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Investigation of the effects of radionuclides used in nuclear medicine on organ dose and effective dose

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ABSTRACT

Aims: The aim of this study is to investigate the effects of ^{68}Ga, ^{18}F, ^{89}Sr, ^{13}N, ^{133}Xe and ^{131}I radionuclide sources on organ doses and effective doses at different distances.

Methods: In this study, radionuclides commonly used in nuclear medicine applications were defined in the VMC dose calculation software to determine organ doses and effective dose values at varying distances. Additionally, the dose rates of each radionuclide were obtained using the Rad pro calculator online program.

Results: For different radionuclides at a 10 mCi dose, average dose rate measurements were conducted at varying distances. Specifically, ^{13}N and ^{89}Sr delivered the highest doses to certain organs, whereas ^{133}Xe ve ^{131}I resulted in lower doses. The effective doses at 100 cm for ^{68}Ga, ^{18}F, ^{89}Sr, 13N, ^{133}Xe and ^{131}I sources were determined to be 2.72 µSv, 2.94 µSv, 2.50 µSv, 2.84 µSv, 0.91 µSv, and 1.16 µSv, respectively. The effective doses at 150 cm for ^{68}Ga, ^{18}F, ^{89}Sr, ^{13}N, ^{133}Xe and ^{131}I sources were determined to be 1.56 µSv, 1.49 µSv, 1.30 µSv, 1.46 µSv, 0.14 µSv, and 0.58 µSv, respectively. As the distance increased, radiation exposure levels decreased.

Conclusion: In this study, radiation exposure decreased significantly with distance from the source, demonstrating the importance of maintaining distance and applying ALARA principles in clinical settings. Furthermore, avoiding close proximity to the radiation source and utilizing appropriate shielding methods are crucial in minimizing radiation exposure.

Keywords: Dose rate, organ dose, VMC program, ICRP female phantom

INTRODUCTION

Nuclear medicine is a rapidly evolving medical field that utilizes radioactive substances for the diagnosis, staging, and treatment planning of various diseases. Radiopharmaceuticals used in this field accumulate in specific organs or tissues, enabling imaging or therapeutic applications. Significant advancements in imaging technology, along with variations in procedures and radionuclide types used in nuclear medicine, have led to notable changes in absorbed doses over time.[1,2]

Most of these changes stem from the widespread adoption of molecular hybrid imaging procedures, such as single-photon emission computed tomography/computed tomography (SPECT/CT), positron emission tomography/computed tomography (PET/CT), and positron emission tomography/magnetic resonance imaging (PET/MRI), which provide both functional and anatomical information. These hybrid systems demonstrate high sensitivity and accuracy. Moreover, they reduce interobserver variability by enabling more precise localization and characterization of scintigraphy findings.[3,4]

New techniques and radioactive compounds are continuously being developed for the diagnosis of clinical diseases. Patients are exposed to ionizing radiation due to radioisotope injection.[5] Therefore, radiation safety is of paramount importance in nuclear medicine applications. The radiation doses received by patients and organs vary depending on the type and activity of the radionuclide used, the route of administration, the patient's physiological characteristics, and the imaging or treatment protocol. During nuclear medicine procedures, patients may receive doses ranging from 740 to 1110 MBq for bone scans, 111 to 740 MBq for renal scans, and 74 to 370 MBq for thyroid scans.[6,7]

Although nuclear medicine procedures provide undeniable diagnostic and therapeutic benefits to patients, the significant increase in radiation exposure among nuclear medicine patients and personnel has raised concerns about potential adverse health effects.[8,9] Nuclear medicine professionals are exposed to varying levels of radiation depending on the radionuclide used during imaging and therapeutic procedures. In SPECT and SPECT/CT scans, radiopharmaceuticals labeled with Technetium-99m (^{99m}Tc) are commonly used. However, with the introduction of PET/CT in nuclear medicine, a substantial increase in radiation doses among nuclear medicine personnel has been observed.[10-13]

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Among the various imaging procedures used in nuclear medicine, Fluorodeoxyglucose (^{18}F-FDG) is widely employed in oncological, neurological, and cardiological imaging. Gallium-68 prostate-specific membrane antigen (^{68}Ga-PSMA) is commonly utilized for prostate cancer imaging, while strontium-89 (^{89}Sr) is frequently administered for the relief of bone pain associated with certain cancer types. Nitrogen-13 (^{13}N) is used in myocardial perfusion imaging, whereas Iodine-131 (^{131}I) is applied in the treatment and imaging of thyroid cancer and hyperthyroidism. Additionally, Xenon-133 (^{133}Xe) is used for lung perfusion and ventilation scintigraphy.[14]

In nuclear medicine applications, the as low as reasonably achievable (ALARA) principle is implemented to minimize radiation doses to the lowest possible levels. This principle is applied by considering key factors such as time, distance, and shielding measures to ensure the safety of both patients and healthcare professionals.[15-18] According to the annual dose limits established by the International Commission on Radiological Protection (ICRP), For the lens of the eye, the annual dose limit is set so as not to exceed 20 mSv averaged over five consecutive years, with no single year exceeding 50 mSv. For the skin, the annual equivalent dose limit is 500 mSv, applied to any 1 cm^2 area of skin. Similarly, for extremities such as the hands, feet, forearms, and ankles, the annual dose limit is also 500 mSv. For other organs, there are no explicit individual limits; instead, exposure is regulated indirectly through the overall effective dose limit. With regard to effective dose, the annual limit for adult radiation workers is 20 mSv, averaged over a period of five years, with a maximum of 50 mSv in any single year.[15-17] While individual radionuclides like ^{68}Ga, ^{18}F, ^{89}Sr, ^{13}N, ^{133}Xe, and ^{131}I are widely used and studied, comparative evaluations of their organ-specific and whole-body dose distributions, particularly at varying distances, are underrepresented in the literature. However, few studies have comprehensively compared multiple commonly used radionuclides side by side in terms of how distance affects both organ level and effective dose. To our knowledge, this is the first study to systematically model and compare dose distributions for this range of radionuclides using both organ-specific and whole-body metrics over varying distances. The results provide crucial guidance for enhancing safety protocols in nuclear medicine environments.

The purpose of this study is to analyze and compare the radiation doses delivered by selected radionuclides (^{68}Ga, ^{18}F, ^{89}Sr, ^{13}N, ^{133}Xe, and ^{131}I) to various organs and the whole body at different distances using simulation software. The study aims to assess how radiation exposure varies with radionuclide type and distance, providing critical information for improving radiation protection strategies for both patients and healthcare professionals. The findings also contribute to a better understanding of dose optimization in clinical nuclear medicine practices. Additionally, ^{68}Ga, ^{18}F, ^{89}Sr, ^{13}N, ^{133}Xe, and ^{131}I radionuclide sources on organ doses and effective doses at varying distances using the visual Monte Carlo (VMC) dose calculation program. Furthermore, the dose rates of these radionuclide sources at different distances were obtained using the Rad Pro Calculator online program.

METHODS

This study did not require ethical approval as it did not involve any human subjects or animal experiments. All procedures were carried out in accordance with the ethical rules and the principles.

The properties of the radionuclides used in the study are shown in Table 1.

Table 1. Properties of radionuclids used in nuclear medicine[8,20,21]

Radionuclide	Half-life	Radiation/MeV	Production	Application
^{68}Ga	67.71 m	β^+/1.89	Generator	PET imaging
^{18}F	109.77 m	β^+/0.63	Accelerator	PET imaging
^{89}Sr	50.56 d	β^-/1.49	Reactor	β^- therapy
^{13}N	9.97 m	β^+/1.20	Accelerator	PET imaging
^{133}Xe	5.24 d	γ, β^-/0.37	Reactor	SPECT imaging
^{131}I	8.03 d	γ, β^-/0.36	Reactor	β therapy, SPECT imaging

The visual Monte Carlo (VMC) is a Monte Carlo simulation software used for radiation dose calculations. It is widely utilized in medical physics and radiation safety. VMC simulates the interactions of radiation particles, such as photons and electrons, within matter, allowing for the computation of dose distributions in various applications.[2] Equivalent and effective dose can be calculated with equations 1 and 2 below.[21,22]

$$H_T = Q \times D_T H_T = Q \times D_T \quad (1)$$

The dose equivalent is expressed in sieverts (or rems) to differentiate it from the absorbed dose, which is measured in grays (or rads). In this context, Q represents the quality factor of the type of radiation, determined by its linear energy transfer (LET) in water such as a value of approximately 1 for X-Rays. DT refers to the absorbed dose at a specific point within a tissue.

$$H_E = \sum w_T H_T H_E = \sum w_T H_T \quad (2)$$

Here, wT denotes the weighting factor assigned to a specific tissue or organ (T), while HT represents the dose equivalent received by that tissue. The effective dose, HE, is calculated by summing the products of each tissue's weighting factor and its corresponding dose equivalent across all tissues.

In this study, radionuclides commonly used in nuclear medicine were defined in the VMC dose calculation software to determine organ doses and effective dose values. Although the dose range of these radiopharmaceuticals in clinical applications varies between 4 mCi and 20 mCi, a standard 10 mCi activity level was used in the simulations to ensure accuracy in comparative analyses. The adult female reference phantom defined by the International Commission on Radiological Protection (ICRP) was selected as the phantom model. In the VMC program, ^{68}Ga, ^{18}F, ^{89}Sr, ^{13}N, ^{133}Xe and ^{131}I sources with 10 mCi activity were simulated at distances of 25 cm, 50 cm, 100 cm, and 150 cm from the ICRP adult female phantom, and organ and effective dose calculations were

performed. Additionally, the Rad Pro Calculator software was used to compute dose rates by incorporating the half-lives of these radiopharmaceuticals.

The Rad Pro calculator is a software program that performs various nuclear calculations and is particularly useful for health physicists, physicians, technicians, and other radiation physics professionals. Furthermore, it enables radioactivity unit conversions and calculates gamma emitter dose rates and activities.

RESULTS

The radiation doses received by organs at different distances are detailed in Tables 2-5. These tables present organ doses and effective doses (μSv) for various radioisotopes and distances. The data provided are crucial for radiation safety and risk assessment. The results indicate that radiation exposure to organs varies significantly depending on the type of radionuclide and the distance from the source. Figure illustrates an image obtained from the VMC program used in this study.

Table 2. Radiation dose to which organs are exposed at a distance of 25 cm

Organ doses D (T)	^{68}Ga	^{18}F	^{89}Sr	^{13}N	^{133}X	^{131}I
Red bone marrow	8.82	9.16	12.23	9.85	0.33	3.30
Colon	16.16	16.96	22.19	26.17	0.90	6.86
Lung	9.42	9.57	10.36	21.35	0.79	3.76
Stomach	11.77	13.40	20.53	29.05	0.79	4.86
Breast	18.06	18.86	20.84	12.23	1.98	8.10
Remainder	10.75	11.36	13.86	19.66	0.59	4.27
Ovaries	17.51	18.18	23.15	16.49	1.48	6.89
Bladder	16.79	18.35	24.17	16.66	0.50	7.10
Oesophagus	7.98	7.28	11.99	16.04	0.36	2.24
Liver	15.84	16.10	16.17	25.32	1.25	6.17
Thyroid	7.58	8.25	11.13	32.64	1.19	3.50
Bone surface	7.59	7.88	9.06	11.06	0.28	2.93
Brain	4.14	4.17	3.89	6.76	0.21	1.56
Salivary gland	7.43	7.87	10.29	11.40	0.78	2.88
Skin	9.46	10.13	11.30	12.89	0.68	3.86
Adrenals	7.50	9.21	12.66	20.40	0.25	3.55
Extrathor airways	7.81	7.16	8.03	16.04	0.89	3.22
Gall bladder	16.56	19.54	18.49	29.05	1.25	7.67
Heart	8.29	8.92	13.26	31.37	0.75	3.35
Kidneys	9.56	10.42	11.62	13.29	0.36	3.90
Lymphatic nodes	12.89	12.38	15.71	31.32	0.70	4.44
Muscle	9.61	10.11	11.53	11.07	0.48	3.78
Oral mucosa	8.45	10.93	8.52	6.76	0.41	2.88
Pancreas	12.50	13.63	17.49	21.57	0.65	5.32
Small intestine	16.81	17.34	24.30	24.03	0.81	6.98
Spleen	5.02	4.99	8.61	14.50	0.14	1.70
Thymus	11.03	7.86	13.12	0.00	0.57	3.41
Eye lens	9.14	9.29	7.72	24.45	0.01	0.36
Effective dose (μSv)	12.61	13.27	16.73	19.91	3.21	5.16

Table 3. Radiation dose to which organs are exposed at a distance of 50 cm

Organ doses D (T)	^{68}Ga	^{18}F	^{89}Sr	^{13}N	^{133}X	^{131}I
Red bone marrow	5.09	5.23	5.74	5.57	0.25	1.82
Colon	8.41	8.64	8.23	10.68	1.16	3.37
Lung	6.20	6.27	5.89	9.16	0.64	2.24
Stomach	6.65	7.76	7.80	11.32	0.99	2.41
Breast	9.60	10.97	12.29	4.22	1.21	4.81
Remainder	6.27	6.39	6.19	8.43	0.69	2.46
Ovaries	9.11	9.76	10.58	8.47	0.87	4.47
Bladder	7.59	9.04	9.64	9.55	0.92	3.01
Oesophagus	5.12	6.48	5.36	7.20	0.57	1.40
Liver	7.52	7.91	7.31	9.61	0.78	3.15
Thyroid	6.26	6.81	8.29	9.69	0.36	2.76
Bone surface	4.71	4.87	4.89	5.73	1.05	1.81
Brain	2.93	3.07	3.00	4.47	0.23	1.02
Salivary gland	5.17	5.75	4.84	5.83	0.40	2.37
Skin	5.54	5.81	5.85	6.54	0.96	2.20
Adrenals	4.72	6.91	4.28	5.63	0.22	1.72
Extrathor airways	5.65	5.29	5.89	7.20	0.57	2.83
Gall bladder	6.49	6.56	5.08	11.32	0.99	3.55
Heart	5.77	5.91	7.32	13.46	0.94	2.61
Kidneys	4.60	4.88	5.16	5.96	0.30	1.76
Lymphatic nodes	6.98	6.84	7.11	13.46	0.94	3.07
Muscle	5.49	5.74	5.94	5.89	0.57	2.22
Oral mucosa	4.90	6.41	5.43	4.47	0.23	1.44
Pancreas	7.08	6.89	8.28	9.59	0.75	3.23
Small intestine	8.16	8.61	9.18	9.51	0.91	3.44
Spleen	3.02	3.44	4.02	6.23	0.31	1.17
Thymus	9.16	7.42	4.60	0.00	0.00	2.44
Eye lens	0.00	3.39	0.00	28.01	4.76	0.00
Effective dose (μSv)	7.04	7.62	7.79	8.54	1.77	2.90

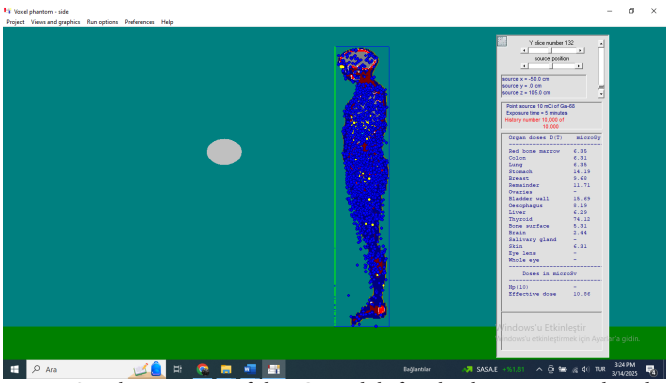

Figure. Simulation image of the ICRP adult female phantom created in the VMC program

Generally, the radiation dose received by organs significantly decreases as the distance increases. For instance, for red bone marrow, ^{89}Sr at a distance of 25 cm results in a dose of 12.23 μSv, while at distances of 50, 100, and 150 cm, this dose decreases to 5.74 μSv, 2.26 μSv, and 1.01 μSv, respectively. Similarly, for the stomach, ^{13}N delivers a dose of 29.05 μSv

Table 4. Radiation dose to which organs are exposed at a distance of 100 cm

Organ doses D (T)	^{68}Ga	^{18}F	^{89}Sr	^{13}N	^{133}X	^{131}I
Red bone marrow	2.03	2.00	2.26	2.20	0.10	0.76
Colon	3.10	3.10	3.03	3.28	0.35	1.15
Lung	2.59	2.79	2.47	3.00	0.23	1.15
Stomach	2.72	2.50	3.14	3.22	0.27	0.94
Breast	2.83	4.24	1.50	2.14	0.65	1.84
Remainder	2.36	2.64	2.32	2.96	0.24	0.93
Ovaries	3.16	3.50	4.27	3.88	0.68	1.52
Bladder	3.53	3.94	3.46	3.94	0.36	1.51
Oesophagus	1.79	2.85	2.04	2.75	0.19	1.20
Liver	2.69	2.81	2.44	3.13	0.27	1.01
Thyroid	3.56	2.85	2.08	0.60	0.70	1.08
Bone surface	2.13	2.18	2.16	2.30	0.43	0.85
Brain	1.51	1.67	1.45	2.03	0.10	0.57
Salivary gland	1.91	2.64	2.01	2.39	0.15	1.25
Skin	2.39	2.48	2.39	2.60	0.37	0.91
Adrenals	0.92	2.51	0.66	0.99	0.00	1.11
Extrathor airways	2.17	2.13	1.72	2.75	0.19	1.02
Gall bladder	2.82	2.12	1.58	3.22	0.27	0.91
Heart	2.31	3.00	2.82	4.41	0.34	1.12
Kidneys	2.08	1.92	1.79	1.91	0.14	1.23
Lymphatic nodes	2.51	2.55	2.84	4.41	0.34	0.94
Muscle	2.32	2.46	2.32	2.43	0.25	0.90
Oral mucosa	2.52	3.68	1.78	2.03	0.10	0.88
Pancreas	2.65	2.81	3.23	4.22	0.15	0.87
Small intestine	3.10	3.02	2.58	3.35	0.31	1.18
Spleen	0.98	1.38	1.65	1.95	0.12	0.26
Thymus	3.32	3.33	4.80	0.00	0.00	1.08
Eye lens	0.00	3.06	0.00	12.88	1.97	0.65
Effective dose (μSv)	2.72	2.94	2.50	2.84	0.91	1.16

Table 5. Radiation dose to which organs are exposed at a distance of 150 cm

Organ doses D (T)	^{68}Ga	^{18}F	^{89}Sr	^{13}N	^{133}X	^{131}I
Red bone marrow	1.25	1.33	1.01	1.31	0.06	0.49
Colon	1.65	1.61	1.53	1.80	0.18	0.65
Lung	1.31	1.56	1.22	1.48	0.12	0.55
Stomach	1.56	1.74	1.40	1.64	0.15	0.67
Breast	1.72	1.30	0.75	0.82	0.23	0.51
Remainder	1.27	1.41	1.26	1.43	0.13	0.57
Ovaries	2.36	1.87	2.35	1.54	0.29	0.49
Bladder	1.47	1.52	1.74	1.62	0.20	0.69
Oesophagus	1.56	1.17	1.43	1.28	0.14	0.69
Liver	1.56	1.44	1.04	1.45	0.13	0.57
Thyroid	2.39	1.17	0.29	1.63	0.18	0.72
Bone surface	1.29	1.35	0.97	1.22	0.24	0.52
Brain	0.86	1.05	0.87	1.00	0.06	0.36
Salivary gland	0.97	1.19	1.15	1.14	0.10	0.45
Skin	1.38	1.49	1.16	1.41	0.20	0.55
Adrenals	0.91	1.39	0.00	0.39	0.11	0.32
Extrathor airways	1.03	1.30	1.43	1.28	0.14	0.38
Gall bladder	1.08	1.41	1.40	1.64	0.15	0.55
Heart	1.34	1.40	1.80	2.17	0.17	0.56
Kidneys	1.02	0.95	0.83	0.98	0.05	0.34
Lymphatic nodes	1.79	1.67	1.80	2.17	0.17	0.73
Muscle	1.34	1.41	1.09	1.27	0.13	0.54
Oral mucosa	1.03	1.45	0.87	1.00	0.06	0.47
Pancreas	1.44	1.60	1.22	2.05	0.10	0.55
Small intestine	1.57	1.73	1.24	1.50	0.16	0.73
Spleen	0.91	1.19	1.07	1.12	0.06	0.45
Thymus	1.44	0.98	0.00	0.00	0.00	1.00
Eye lens	0.00	0.00	3.36	2.90	1.29	0.00
Effective dose (μSv)	1.56	1.49	1.30	1.46	0.14	0.58

at 25 cm, whereas at 50 cm, 100 cm, and 150 cm, this value decreases to 11.32 μSv, 3.22 μSv, and 1.64 μSv, respectively. In Table 2, the doses received by the ovaries when exposed to ^{68}Ga, ^{18}F, ^{89}Sr, ^{13}N, ^{133}Xe and ^{131}I sources at 25 cm are obtained as 17.51 μSv, 18.18 μSv, 23.15 μSv, 16.49 μSv, 1.48 μSv, and 6.89 μSv, respectively. Additionally, in Table 1, the doses received by the breast when exposed to ^{68}Ga, ^{18}F, ^{89}Sr, ^{13}N, ^{133}Xe and ^{131}I sources at 25 cm are found to be 18.06 μSv, 18.86 μSv, 20.84 μSv, 12.23 μSv, 1.98 μSv, and 8.10 μSv, respectively. The highest dose exposure in the ovaries and breast organs was obtained with the ^{89}Sr radionuclide. The effective doses at a distance of 25 cm for ^{68}Ga, ^{18}F, ^{89}Sr, ^{13}N, ^{133}Xe and ^{131}I sources were found to be 12.61 μSv, 13.27 μSv, 16.73 μSv, 19.91 μSv, 3.21 μSv, and 5.16 μSv, respectively.

Table 3 presents the radiation doses received by the ovaries and the mammary gland at a distance of 50 cm from various radioactive sources. The ovaries, when exposed to ^{68}Ga, ^{18}F, ^{89}Sr, ^{13}N, ^{133}Xe and ^{131}I sources, received doses of 9.11 μSv, 9.76 μSv, 10.58 μSv, 8.47 μSv, 0.87 μSv, and 4.47 μSv, respectively. At the same distance, the mammary gland received doses of 9.60 μSv, 10.97 μSv, 12.29 μSv, 4.22 μSv, 1.21 μSv, and 4.81 μSv from the same respective sources. The effective doses at 50 cm for ^{68}Ga, ^{18}F, ^{89}Sr, ^{13}N, ^{133}Xe and ^{131}I sources were determined to be 7.04 μSv, 7.62 μSv, 7.79 μSv, 8.54 μSv, 1.77 μSv, and 2.90 μSv, respectively.

Table 4 details the radiation doses received by the ovaries, mammary gland, and kidneys at a distance of 100 cm from various radioactive sources. The ovaries, when exposed to ^{68}Ga, ^{18}F, ^{89}Sr, ^{13}N, ^{133}Xe and ^{131}I sources, received doses of 3.16 μSv, 3.50 μSv, 4.27 μSv, 3.88 μSv, 0.68 μSv, and 1.52 μSv, respectively. At the same distance, the mammary gland received doses of 2.83 μSv, 4.24 μSv, 1.50 μSv, 2.14 μSv, 0.65 μSv, and 1.84 μSv from the same respective sources. The kidneys, another radiation-sensitive organ, received doses of 2.08 μSv, 1.92 μSv, 1.79 μSv, 1.91 μSv, 0.14 μSv, and 1.23 μSv from ^{68}Ga, ^{18}F, ^{89}Sr, ^{13}N, ^{133}Xe and ^{131}I sources, respectively, at a distance of 100 cm. The effective doses at 100 cm for ^{68}Ga, ^{18}F, ^{89}Sr, ^{13}N, ^{133}Xe and ^{131}I sources were determined to be 2.72 μSv, 2.94 μSv, 2.50 μSv, 2.84 μSv, 0.91 μSv, and 1.16 μSv, respectively.

Table 5 further presents the radiation doses received by the ovaries, mammary gland, and kidneys at a distance of 150 cm from the same radioactive sources. At 150 cm, the ovaries received doses of 2.36 µSv, 1.87 µSv, 2.35 µSv, 1.54 µSv, 0.29 µSv, and 0.49 µSv, respectively, while the mammary gland received doses of 1.72 µSv, 1.30 µSv, 0.75 µSv, 1.43 µSv, 0.13 µSv, and 0.51 µSv. The effective doses at 150 cm for ^{68}Ga, ^{18}F, ^{89}Sr, ^{13}N, ^{133}Xe and ^{131}I sources were determined to be 1.56 µSv, 1.49 µSv, 1.30 µSv, 1.46 µSv, 0.14 µSv, and 0.58 µSv, respectively. At 150 cm, the kidneys received doses of 1.02 µSv, 0.95 µSv, 0.83 µSv, 0.98 µSv, 0.05 µSv, and 0.34 µSv from the same radioactive sources.

Analysis of organ doses from radionuclides reveals that certain organs receive higher doses from specific radionuclides. The stomach exhibited the highest dose from ^{13}N (29.05 µSv) and ^{89}Sr (20.53 µSv). The large intestine was also exposed to elevated doses from ^{13}N (26.17 µSv) and ^{89}Sr (22.19 µSv). The gallbladder received the highest dose from ^{13}N (29.05 µSv). The thyroid gland (32.64 µSv) was among the organs receiving the highest dose from ^{13}N. The heart (31.37 µSv) and lymph nodes (31.32 µSv) also experienced significant doses from ^{13}N. These findings indicate that ^{13}N and ^{89}Sr radionuclides, in particular, induce concentrated doses in specific organs. When comparing organ doses from various radionuclides, ^{13}N and ^{89}Sr were generally identified as the radionuclides imparting the highest radiation doses. Conversely, ^{133}Xe and ^{131}I radionuclides typically exhibited the lowest doses. The doses received by the thyroid and red bone marrow from ^{133}Xe at 25 cm were 1.19 µSv and 0.33 µSv, respectively. The highest dose from ^{131}I was observed in the gallbladder (7.67 µSv), with other organs generally receiving less than 5 µSv. Notably, the radiation dose received by organs significantly decreased as distance increased. For instance, the ^{13}N dose to the stomach decreased from 29.05 µSv at 25 cm to 1.64 µSv at 150 cm. Similarly, the ^{13}N dose to the thyroid decreased from 32.64 µSv to 1.63 µSv, and the ^{13}N dose to the lymph nodes decreased from 31.37 µSv to 2.17 µSv. These values emphasize the critical importance of maintaining distance for clinical radiation safety.

In this study, average dose rate measurements were conducted at varying distances for different radionuclides at a dose of 10 mCi (Table 6). The results obtained demonstrate that the dose rate decreases inversely proportional to distance. This is an expected phenomenon and aligns with the fundamental principles of radiation physics. While the dose rate is high at close proximity to the source, it significantly diminishes with increasing distance. Notable differences were observed among the radionuclides. ^{13}N and ^{18}F radionuclides exhibited the highest dose rates across all distances, whereas the ^{89}Sr isotope displayed the lowest dose rate. This variation stems from the characteristic properties of the radionuclides. For instance, the emission of high-energy gamma rays by ^{13}N and ^{18}F contributes to their elevated dose rates, while the emission of low-energy beta particles by ^{89}Sr results in its lower dose rate.

Table 6. For 10 mCi dose, average dose rate measurements at different distances (mR/h)

	25 cm	50 cm	100 cm
^{68}Ga	10.30	2.57	0.64
^{18}F	91.22	22.78	5.68
^{89}Sr	0.076	0.019	0.004
^{13}N	94.30	23.55	5.87
^{133}X	7.76	1.94	0.48
^{131}I	32.68	8.16	2.03

DISCUSSION

In this study, the radiation doses delivered by different radionuclides to organs and the body at various distances were investigated. The results indicate that factors such as radionuclide type and distance significantly affect organ doses. These findings highlight the critical importance of radionuclide selection and distance control in radiation safety practices. Specifically, it was observed that the isotopes ^{13}N and ^{89}Sr delivered the highest doses to certain organs, whereas ^{133}Xe and ^{131}I exhibited lower dose levels. The organ doses obtained using the VMC dose calculation program were generally consistent with those reported in the literature.[23,24] For instance, ^{18}F-FDG is one of the most commonly used radiopharmaceuticals in PET imaging, particularly in oncological, neurological, and cardiological applications. Our study also demonstrated that ^{18}F resulted in significant doses in multiple organs. Similarly, ^{131}I is widely used in the treatment of thyroid cancer and hyperthyroidism, leading to high doses in thyroid tissue. Our findings confirmed that the thyroid dose of ^{131}I was higher than that of other organs. Previous studies have shown that high-energy beta- and gamma-emitting radionuclides increase organ doses.[1,2,23] Likewise, several studies have emphasized that maintaining an adequate distance is a crucial factor in reducing radiation doses.[9,23] In this context, applying the ALARA principle is essential for both patients and nuclear medicine personnel. An analysis of the dose distribution revealed that the thyroid, stomach, and lymph nodes were exposed to high radiation doses. This outcome may be attributed to the biological characteristics and vascularization levels of these organs. The literature suggests that highly vascularized organs tend to accumulate more radioisotopes.[23-25] Therefore, additional protective measures should be considered for these organs in clinical applications.

Limitations

The VMC dose calculation program and the Rad Pro Calculator online tool used in this study provided a high level of accuracy in radiation dose calculations. However, simulation-based studies have certain limitations. Firstly, these simulations were performed using idealized phantom models, which do not fully reflect individual patient variability. Additionally, environmental factors, patient metabolism, and radioisotope bioavailability can influence dose distribution in real clinical applications.

CONCLUSION

In this study, the radiation doses delivered by different radionuclides to organs and the body at specific distances were investigated. The findings indicate that radionuclide type and distance significantly affect organ doses. At a distance of 25 cm, ^{13}N gave the highest stomach dose of 29.05 µSv, while ^{13}Xe

showed the lowest dose values in most organs. At 25 cm the effective dose ranged from 3.21 μSv (^{13}Xe) to 19.91 μSv (^{13}N). At 150 cm all doses decreased significantly, with the highest effective dose being only 1.56 μSv (^{68}Ga). These quantitative findings reinforce the importance of maintaining distance and implementing protective measures in nuclear medicine environments. In particular, the isotopes ^{13}N and ^{89}Sr were found to deliver the highest doses to certain organs, whereas ^{133}Xe and ^{131}I exhibited lower dose levels. It was observed that maintaining distance significantly reduces radiation exposure levels. In this context, it was concluded that implementing the ALARA principle is of great importance, particularly for nuclear medicine personnel and patients. By providing direct dose comparisons under controlled simulation conditions, this research contributes a novel, dataset for six commonly used radionuclides in nuclear medicine. These insights can inform risk assessment, staff training, and protective measure development, leading to improved radiation safety protocols. The study's findings may contribute to the development of more effective protective measures to minimize radiation doses in clinical applications. Future studies incorporating more detailed analyses of individual patient variability and environmental factors will allow for a better understanding of radiation exposure.

ETHICAL DECLARATIONS

Ethics Committee Approval

This study did not require ethical approval as it did not involve any human subjects or animal experiments.

Informed Consent

Because the study has no study with human and human participants, no written informed consent form was obtained.

Referee Evaluation Process

Externally peer reviewed.

Conflict of Interest Statement

The authors have no conflicts of interest to declare.

Financial Disclosure

The authors declared that this study has received no financial support.

Author Contributions

All the authors declare that they have all participated in the design, execution, and analysis of the paper, and that they have approved the final version.

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