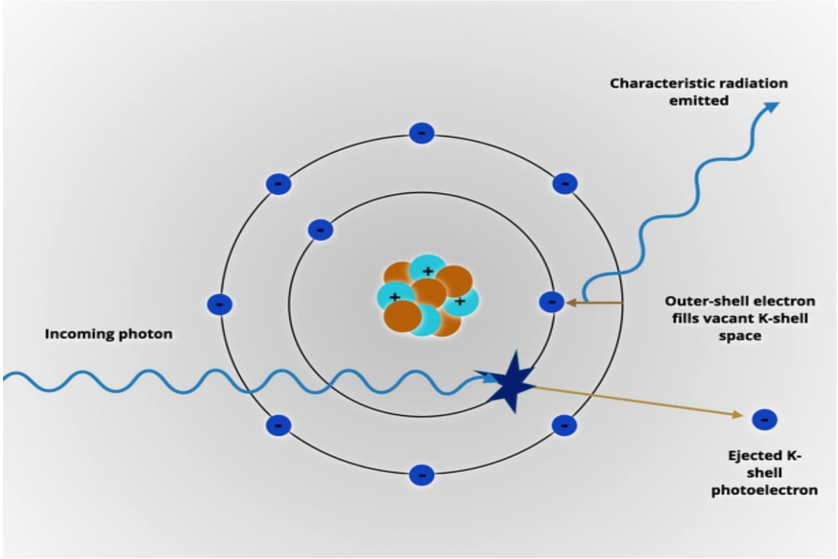
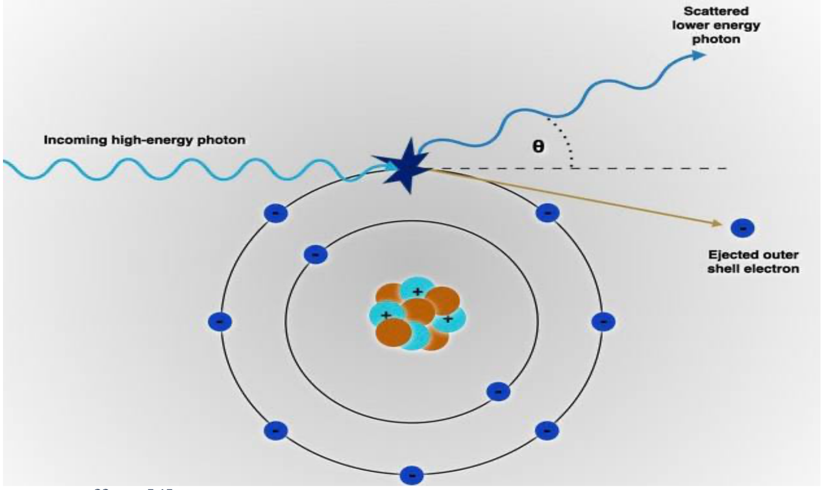


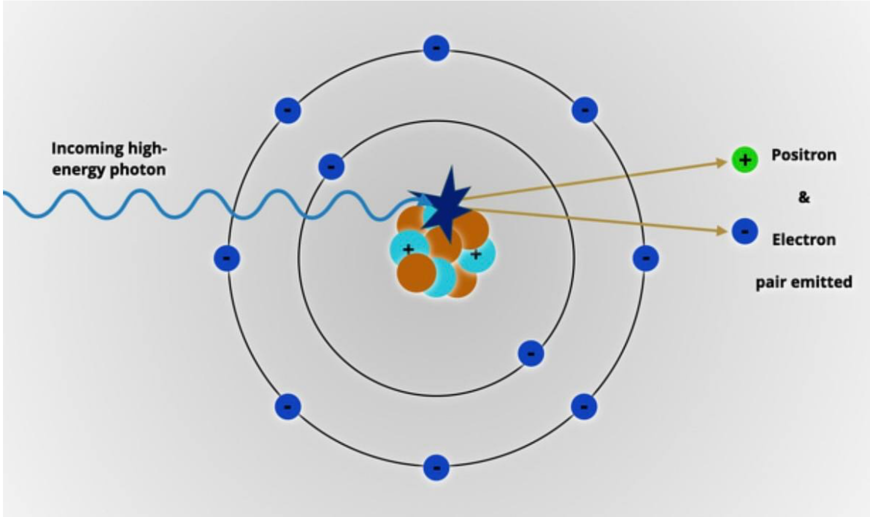
Figure 1.1 The photoelectric effect. [4]

The Compton effect is an inelastic collision process that usually occurs with high energy photon (greater than 0.1 Mev), such as gamma rays. In this process, a high energy photon collides with an electron in the valence band, ejecting the electron from the atom. The collision produces a lower energy photon with a different frequency than the original photon, which travels at an angle to the direction of the incident photon, as determined by the conservation of momentum. The energy of the ejected Compton electron can be calculated using the energies of the incoming and scattered photon. Similar to the photoelectric effect, the ejected electron travels through the surrounding medium, creating ion pairs in the same manner as a beta particle with equivalent energy [3]. The Compton effect is shown in Figure 1.2.



*Fi*gure 1.2 The Compton effect. [4]

Pair production is a photon matter interaction that is not typically observed in diagnostic procedures, as it only occurs with photons having energies exceeding 1.022 Mev. In this interaction, the photon engages with a nucleus in a way that allows its energy to be converted into matter. This process results in the creation of a pair of particles: an electron and a positron (a positively charged counterpart of the electron). Both of these particles have the same mass, with each having a rest mass energy of 0.511 Mev [5]. The Pair production is shown Figure 1.3.



*F*igure 1.3 The pair production. [4]

1.4 Iodine-131

Iodine-131 is an important radioisotope of iodine discovered by Glenn Seaborg and John Livingood in 1938, It has a radioactive decay half-life of about eight days [6].

Iodine-131 is produced through the fission of uranium or plutonium atoms during the operation of nuclear reactors or the detonation of nuclear weapons. It naturally exists in an ionic form with sodium, potassium, and magnesium and can be extracted from certain types of marine algae. Iodine-131 belongs to the halogen group in the periodic table [7].

It consists of a black metallic substance with the ability to sublimate, transitioning directly from a solid to a gaseous state without passing through the liquid phase. The emitted vapors are purple in color [7].

It reacts readily with alcohol, water, and other chemical substances, it easily mixes with soil and organic materials, allowing it to spread through air and water efficiently [7].

Iodine-131 is the most commonly used iodine radioisotope, and it decays by beta-emission.

It is notable for causing death in cells that it penetrates and other cells up to several millimeters away. For this reason, iodine-131 used for the treatment of thyrotoxicosis (hyperthyroidism) and some types of thyroid cancer that absorb iodine [8].

There are 37 isotopes of iodine with mass number ranging from 108 to 144. All these isotopes undergo radioactive decay, except for iodine-127, which is stable. This makes iodine a monoisotopic element [9].

An example is iodine-129, which has a half-life of 15.7 million years. This is considered a very short period on a cosmic scale. Iodine-129 is produced in extremely small quantities, making it insignificant in determining atomic weight. Naturally occurring iodine is monoisotopic, with iodine-127 being the only isotopes found in nature. The radioactive iodine on earth is primarily a byproduct of early undesirable secondary result [9].

Short-lived isotopes with a half-life less than 60 days include four radioactive iodine isotopes used in medical applications: iodine-123, iodine-124, iodine-125, and iodine-130. All of these isotopes are produced artificially and are essential for medical and therapeutic uses [9].

Iodine-131 undergoes beta decay rather than positron decay duo to its high neutron-to proton ratio (N/Z), making it neutron-rich and unstable. During beta decay, a neutron converts into a proton, reducing the N/Z ratio and increasing the stability of the isotope [10].

The beta decay equation for iodine-131 is:

$$^{131}_{53}I \rightarrow ^{131}_{54} Xe \ + ^{-1}_{0}\beta$$

This reaction increases the number of protons by 1 (from 53 to 54) while keeping the atomic mass unchanged [10]. The Iodine-131 decay into xenon is shown in Figure 1.4.

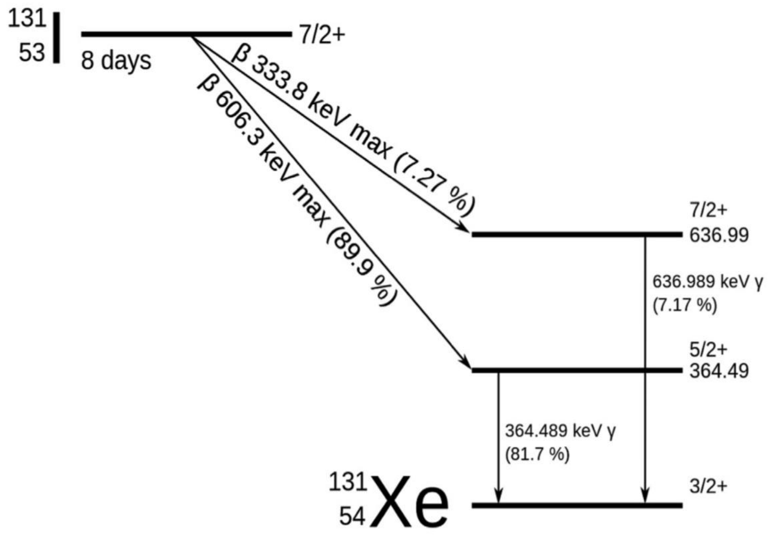


Fig. 1. Decay scheme for iodine.

Figure 1.4 Iodine into decay xenon. [11]

1.5 Iodine in food

Open-air crops and plants can become contaminated with radionuclides released into the atmosphere. As a result, radionuclides are often found in leafy vegetables, especially those with large leaves, during the early stages following a nuclear accident. Milk is also associated with early-stage contamination duo to the rapid transfer of radioactive iodine and cesium from contaminated animal feed to milk [9].

Over time, radioactivity can accumulate in food as radionuclides are transferred through soil into crops or animals, or into rivers, lakes, and seas where fish and other marine life can absorb them. Wild foods such as mushrooms, berries, and game meat may remain microorganisms can concentrate radionuclides, but duo to the significant dilution of radiation in contamination is usually confined to areas near the source [9].

Iodine-131 is one of the most dangerous isotopes released during nuclear accidents duo to its radioactive properties and biological behavior. Once in the body, it concentrates in the thyroid gland, where it emits beta radiation, causing cellular damage. With a half-life of 8 days, its radioactivity decreases by half over this period, but its harmful effects on the thyroid can be severe, which may cause thyroid cancer [12].

Potassium iodide prophylaxis can significantly reduce the radiation dose to the thyroid duo to exposure to iodine-131. In an experimental situation potassium iodide (kl) given prior to exposure reduced the accumulation of iodine-131 in the thyroid gland from an average of 20% to less than 2% [13].

The easiest way to reduce or eliminate internal contamination from iodine-131 following a release is to find an alternate source of food items produced outside the contamination zone [13].

1.6 Radiation measurements

Most scientists in the international community measure using the international system of units (SI). Different units of measurement are applied depending on the type of radiation being. For example, the unit “curie “is used to measure the amount of radiation emitted by a radioactive source and is named after the famous scientist Marie Curie. The unit "becquerel " measurese the radiation absorbed by a person, While the conventional unit “rad” or the SI unit “sievert “is used to quantify the biological risk from radiation exposure [14].

The ci or Bq measures the number of disintegrations of radioactive atoms over a certain period. For example, one curie equals 37 billion disintegrations per second. The curie is being replaced by the becquerel as the preferred unit. Additionally, Ci or Bq can indicate the amount of radioactive materials released into the environment [14].

1.7 Literature review

C. P. Straub *et al*, conducted a study to explore the characteristics of iodine-131 by examining its sources, forms, and mechanisms of entry into the food chain, with a focus on milk. It highlights the significance of this radioactive isotope in the environment and its health impacts, particularly on children.

Results indicate that iodine-131 primarily originates from nuclear testing, emissions from nuclear reactors, during the peak of nuclear tests between 1961 and 1962, iodine-131 levels in milk reached extremely high values, ranging from 40 to 1600 picocuries per liter, with some individual cases, such as in Alaska, recording up to 7000 picocuries per liter. These elevated levels resulted in radiation doses to children’s thyroid glands, peaking at approximately 14 rad in areas like Utah during nuclear testing periods. And certain medical applications, the findings reveal that milk is the main dietary source of iodine-131, where it concentrates in the thyroid gland, increasing health risks.

Additionally, the results show that exposure to iodine-131 can lead to negative health effects, particularly in children, necessitating the implementation of preventive policies and continuous monitoring [15].

CHAPTER 2: METHOD

This chapter explains how to calculate the number of nuclei with emphasis on salt as a major source.

2.1 Radioactive Calculation of iodine-131 in salt

Radioactivity is the process by which unstable atomic nuclei release energy in the form of radiation to achieve a more stable state. This occurs spontaneously when there is an imbalance in the number of protons and neutrons in the nucleus, Radioactivity is measured in units Bq [16].

To calculate the radioactivity, we use the following equation:

$$A = \lambda \times N \qquad (1)$$

where Activity (A) represents the number of radioactive decays occurring per unit of time. (λ) is the decay constant that describes the rate of radioactive decay and is measured in units of inverse time. The Number of atoms (N) represents the total number of radioactive atoms in a sample.

The decay constant (λ) can be calculated from the following equation:

$$\lambda = \frac{\ln(2)}{t_{1/2}} \qquad (2)$$

where $t_{1/2}$ is Half-life that represents the time required for half of the radioactive atoms in sample to decay (8 days).

The number of atom (N) can be calculated from the following equation:

$$N = \frac{m \times N_a}{M} \qquad (3)$$

where Mass (m) represents the mass of the material measured in grams. (N_a) is the Avogadro number of particles in one mole of a substance (6.022×10^{23}) is measured in unit mol^{-1}. The molar mass(M) is the mass of one mole the substance (131) measured in grams/mole.

2.2 Salt Daily intake

Salt was chosen for this study because it is a widely consumed staple in most diets and often added with iodine to prevent deficiencies. Its consistent and common presence in meals makes it an ideal medium to assess potential iodine-131 exposure and its subsequent dose impact on human organs.

The average American consumes approximately 3,500 milligrams of sodium daily, far exceeding the recommended limit of 2,300 milligrams set by the American Heart Association. For optimal health, adults should aim to limit their sodium intake to on more than 1,500 milligrams per day [17].

Reducing sodium consumption by just 1,000 milligrams a day can significantly improved blood pressure and promote better heart health. It's important to note that over 70% of the sodium consumed by American comes from processed, packaged, and restaurant foods, rather than from table salt [17].

The body needs only a small amount of sodium less than 500 mg per day to function properly. The amount in less than ¼ teaspoon [17].

The activity in salt was calculated to estimate the iodine-131 levels and assess its potential contribution to organ radiation doses.

Example:

Calculation the radioactivity of iodine-131 in salt, knowing that the mass of the salt is 0.5 mg. The mass of total iodine in the salt is 0.033 µg/100g [18].

Convert the mass of salt from milligrams to grams:

$$\frac{0.5}{1000} = 5 * 10^{-4} g$$

Convert total iodine mass to kilograms:

$$\frac{5*10^{-4}}{100} \times 0.033 = 1.65 * 10^{-7} \mu g$$

$$(1.65 * 10^{-7})(10^{-9}) = 1.65 * 10^{-16} kg$$

Since the proportion of radioactive iodine in the total iodine is very small (One percent), we divide the mass by 100. Which will become:

$$1.65 * 10^{-18} kg$$

Using equation 2 the decay constant was calculated:

$$\lambda = \frac{\ln(2)}{8.02*24*3600} =$$

$$\lambda = 1 * 10^{-6}\ seconds^{1}$$

Using equation 3 the number of nuclei was calculated:

$$N = \frac{(1.65*10^{-18})*(6.022*10^{23})}{131}$$

$$\text{N} = 7584.9\ nuclei$$

Using equation 1 the activity was calculated:

$$A = (1 * 10^{-6})(7584.9)$$

$$\text{A} = 7.5849 * 10^{-3}\ \text{Bq}$$

2.3 Geant4

Geant4 is a toolkit designed for simulating the transport of radiation through matter. With its flexible core and a variety of physics modeling options, it caters to a wide range of applications [19].

The toolkit allows users to define the geometry and materials of a setup or detector, navigate within it, simulate physical interactions using different physics engines and cross-section models, and visualize and store results [19].

It provides physics models that describe electromagnetic and hadronic interaction, as well as processes like decays and interaction of optical photons. Several models with varying levels of precision and performance are available to suit different processes. The toolkit includes pre-configured physics setups known as physics lists, which users can either adopt or customize based on their specific requirements and applications areas. Its clear structure and readable code enable users to explore the origins of physics results effectively [19].

Applications areas include detector simulation and background studies in high-energy physics experiments, accelerator setup simulations, medical imaging, and radiation therapy studies, and investigating the effects of solar radiation on spacecraft instruments [19].

2.4 Phantom human model

The phantom in GEANT4 is a simulation model that represents the human body or parts of it, used to study the effects of radiation on tissues and organs. It helps analyze radiation dose distribution, understand radiation interactions with the body, and improve imaging and radiotherapy techniques. GEANT4 provides a safe and accurate environment for simulations, reducing the need for direct experiments on humans or animals, and is widely used in developing medical devices and protocols [20]. The Phantom human model is shown in Figure 2.5.

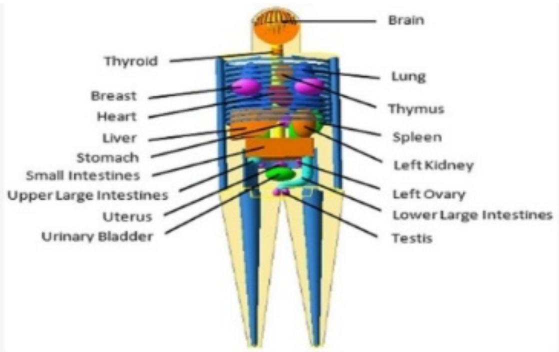


Figure 2.2 The phantom human model. [21]

2.5 Permissible radiation doses for external exposure

Outlines the permissible equivalent radiation doses limits external exposure that specific organs or tissues can be exposed to annually. It distinguishes between nuclear energy workers and the general public [22]. Table 2.1 shows equivalent dose for external exposure.

Table 2.1 permissible external exposure limit.

Organ or Tissue	person	Equivalent Dose (mSv/y)
Lens of an eye	Nuclear energy worker	50
	Any other person	15
Skin	Nuclear energy worker	500
	Any other person	50
Hands and Feet	Nuclear energy worker	500
	Any other person	50

CHAPTER 3: RESULT

This chapter presents the results of the study obtained using GEANT4 simulations to estimate organ doses from iodine-131 exposure through food consumption, with a specific focus on salt as the primary source of radioactivity. The number of nuclei of iodine-131 in salt was used as a key input parameter in the simulations, enabling accurate analysis of dose distribution and assessment of the radiological impact on various organs.

3.1 Phantom after exposure to radioactivity

The images represent particle tracks (in green) resulting from the interaction of radiation with the human phantom model. The dense clustering of particle tracks reflects regions of strong interaction between the radiation and the tissues and organs. These visualizations illustrate how radiation affects various part of the body, helping to identify the absorbed doses in specific areas. The Phantom human model after exposure to iodine-131 radiation is shown in Figure 3.6.

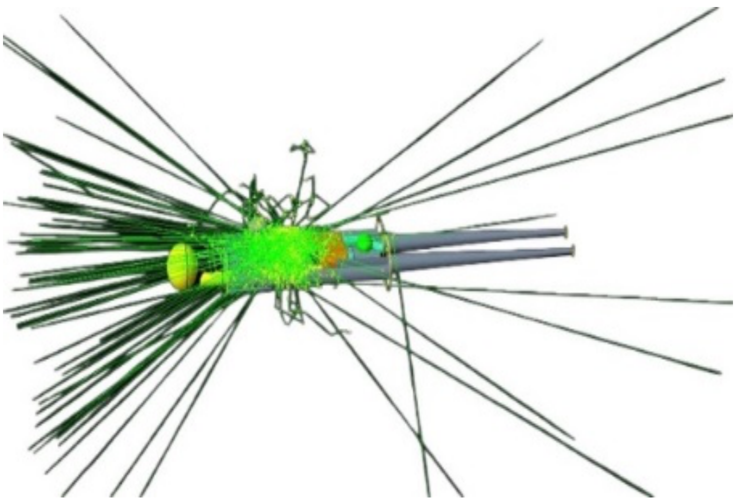


Figure 3.6 The phantom after exposure to radioactivity.

3.2 Absorbed doses to organs

When ionizing radiation pass through matter they pass on some or all of their energy to the material by ionizing and exciting the atoms of the material, the damage done by this depends both on the energy deposited and the amount of material involved. The radiation damage increases as the amount of energy deposited increases and decreases if it is spread throughout a greater amount of material. I got the energy values using Geant4, where the values are given in Megaelectronvolts (MeV). I converted them to Joules (J), and the mass values are given as constants in grams (g). I converted these values to kilograms (kg). The radiation absorbed dose is therefore defined as the energy absorbed divided by the mass of material involved. Table 3.2 shows absorbed dose calculation

Table 3.2 Absorbed dose calculation.

Organ	Mass (kg)	Energy (J)	Absorbed dose (Gy)
Head	3.5	$1.633 * 10^{-12}$	$4.667 * 10^{-13}$
Trunk	35	$1.052 * 10^{-10}$	$3.006 * 10^{-12}$
Total body	58	$5.585 * 10^{-10}$	$9.629 * 10^{-12}$
Stomach	0.25	$4.339 * 10^{-10}$	$1.736 * 10^{-9}$
Pancreas	0.12	$1.778 * 10^{-12}$	$1.482 * 10^{-11}$
Brain	1.3	$3.452 * 10^{-13}$	$2.655 * 10^{-13}$
Thymus	0.02	$1.025 * 10^{-14}$	$5.125 * 10^{-13}$
Left Kidney	0.1375	$8.793 * 10^{-13}$	$6.395 * 10^{-12}$
Right Kidney	0.1375	$2.633 * 10^{-13}$	$1.915 * 10^{-12}$
Spleen	0.15	$2.902 * 10^{-12}$	$1.935 * 10^{-11}$
Small Intestine	0.64	$1.201 * 10^{-12}$	$1.877 * 10^{-12}$

Figure 3.7 shows a graph of the high absorbed doses to organs after exposure to radiation. The most exposed organs are the stomach. The stomach is the most exposed organ to radiation duo to its central location in the digestive system. The dose absorbed by the stomach is greater than the dose absorbed by the total body, because the mass of the total body is much greater than the mass of the stomach. When we divide it, the absorbed dose becomes smaller.

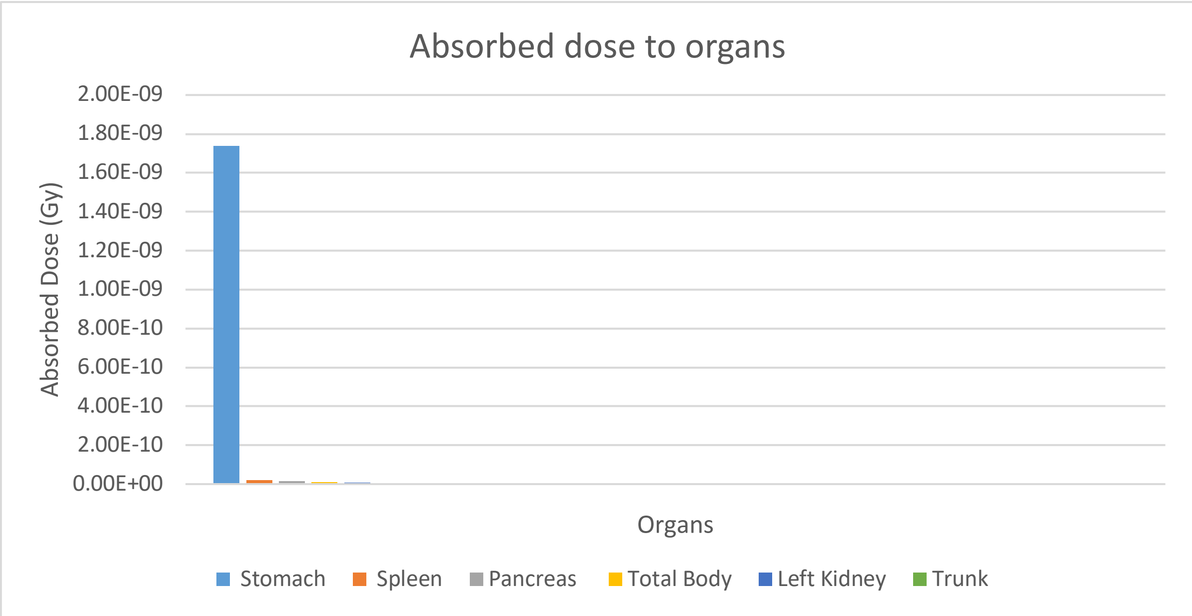


Figure 3.3 Absorbed dose to organs.

Figure 3.8 shows a graph of the low absorbed doses to organs after exposure to radiation. The organ most in exposed to low doses is the right kidney, and the organ least exposed is the brain.

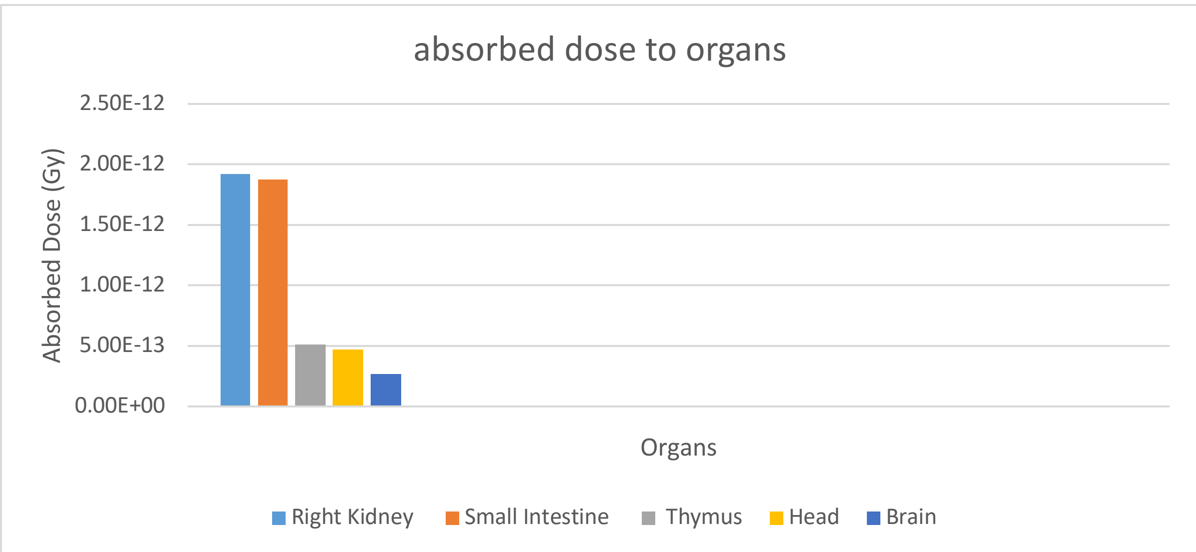


Figure 3.8 Absorbed dose to organs except stomach

We will convert the absorbed dose for the total body from Gray (*Gy*) to Sievert (*Sv*)

We will take the value of the absorbed dose for the total body from table 3.2, which is:

$9.63 * 10^{-12} Gy$

Convert absorbed dose (*Gy*) to equivalent dose (*Sv*):

Using the equation:

$$\text{Equivalent dose } (Sv) = \text{absorbed dose } (Gy) * \text{radiation weight factor } (W_R)$$

Table 3.3 Radiation weighting factor for each type of radiation. [23]

Tyap of radiation	Radiation Weighting Factor (W_R)
Alpha particles	20
Gamma rays, X-rays, Beta particles	1
Neutron beams	2.5-21

$$\text{Equivalent Dose } (Sv) = 9.63 * 10^{-12}\ Gy * 1 = 9.63 * 10^{-12} Sv$$

This value expresses the dose absorbed by the human body when consuming 0.5 mg of salt daily. To find the equivalent dose by year:

$$(9.63 * 10^{-12})(365) = 3.51 * 10^{-9}\ Sv/y$$

Convert the equivalent dose from (*Sv*) to (*mSv*):

$$\frac{3.51*10^{-9}}{1*10^{-3}} = 3.51 * 10^{-6} mSv/y$$

To compare the value with the permissible external exposure limit, Table 2.1:

$$\frac{3.51 * 10^{-6}}{50} \times 100 = 7.02 * 10^{-6}\%$$

The percentage of radiation emitted by the total human body after consuming 0.5 mg of salt daily is considered not dangerous and harmless to health.

Conclusion

Studying the estimation of organ doses from iodine-131 in food is crucial for understanding its potential health impacts and guiding effective strategies for risk reduction. This research is particularly significant in addressing public health concerns and minimizing exposure to harmful radiation. The results showed that the stomach is the most exposed organ to iodine-131 radiation. However, the exposure level is minimal harmless. In regard to recommendations for salt reduction, it is advised to primarily focus on consuming fresh products, as they are a healthier option. It is also important to choose low-sodium products, which helps minimize salt intake in the diet. When cooking, it is preferable to use little or no added sodium or salt, thereby enhancing health benefits. Additionally, herbs and spices can be used to improve the flavor of food instead of relying on salt. Iodized salt can also be replaced with rock salt or natural salt. Reducing the consumption of processed foods is also recommended, as these often contain high levels of sodium. Furthermore, it is important to raise awareness about reading food labels to identify hidden sodium and encourage gradual reduction in salt intake to adapt to less salty tastes over time.

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