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Research Article

Monte Carlo Simulation of Organ Absorbed Dose of Worker's Radiation Exposure in Bone Scintigraphy

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Abstract

Objectives: This study examines individual organ doses and the impact of ionizing radiation sources on effective radiation doses.

Methods: In the research, the ICRP-defined adult standing phantom was used as the phantom material in the Visual Monte Carlo Dose Calculation Program (VMC). Subsequently, the incurred doses were calculated by defining different doses, distances, and durations for the 99mTc radioactive source.

Results: Exposure times were set at 5 minutes and 20 minutes in comparison. The results indicated that for 5 minutes and 20 minutes at 360 cm, doses remained below the ICRP recommended annual dose limit of 5.7 µSv/h for occupational exposure.

Conclusion: Organ absorbed and effective doses varied with exposure time and source-phantom distance. To optimize radiation exposure, people working in radiation fields must make an increased effort to reduce radiation doses following the ALARA principles.

Keywords: Effective dose, absorbed dose, VMC software, Monte Carlo

INTRODUCTION

Nuclear medicine has developed enormously over the last 10 years with the use of a wide variety of new radioisotopes. However, technetium-99m (^{99m}Tc) continues to be the most widely used, accounting for nearly 80% of image diagnostics worldwide due to its half-way physical characteristics. Half-life of 6.04 h, a single-energy gamma emission of 140 keV and an external photon efficiency of 90% [1]. Gamma radiation emitted by ^{99m}Tc produces a significant amount of irradiation to adjacent tissues, because a substantial fraction of the gamma rays leave the patient's body with little interaction. The half-life of 6.04 h and rapid release of the radiopharmaceutical provides sufficient time for diagnostic imaging while minimizing patient exposure to radiation. Unfortunately, the rise of nuclear medicine significantly increases the potential radiation exposure for patients and medical staff [1]. Therefore, there is a growing obligation to minimize the risks of radiation such as tissue damage and cancer. This is why the International Commission on Radiological Protection (ICRP) has recognized these risks. It sets a limit of 1 mSv/year for the public and 20 mSv/year for nuclear medicine personnel (on average over 5 consecutive years) and a maximum of 50 mSv/year per year [2,3].

Bone scan is one of the most common nuclear medicine diagnostic procedures. It allows for whole-body bone examinations that can lead to the diagnosis of many pathological conditions. It is a relatively inexpensive, widely available and extremely sensitive examination and is invaluable in the diagnostic assessment of many pathological conditions[4]. The procedure is performed with a radiopharmaceutical known as "metastatic ^{99m}Tc-HMDP" (technetium 99 methylene diphosphonates).

Protocols vary from nuclear medicine centre to nuclear medicine centre, but typically performed 2-6 hours after intravenous administration of the radiopharmaceutical with an activity level of 740-925 MBq (20-25 mCi)[5]. The use of ionizing radiation in scintigraphy procedures remains a concern regarding exposure of workers handling these radioisotopes. Therefore, accurate assessment of the organ intake of these health professionals is crucial to ensure their safety and improve protocols. Direct measurement of organ and tissue dose from radionuclides distributed in the patient's anatomy is not feasible. Nevertheless, dosimetry in nuclear medicine is based on a calculation method called internal radiation dose formalism (MIRD)[6]. In this context, the Monte Carlo simulation method is a powerful tool for modelling and quantifying radiation doses received by organs during bone scintigraphy procedures. By allowing a probabilistic approach to simulate complex interactions between radiation particles and biological matter, this method provides a fine and detailed analysis of radiation flows. Through realistic anatomical models and the consideration of various physical parameters, Monte Carlo simulation provides a better understanding of radiation exposure risks and appropriate recommendations to minimize these risks. Software suites such as EGS[7], MCNP[8], MABDOSE[9], GEANT4, GATE (GEANT4 application for tomographic emission) and Visual Monte Carlo-dose calculation (VMC-dc) were used by several research groups for the prediction and dosimetric evaluation in clinical routines in diagnostic, therapy and radiation protection[10, 11]. This work therefore explores the application of Monte Carlo simulation to assess organ dose in exposed workers, with a view to enhancing radiological safety and improving clinical practices in bone scintigraphy. The exposure situation was simulated from the work of establishing the diagnostic reference level (NDR) of the activity administered to patients who underwent a ^{99m}Tc-HMDP bone scintigraphy at the Institute of Nuclear Medicine in Abidjan (IMENA)[12].

MATERIAL AND METHOD

VMC code

The Monte Carlo technique is used to simulate tissue contamination (or an external source of radiation), to transport photons through tissues and, if necessary, to simulate the detection of radiation[13]. Since radionuclides of interest for radiation protection are mainly in the range 0.06 -1.5 MeV, only photoelectric and Compton interactions are considered[14]. The Visual Monte Carlo dose calculation (VMC DC) program is written in Visual Basic®, a Microsoft Windows based program that is easy to use and has an extended graphics output. Photon transport is simulated through a voxel phantom using the kerma approximation, where it is assumed that the energy transferred by the photon during an interaction in the tissue is deposited at the point of interaction, and that electrons are not transported[14,15]. In this study, the adult male phantom proposed by the ICRP was used as a simple model of the human body. The VMC-dc software was used to simulate the activity administered to patients who underwent bone scintigraphy with ^{99m}Tc-labelled hydroxy-methylene diphosphonates (^{99m}Tc-HMDP).

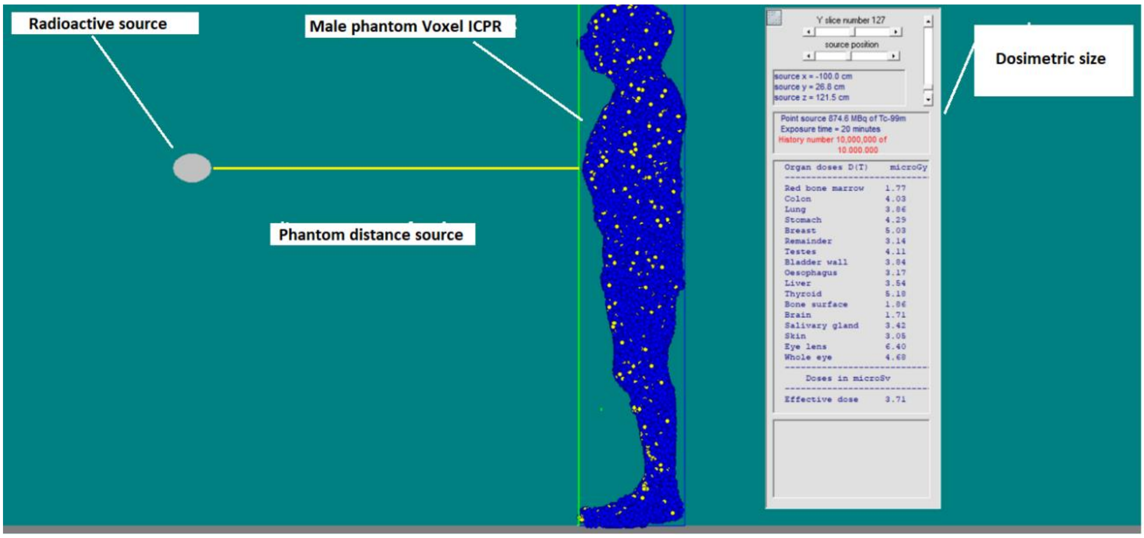
Simulation

Usually, in the ^{99m}Tc-HMDP bone scan procedure, injection lasts between 05 to 15 minutes[16]. During the injection of the radiopharmaceutical, doctors, technicians and nurses are present in the room. These workers in the room are therefore exposed to radiation. For this study, we simulated two situations:

- The situation (S1): the phantom is exposed to the radioactive source for 20 minutes. It is placed at 100 cm and then 360 cm. This situation is the illustration of a technician in the operating room and outside the operating room.

- The situation (S2): the phantom is exposed to a radioactive source for 5 minutes. The context is the same.

A 10^7 photons execution option was chosen. Figure 1 illustrates an example of exposure situations.



```
source x = -100.0 cm
source y = 26.8 cm
source z = 121.5 cm

Point source 874.6 MBq of Tc-99m
Exposure time = 20 minutes
History number 10,000,000 of
            10.000.000

Organ doses D(T)      microGy
-----------------------------
Red bone marrow       1.77
Colon                 4.03
Lung                  3.86
Stomach               4.29
Breast                5.03
Remainder             3.14
Testes                4.11
Bladder wall          3.84
Oesophagus            3.17
Liver                 3.54
Thyroid               5.18
Bone surface          1.86
Brain                 1.71
Salivary gland        3.42
Skin                  3.05
Eye lens              6.40
Whole eye             4.68
-----------------------------
     Doses in microSv
-----------------------------
Effective dose        3.71
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Figure 1: Illustration of exposure to a radioactive source (^{99m}Tc) placed at a distance of 100 cm from male phantom

RESULTS AND DISCUSSION

Results

The results of organ dose and effective dose are shown in Table 1.

In the S(1) situation, when the phantom is placed at 100 cm, the highest doses were received by the lens (6.04 µGy), thyroid (5.18 µGy) and breast (5.03 µGy). However, when the radioactive source is located at a distance of 360 cm, the highest doses decreased to (0.67 µGy) for breast, (0.64 µGy) for lens and (0.52 µGy) for thyroid (Figure 1). It is found that as the distance increases, the effect of radiation dose decreases. Therefore, personnel working in the radiation field should operate as far away from the radiation source as possible[17]. In S(2) the exposure time is reduced to 5 minutes. When the phantom is placed at 100 cm, the highest doses received are (1.6 µGy), (1.3 µGy), (1.26 µGy) for the lens of eye, thyroid and breast respectively (Figure 1). We find that the absorbed dose is inversely proportional to the distance of exposure. For the same ^{99m}Tc radioactive source with the same activity level of 874.6 MBq, the effective doses obtained over a 20-minute exposure time at 100 cm and 360 cm distances were found to be 3.71 µSv, 0.39µSv respectively. When the duration was reduced to 5 minutes with the same activity and at the same distances, effective doses were found to be 0.93 µSv, and 0.097 µSv, respectively. We can say that the effective dose received increases with the time of exposure to a radioactive source.

Table 1: Dose absorbed by organs irradiated by the radionuclide ^{99m}Tc (874.6 MBq) placed at 100 cm and 360 cm from the Phantom

Exposure duration	S (1)-20 minutes		S (2)-5 minutes	
Organs and tissues	**100 cm**	**360 cm**	**100 cm**	**360 cm**
Red bone marrow	1.77	0.2	0.44	0.051
Colon	4.03	0.36	1.01	0.089
Lung	3.86	0.37	0.97	0.093
Stomach	4.29	0.41	1.07	0.103
Breast	5.03	0.67	1.26	0.168
Remainder	3.14	0.3	0.78	0.076
Testes	4.11	0.48	1.03	0.119
Wall bladder	3.84	0.37	0.96	0.094
Oesophagus	3.17	0.31	0.79	0.078
Liver	3.54	0.35	0.89	0.087
Thyroid	5.18	0.52	1.3	0.131
Bone surface	1.86	0.23	0.47	0.058
Brain	1.71	0.2	0.43	0.05
Salivary gland	3.42	0.33	0.85	0.082
Skin	3.05	0.35	0.76	0.087
Eye lens	6.04	0.5	1.6	0.125
Whole eye	4.68	0.64	1.17	0.16
Effective dose (µSv)	3.71	0.39	0. 93	0.097

DISCUSSION

Effective dose and dose rate

Bone scan protocols vary from one nuclear medicine facility to another, imaging is usually performed 2-6 hours after intravenous administration of 740-925 MBq (20-25 mCi) of the radiopharmaceutical ^{99m}Tc-HMDP[16,18]. At the Institute of Nuclear Medicine in Abidjan (IMENA), patients received an injection activity of approximately 874.6 MBq of ^{99m}Tc-HMDP corresponding to a diagnostic reference level (NRD) which gave an effective dose of 3.30 mSv to the bone structures. Effective dose is in agreement with an international standard [12]. Indeed, the effective dose in optimizing protection against stochastic effects is at low doses and at low dose rates. We have evaluated the impact of radiation on technicians at this centre by means of a Monte Carlo simulation. When the exposure time was 5 minutes with the same activity, at a distance of 100 cm and 360 cm, the effective doses were found to be 0.93 µSv, and 0.097 µSv, respectively. This situation S1 corresponds to a dose rate of 11.20 µSv/h and 1.16 µSv/h at 100 cm and 360 cm respectively. According to the radiation protection regulations established by the International Commission on Radiological Protection (ICRP), workers must not exceed an effective annual dose of 50 mSv [2] , is 5.70 µSv/h. The worker's dose rate at 360 cm is well below the dose rate limit and is in accordance with the ICRP standard. In S2, the exposure time was 20 min. Effective doses were 3.71 µSv and 0.39 µSv at 100 cm and 360 cm respectively. This situation S1 corresponds to a dose rate of 11.24 µSv/h and 1.18 µSv/h at 100 cm and 360 cm respectively. The dose rate obtained at 360 cm, or 1.18 µSv/h is less than 5.70 µSv/h. It is therefore in accordance with the limit dose. However, the International Atomic Energy Agency (IAEA) recommends an average annual dose of less than 5 mSv for radiology workers working in nuclear medicine departments[19,20] (see Figure 2). In this study, a linear dependence of the effective dose on the time of human exposure was observed [21].

Dose absorbed by organs and tissues

Protection is provided by using well-established dose quantities: absorbed dose and equivalent dose for organs and tissues in the prevention of tissue reactions. The use of these quantities was presented in ICRP Publication 147 [22] where low doses correspond to radiation with low linear energy transfer (TLE) of less than 100 mGy on organs and tissues, and low dose rates correspond to radiation of less than 5 mGy/h [23] 5000 µG/h. Compliance with the annual dose limit recommended by ICRP has a direct effect on the dose absorbed by organs and tissues. It was observed that in both exposure situations, only the doses taken at 360 cm were below the dose limit. Therefore, it could be said that the absorbed dose determined in this situation is well below 1 µG/h and free of any tissue damage. Figure 2 shows the values of dose absorbed by organs and tissues. Taking into account the two exposure situations, the most irradiated organs and tissues which are the lens of eye, thyroid and breast do not exceed 6 µG/h. This value is very low compared to the linear energy transfer of ionizing radiation.

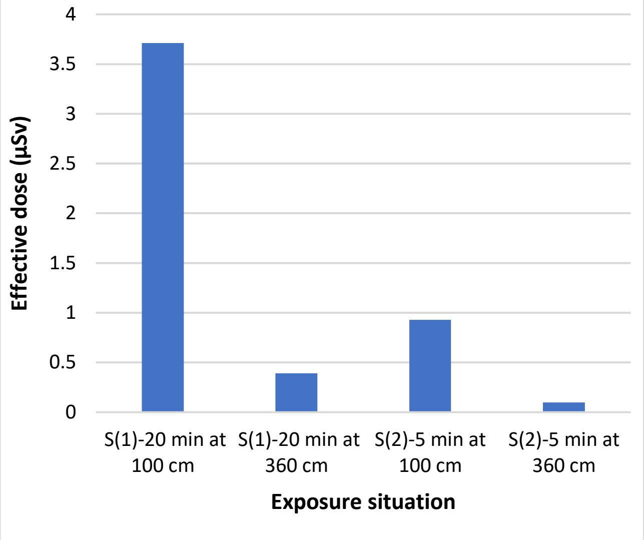

Figure 2: Effective dose comparison in situations 1 and 2

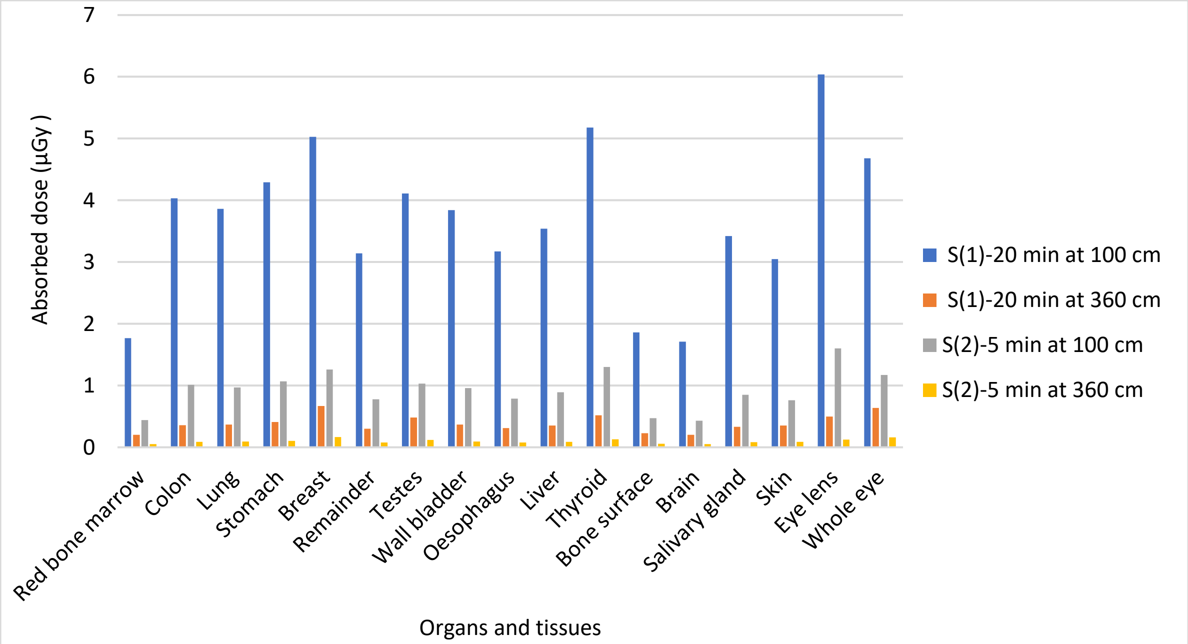

Figure 3: Organ dose distribution after exposure to a ^{99m}Tc point source of activity of 874.6 Bq

Figure 3 shows a comparative study of the dose absorbed by organs and tissues from literature and ours. For activity administered to patients slightly to that of IMENA, about 1.5% increase, we find that our results are below the one taken from the author of the literature[24].

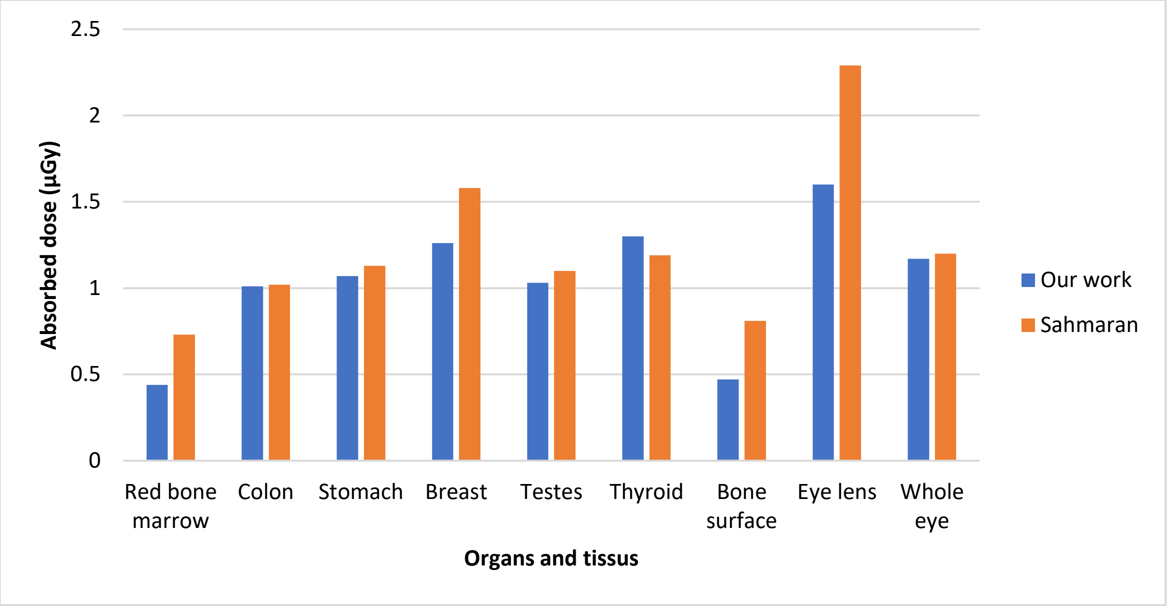

Figure 4: Comparison of dose to the most irradiated organs and tissues

CONCLUSION

The less radiation exposure, the lower the dose. VMC-dc is a robust dosimetric modelling tool. It allowed us to confirm the basic rules of radiation protection. This study shows that distance, time and activity are indicators of radiation protection performance to be respected. It was observed that organ dose and effective dose vary with the strength of the source and duration of exposure. Regardless of dose, radiation workers should plan their tasks in advance and avoid spending time in the radiation field by following ALARA principles.

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Source of Support: Nil

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Ethics approval and consent to participants: Not applicable

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