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ORIGINAL RESEARCH ARTICLE

Calculation of hand dose in nuclear medicine staff during the administration of syringes and handling of vials containing Sr-89 and In-111

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ABSTRACT

Introduction: Nuclear medicine (NM) staff are frequently exposed to higher radiation doses than other occupational groups, particularly in the hands, due to the direct manipulation of radiopharmaceutical syringes and vials. This study aimed to quantify the absorbed dose to the hands of NM staff during syringe injection and vial handling of two clinically relevant radionuclides, Sr-89 and In-111, using the GATE Monte Carlo code.

Methods: A high-resolution voxelized hand phantom was employed to model syringe injections with 2 mm and 9 mm tungsten shields, and vial handling with and without a 25 mm lead shield. Absorbed dose was quantified at the skin of the fingertips and hand.

Results: Our results showed that unshielded syringe injections of In-111 produced absorbed doses nearly 4.7-fold higher than those of Sr-89. Application of a 9 mm tungsten syringe shield reduced the hand dose from In-111 by approximately 5600 fold. During unshielded vial handling, the In-111 dose was about 65 times higher than that of Sr-89, whereas using a 25 mm lead shield reduced the absorbed dose to nearly negligible levels.

Conclusion: Spatial dose distribution revealed that the index fingertip received the highest dose during syringe injection, whereas the thumb was most exposed during vial handling. These findings highlight the need for optimized shielding strategies and improved dosimetry approaches to ensure occupational safety in NM practice.

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INTRODUCTION

Nuclear medicine (NM) staff are often exposed to higher radiation doses than other radiation workers due to their direct involvement with radioactive materials. Studies indicate that occupational exposure among NM staff can be significantly higher, particularly among those involved in manual handling of radiopharmaceuticals or performing quality control procedures [1, 2]. Hand exposure is a significant concern in the radiation protection of NM staff who handle and administer radiopharmaceuticals to patients [3].

Evaluating hand exposure in NM staff is especially difficult, as the fingertips receive the highest levels of exposure. This is caused by an uneven distribution of radiation dose across the hands and fingers [4]. The standard method for hand dosimetry involves the use of a ring thermoluminescence dosimeter (TLD) [3, 5, 6]. However, estimating absorbed doses in specific areas, such as the fingers, using ring dosimeters can be problematic when there is no consistent placement location on the hand. In conclusion, although ring dosimeters offer essential insights into radiation exposure, their limitations in accurately estimating finger dose underscore the need for a more refined approach to hand dose assessment [7]. Monte Carlo simulation, an essential tool in medical physics, enables precise modeling of radiation transport and interactions with matter, which is vital for accurate dose calculations [8]. Its integration into NM dosimetry further improves the precision of dose assessments, making it indispensable in dosimetry [9].

Studies on hand-dose measurements among NM staff have primarily focused on commonly used diagnostic and therapeutic radionuclides, including I-131, Tc-99m, Lu-177, Y-90, I-125, F-18, Lu-177, and Ga-67 [4, 5, 7]. Studies have shown that the absorbed dose to the hand skin is maximized during the preparation and administration of Y-90 [10]. Sr-89 is a therapeutic radionuclide that emits beta particles and is administered as Sr-89 chloride for the targeted palliation of pain associated with metastatic bone disease [11]. In-111, when used to label autologous white blood cells, is a diagnostic radiotracer in NM. In-111 white blood cell scintigraphy is valuable for detecting occult or difficult-to-localize infections, particularly when conventional imaging modalities are inconclusive or unsuitable [12]. To date, no studies have assessed the absorbed dose to NM staff's hands during syringe injections or vial handling involving Sr-89 and In-111.

Due to practical limitations in measuring the absorbed dose to the hands of NM staff, as well as the lack of studies on hand absorbed dose during the preparation and administration of Sr-89 and In-111, this study was conducted to assess the absorbed dose to the hands of NM staff during vial handling or syringe injection containing Sr-89 and In-111, utilizing the GATE Monte Carlo simulation code.

METHODS

In this study, the Geant4 Application for Tomographic Emissions (GATE) package (version 9.3) was employed [9]. This Monte Carlo toolkit is highly advanced and reliable for modeling time-dependent processes [13]. Due to its precision, GATE is extensively used for internal dose assessments [9] .A voxelized hand phantom was employed to represent realistic exposure conditions encountered by NM staff during radiopharmaceutical handling. The phantom geometry reproduced two clinically relevant configurations: vial handling and syringe injection. In the vial-handling scenario, the hand was modeled both without shielding and with a 25 mm lead vial shield. In the injection scenario, the syringe was simulated without shielding and with tungsten syringe shields of 2 mm and 9 mm thickness. The geometric models included detailed representations of the fingers, palm, and surrounding soft tissues, together with the syringe and vial structures containing the radioactive solution. Individual components of the system were assigned appropriate materials, including skin and soft tissue for the hand, plastic for the syringe body, glass for the vial, shielding materials such as tungsten or lead, and water to represent the radiopharmaceutical solution [14]. Material compositions were defined according to ICRU-44 to ensure accurate particle interaction modeling in the Monte Carlo simulations [15]. The final geometry consisted of a 392 × 392 × 250 voxel matrix with an isotropic voxel size of 0.5 mm, providing sufficient spatial resolution for detailed dose estimation across different regions of the hand. The voxelized hand phantom used in the present study was previously developed and experimentally validated in our earlier work [10]. In that study, a realistic clinical handling scenario was replicated in which NM staff manipulated an F-18-filled syringe equipped with a 9 mm tungsten shield containing approximately 7 mCi of activity. Absorbed doses at the tips of the index and middle fingers were experimentally measured using TLD ring dosimeters worn during routine syringe handling. The same irradiation setup, including the source activity, shielding configuration, and hand and syringe positioning, was reproduced in the Monte Carlo simulations employing the voxelized hand phantom. Simulated fingertip doses were then compared with the corresponding measured values. As reported, the maximum deviation between simulation and experiment was 4%, demonstrating excellent agreement and confirming that the phantom geometry and material definitions are sufficiently accurate for detailed hand dosimetry[10]. Based on this validated performance, the same hand phantom was used in the present work to model exposure during syringe injection and vial-handling procedures.

Calculation of hand absorbed dose

The generated phantoms were implemented in the GATE code. The decay characteristics of Sr-89 and In-111 were extracted from the MIRD Radionuclide Data and Decay Schemes, including all relevant beta and photon emissions with their corresponding energies and emission probabilities [16]. Each radionuclide was simulated using its complete emission spectrum to ensure accurate modeling of particle transport and energy deposition within the hand phantom. Radionuclides were modeled as uniformly distributed sources within the water-filled volumes of the syringes and vials. This assumption reflects standard radiopharmaceutical preparation procedures, in which the radioactive solution is thoroughly mixed before administration, resulting in a homogeneous distribution of activity within the aqueous medium. Given the liquid nature of the radiopharmaceuticals and the relatively small source volumes considered in this study, the uniform distribution assumption provides a realistic and widely accepted approximation for external hand dosimetry simulations. To ensure that the dose estimates remain applicable to any clinically administered activity, the Monte Carlo output was normalized to absorbed dose per unit activity time, expressed as mGy per MBq·s. This approach allows the resulting dose values to be directly scaled to the actual activity used in clinical practice. Normalizing the absorbed dose per MBq·s therefore provides a robust, generalizable framework that accommodates variations in administered activity and ensures that dosimetric results remain valid across different clinical scenarios. For all phantoms, the absorbed dose was computed at the skin of each fingertip, the wrist, and the TLD ring position. In addition, the absorbed dose to the entire hand was evaluated. Figure 1 shows the specific hand regions for which dose calculations were performed, each labeled with an alphabetic marker. A voxelized Dose Actor was used for scoring absorbed dose in the hand phantom. The actor stored the deposited energy in each voxel and computed absorbed dose according to the mass of the corresponding voxel [9]. Dose maps were exported in matrix format for further analysis. Electromagnetic interactions were modeled using the Livermore low-energy physics list, which provides detailed cross sections for photon and electron interactions, including the photoelectric effect, Compton scattering, Rayleigh scattering, ionization, and bremsstrahlung [17]. This model is specifically optimized for accurate particle transport at low energies and is well-suited for the photon emissions of In-111 and the beta emissions of Sr-89. To ensure high precision in energy deposition and to account for the small dimensions of the hand's anatomical structures, the simulations were performed with an energy cutoff of 1 keV and a maximum step size of 0.1 mm. These parameters allow for a realistic representation of energy-loss processes and ensure that secondary-particle transport is tracked with sufficient spatial resolution within the voxelized phantom. A total of 10^9 particles were simulated for each case, ensuring that the statistical uncertainty of the mean absorbed dose remained below 1%.

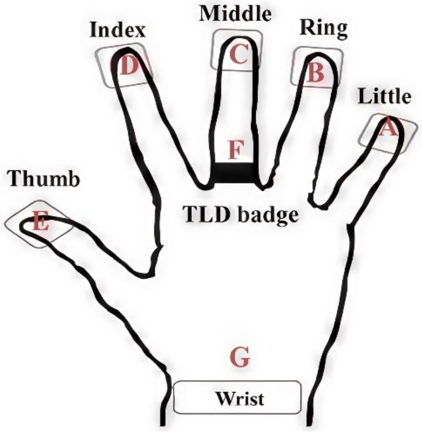

Figure 1. Anatomical regions of the hand considered for dose calculations

RESULTS

Table 1 shows the characteristics of In-111 and Sr-89. Table 2 presents the absorbed dose to the hands of NM staff during vial handling and syringe injection involving In-111 and Sr-89. During syringe injection without shielding, the absorbed dose to the hand from In-111 was nearly 4.7 times greater than that from Sr-89. The absorbed dose to the hand was significantly reduced when using syringes equipped with 2 mm and 9 mm tungsten shields. When using a 9 mm tungsten shield, the absorbed dose to the hand during syringe injection with In-111 decreased by approximately 5600 fold compared with the unshielded condition. At the same time, for Sr-89, the reduction was about 5300 fold. In the case of unshielded vial handling, the absorbed dose to the hand from In-111 was nearly 65-fold greater than that from Sr-89. Applying a 25 mm lead shield around the vial substantially reduced the absorbed dose to the hand. Specifically, during handling of an In-111 vial with this shielding, the absorbed hand dose was reduced to nearly zero.

Figure 2 shows the absorbed dose at the fingertips, wrist, and the TLD ring position during syringe injection of In-111 and Sr-89. During syringe injection, the absorbed dose to the skin of the index and middle fingers was markedly higher than in other parts of the hand, while the wrist received the lowest dose. The absorbed dose across various regions of the hand was considerably higher during injection with In-111 than Sr-89. Notably, the dose to the skin of the index fingertip during In-111 syringe injection was about 4.4-fold higher than the corresponding dose for Sr-89. With increasing shield thickness on the syringe, the absorbed dose to different parts of the hand decreased significantly. Figure 3 shows the absorbed dose to different regions of the hand during vial handling containing In-111 and Sr-89. The dose at the thumb's skin and the TLD ring position were markedly higher than in other regions, while the absorbed dose at the wrist was negligible. Overall, the absorbed dose in all hand regions during handling of In-111 vials was higher than that during handling of Sr-89 vials.

Table 1. The characteristics of radionuclides [16]

Radionuclide	Half-Life	Decay mode (major)	$E_{\beta average}$ (MeV)	$E_{\beta max}$ (MeV) (%)	E_{γ} (keV) (%)
In-111	2.8 (days)	Electron capture	-	-	**245 (94), 171 (90)**
Sr-89	50.571 (days)	β^-	0.583	1.491 (100)	-

Table 2. Absorbed dose to the hands (mGy / (MBq·s)) ×10⁻⁸ during syringe injection (and vial handling with different shielding

	Syringe injection			Vial handling	
	Tungsten Shield (0 mm)	Tungsten Shield (2 mm)	Tungsten Shield (9 mm)	Lead Shield (0 mm)	Lead Shield (25 mm)
In-111	1.7×10^{-1}	1.3×10^{-2}	3.0×10^{-5}	1.3×10^{-3}	0.0
Sr-89	3.6×10^{-2}	7.2×10^{-4}	6.8×10^{-6}	2.0×10^{-5}	3.6×10^{-6}

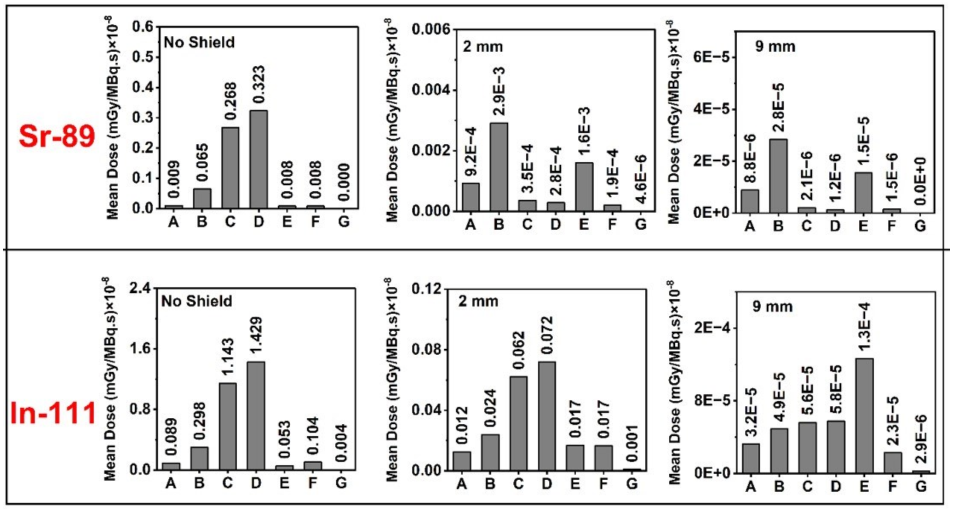

Figure 2. Absorbed dose to various hand regions during syringe injections of In-111 and Sr-89, for unshielded syringe and syringes fitted with 2 mm and 9 mm tungsten shields

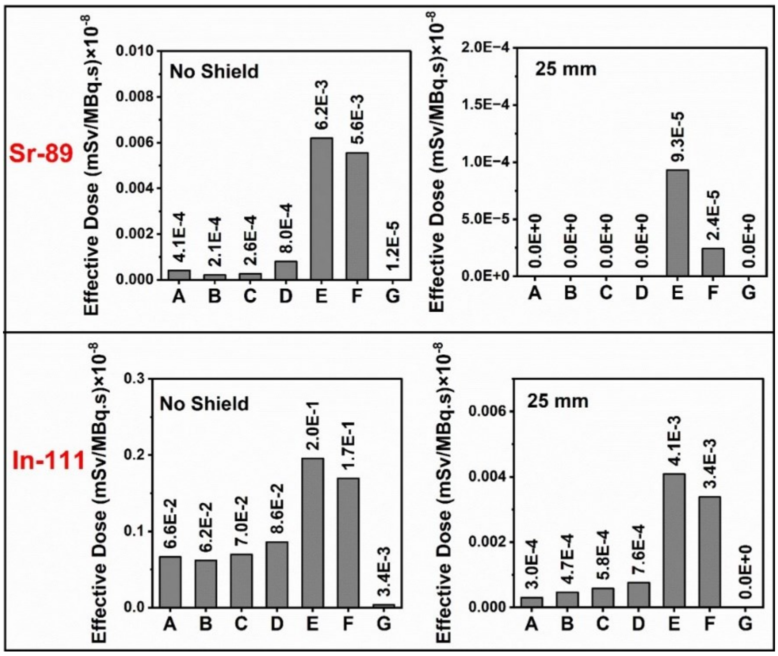

Figure 3. Absorbed dose to different regions of the hand during vial handling containing In-111 and Sr-89 for an unshielded vial and a vial with a 25 mm lead shield

DISCUSSION

A major concern in nuclear medicine is occupational exposure of staff's hands to radionuclides during the manipulation of vials or the administration of radiopharmaceuticals [5]. Accurate assessment of absorbed dose to the hands is crucial for developing effective radiation protection strategies and ensuring compliance with safety standards [18]. In this study, we calculated the absorbed dose to the hands of NM staff during vial handling and syringe injection containing In-111 and Sr-89 using high-resolution voxelized hand phantoms and Monte Carlo simulations. Given the increasing use of diagnostic and therapeutic radionuclides, no studies have specifically evaluated hand dose during the manipulation of vials or injection of syringes containing In-111 and Sr-89.

As shown in Table 2, the absorbed dose to the hand during syringe injection is significantly higher than that observed during vial handling. The observed difference is primarily due to the distinct material composition and varying wall thickness between the syringe and the vial [14]. Vials are made of glass, which has a substantially higher density than the plastic used in syringes, resulting in greater attenuation of both gamma and beta radiation. Moreover, the wall thickness of the vials (2.1 mm) is considerably greater than that of syringes (0.9), further enhancing the shielding effect [14]. The absorbed dose to the hands of NM staff during syringe injection or vial handling is higher for In-111 than for Sr-89. In-111 emits gamma rays with energies of 245 and 171 keV, whereas Sr-89 is a pure beta emitter with an average beta energy of 0.583 MeV [16]. Most beta particles are absorbed by the syringe or vial walls due to their limited range, resulting in minimal contribution to the hand dose. In contrast, gamma photons from In-111 have much higher penetration ability and can pass through the syringe or vial, leading to a greater absorbed dose in the hands.

Our results show that during syringe injection, the highest absorbed dose occurs at the skin of the index fingertip, while during vial handling, the skin of the thumb fingertip receives the greatest dose. This distribution reflects the different hand grips and biomechanics associated with each task. In syringe injection, the thumb is primarily used to depress the plunger. In contrast, the index and middle fingers stabilize and guide the syringe, placing the skin of these fingertips in proximity to the radioactive source. Conversely, when handling a vial, the thumb often exerts pressure to lift and stabilize the vial, positioning the thumb's skin closer to the source than the other fingers. These findings are consistent with previous studies [4, 5, 19]. Although the present simulations were conducted using static hand configurations, these postures were intentionally selected to represent the dose-dominant phases of syringe injection and vial handling, namely the moments of closest proximity between the fingers and the radioactive source. Such static modeling approaches are widely used in extremity dose assessments, as short, high-exposure intervals contribute disproportionately to the total hand dose. To maintain applicability under realistic clinical conditions involving variable task durations and hand motion, all absorbed dose values were normalized to dose per unit activity time (mGy per MBq s). This normalization enables the reported values to be directly scaled to any procedure-specific time activity pattern, making the results generalizable to dynamic workflows despite the use of static geometries. Nevertheless, we acknowledge that dynamic factors such as continuous hand movement, evolving source finger distances, and operator-dependent timing were not explicitly modeled in this study. Incorporating motion-tracking data or time-weighted exposure modeling represents a valuable direction for future research.

In NM, ring or wrist dosimeters are commonly used to monitor absorbed dose in personnel's hands [7, 20]. Previous research by Wrzesień et al. demonstrated that wrist dosimeters can provide estimates of personal hand doses; however, their readings require correction factors and depend on the dosimeter's positional stability during routine tasks [19]. Our results revealed that the absorbed dose at the skin of the little fingertip strongly correlates with the total hand dose. Consequently, measurements at the little fingertip can be a reliable surrogate for estimating the overall hand dose in NM staff. For Sr-89, even a thin 2 mm tungsten shield lowered the total hand dose by roughly 50-fold, while increasing the thickness to 9 mm produced an improvement on the order of several thousand-fold, indicating that modest shielding already offers substantial protection for beta emitters.

In contrast, for In-111, the same 2 mm tungsten shield achieved only about a ten-fold reduction, whereas switching to a 9 mm tungsten shield resulted in a multi-thousand-fold decrease, underscoring the necessity of thicker shielding for gamma emitters. For vial manipulation, a 25 mm lead shield reduced exposure by several orders of magnitude for both radionuclides, effectively minimizing hand dose. Overall, these quantitative comparisons show that 2 mm tungsten is adequate for Sr-89 syringe work, whereas In-111 requires at least 9 mm tungsten for syringe handling and substantial lead shielding for vial-based tasks.

This study is subject to several methodological limitations that should be considered when interpreting the findings. The simulations were conducted using fixed hand postures representing dose-dominant steps of syringe injection and vial handling, which do not fully reflect the variability of hand movements and operator techniques in clinical practice. In addition, radiation transport modeling was primarily limited to direct and locally scattered components within the hand and immediate setup, while scatter from the surrounding clinical environment was not explicitly included, potentially leading to a slight underestimation of extremity dose in some cases. The simulations also did not account for possible radioactive contamination of the skin or gloves, which, although typically minimized, can locally increase dose. Furthermore, variations in workflow, such as procedure duration and operator-specific habits, were not individually modeled; instead, results were reported as activity-time–normalized doses (mGy per MBq·s) to enable broader applicability. While practical, this approach cannot fully replace detailed, scenario-specific modeling, underscoring the need for future studies that incorporate motion variability, environmental scatter, and contamination effects.

CONCLUSION

This study highlights that hand exposure in nuclear medicine staff is significantly higher during syringe injections of In-111 and vial handling. The absorbed dose distribution is strongly influenced by fingertip positioning and hand mechanics. The skin of the little fingertip reliably correlated with the total hand dose, providing a practical site for dosimeter placement. Furthermore, task-specific shielding markedly reduced hand doses, particularly for beta-emitting Sr-89, while gamma-emitting In-111 requires more robust protection. These findings underscore the importance of optimized protective measures and informed dosimetry strategies to enhance occupational safety in nuclear medicine.

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