# MONTE CARLO ASSESSMENTS OF ABSORBED DOSES TO THE HANDS OF RADIOPHARMACEUTICAL WORKERS DUE TO PHOTON EMITTERS

RADIATION PROTECTION

**KEYWORDS:** *extremity monitoring, radiopharmacy, Monte Carlo*

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*This paper describes the characterization of radiation doses to the hands of nuclear medicine technicians resulting from the handling of radiopharmaceuticals. Radiation monitoring using ring dosimeters indicates that finger dosimeters that are used to show compliance with applicable regulations may overestimate or underestimate radiation doses to the skin depending on the nature of the particular procedure and the radionuclide being handled. To better understand the parameters governing the absorbed dose distributions, a detailed model of the hands was created and used in Monte Carlo simulations of selected nuclear medicine procedures. Simulations of realistic configurations typical for workers handling radiopharmaceuticals were performed for a range of energies of the source photons. The lack of charged-particle equilibrium necessitated full photon-electron coupled transport calculations. The results show that the dose to different regions of the fingers can differ substantially from dosimeter readings when dosimeters are located at the base of the finger. We tried to identify consistent patterns that relate the actual dose to the dosimeter readings. These patterns depend on the specific work conditions and can be used to better assess the absorbed dose to different regions of the exposed skin.*

## I. INTRODUCTION

The fingers of a nuclear medicine technician preparing and administrating radiopharmaceuticals often are the most highly irradiated tissue of the body. Measuring the radiation dose to the fingers is considerably more complex than monitoring the dose to the whole body. In the latter case, a single personnel dosimeter (radiation badge) is generally sufficient because the external radiation field averaged over the body is typically rather uniform in its spatial and angular distribution. A technician's hands, however, are in close contact with the radiation source as various tasks are performed, resulting in a nonuniform distribution of the skin dose to the fingers. Placement of dosimeters on the hands to monitor the dose distribution must balance the convenience and comfort of the worker with the objective of assessing the shallow dose equivalent for regulatory compliance.

Previous studies have shown that nuclear medicine technicians are likely to receive the largest radiation dose to their fingers during the preparation of a radiopharmaceutical for administration and that the effective shielding of the radiation sources is very important in minimizing the doses to the extremities.[1–3] While these studies recommended that thermoluminescent dosimeters (TLDs) be worn at the base of the middle finger, it was noted that the most exposed regions are the fingertips. Therefore, correction factors had to be applied to the TLD readings to obtain the doses to the fingertips. These correction factors were in the range of 1.3 to 2.3, depending on the procedure and the radionuclide used.[4] More extensive and recent research[5] indicates that in certain situations

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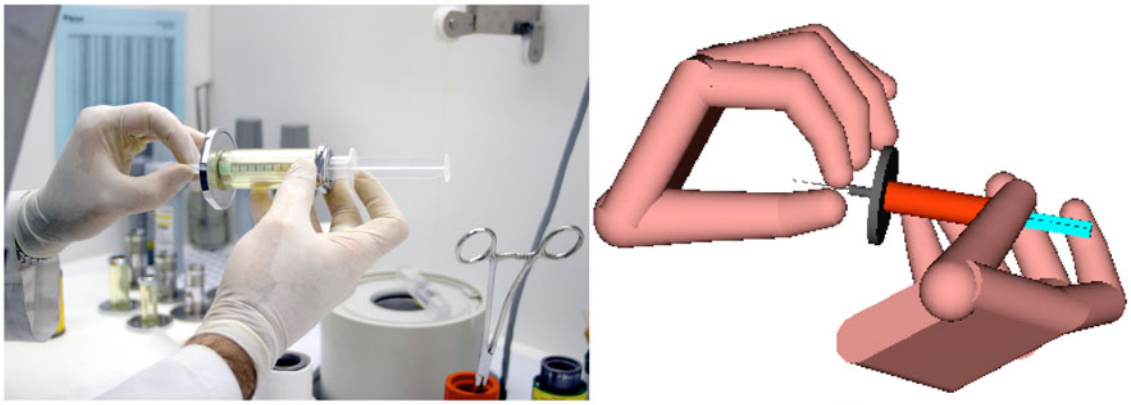

(a) (b)

Fig. 1. (a) Photograph and (b) MCNP rendering of a representative geometry for a technician handling radiopharmaceuticals.

the ratio of the dose to the fingertips can be as much as 6.9 times that indicated by the dosimeter.

The objective of this study was to better understand the distribution of absorbed dose in the hands under exposure geometries typically encountered in handling radiopharmaceuticals. Detailed models of the hands and specific exposure geometries typical of those encountered in handling radiopharmaceuticals within shielded vials and syringes were created for use in Monte Carlo simulations. The simulations, using the Monte Carlo N-particle (MCNP) transport code, version 5.1.40 (Ref. 6), were carried out for several energies of the source photons, and the results were interpolated in energy to obtain the doses corresponding to the radionuclides of interest. Previous results[7] were obtained on a more simple geometry of the hand using a monoenergetic point or planar source. Because regulatory bodies require the dose be calculated at a depth of 70 $\mu$m (Ref. 8), where the charge-particle equilibrium hypothesis does not hold, the *F8 tally of MCNP was used instead of the faster F6 tally, as also suggested by previous studies.[9,10]

## II. MCNP MODELING

Several representative geometries for a technician handling radiopharmaceuticals have been modeled. One such geometry is shown in Fig. 1, where Fig. 1a is a real photograph while Fig. 1b is the MCNP rendering [obtained with MORITZ (Ref. 11)]. The other geometrical configurations are similar to the one in Fig. 1 but have different orientations of the technician's hands relative to the syringe. In addition to the hand-syringe positions, several syringe capacities and filling factors were considered as well. The fingers of the hand were represented as three conical frustum segments joined by spheres. The bones were simulated as cylinders placed eccentrically inside each segment. Figure 2 shows a cross-sectional view of a finger and the anterior positions of the tally

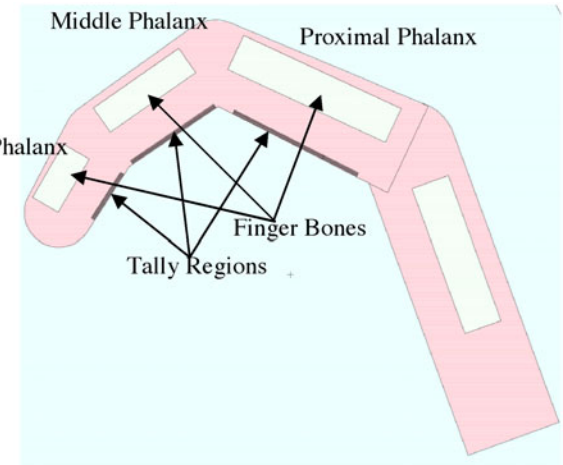


Fig. 2. Two-dimensional representation of a finger showing the nomenclature.

regions in each segment (phalanx) of a finger. The dosimeter was simulated as a shallow region placed at the base of the proximal phalanx. The thickness of each tally region was 0.14 mm, and the average dose in this region was taken to represent the dose at a depth of 70 $\mu$m. This would be exact if the dose distribution inside this tally region were constant or linear. The linear behavior is assumed to represent a reasonable assumption.

The simulations were performed using fully coupled photon-electron transport in MCNP. Because of the electron transport, the simulations were very time-consuming and necessitated using the parallel version of the MCNP code. For certain combinations of geometry and energy of the source photons, the CPU time to achieve good statistics could exceed 100 000 min (~70 days). This was not particularly problematic as it meant that the number of events, and hence the absorbed dose in the region of interest, was small. Depending on the energy of the source

photons, up to 2 billion source particles were simulated, and the CPU time ranged from $10^{-5}$ min/source particle at lower energies to $10^{-3}$ min/source particle at higher energies. Even with extensive computational resources, the statistics in certain cases (at low energies) were not satisfactory.

The primary Monte Carlo results obtained at monoenergetic grid energies of the source photons were used to compute the skin doses for radionuclides routinely used in medical applications. The selection of radionuclides of interest and their principal photon emissions was based on the tabulations of Eckerman et al.[12] Table I summarizes the radionuclides of interest and their principal photon emissions. The energies of the primary photons emitted by these radionuclides ranged from tens of kilo-electron-volts up to 811 keV for $^{58}$Co. The absorbed dose rate coefficient for the skin of segment $j$ of finger $i$, $\dot{D}(i,j)$, per unit activity of a radionuclide is computed as

$$\dot{D}(i,j) = \sum_{k=1}^{n} F_k R_{i,j}(E_k) \ , \qquad (1)$$

TABLE I

Properties of Radionuclides in This Study

| Nuclide | Decay Mode[a] | $T_{1/2}$ | Photon Emissions Energy (keV) | Photon Emissions Yield[b] (%) |
|---|---|---|---|---|
| $^{18}$F | EC $\beta+$ | 109.77 min | 511 | 200.00 |
| $^{51}$Cr | EC | 27.704 days | 320 | 9.83 |
| $^{57}$Co | EC | 270.9 days | 122 | 85.59 |
| | | | 136 | 10.61 |
| $^{58}$Co | EC $\beta+$ | 70.80 days | 511 | 30.00 |
| | | | 811 | 99.43 |
| $^{67}$Ga | EC | 78.26 h | 93 | 38.26 |
| | | | 185 | 20.94 |
| | | | 300 | 16.78 |
| $^{99m}$Tc | IT | 6.02 h | 140 | 88.94 |
| $^{111}$In | EC | 2.83 days | 171 | 90.48 |
| | | | 245 | 94.00 |
| $^{123}$I | EC | 13.2 h | 159 | 82.78 |
| $^{125}$I | EC | 60.14 days | 27 | 74.08 |
| $^{131}$I | $\beta-$ | 8.04 days | 284 | 6.06 |
| | | | 364 | 81.24 |
| | | | 637 | 7.27 |
| $^{137}$Cs[c] | $\beta-$ | 30.0 yr | 662 | 84.93 |
| $^{201}$Tl | EC | 3.044 days | 80 | 10.53 |
| | | | 167 | 10.00 |

[a]EC: electron capture, $\beta+$: positron decay, $\beta-$: negatron decay, IT: internal transition.
[b]Energy and yield of principal photon emissions.
[c]The photon emission is associated with the short-lived daughter nuclide $^{137m}$Ba produced in ~95% of the decays of $^{137}$Cs.

where

$F_k$ = average number of photons of energy $E_k$ emitted per nuclear decay (Bq s)$^{-1}$

$R_{i,j}(E_k)$ = absorbed dose in segment $j$ of finger $i$ per source photon of energy $E_k$ (nGy/photon).

The resultant value of $\dot{D}(i,j)$ has units of nGy s$^{-1}$ Bq$^{-1}$. In implementing Eq. (1) for specific radionuclides, the values of $R_{i,j}(E_k)$ at energy $E_k$ are obtained by cubic spline interpolation of the Monte Carlo calculation data in log-log space.[13]

### II.A. Charged-Particle Equilibrium

As noted in Sec. I, previous studies showed the necessity for absorbed dose calculations (tally *F8 in MCNP) in evaluating the dose to the skin of the hand. Our studies on a realistic geometry (Fig. 1) showed that the discrepancy between the *F8 result and the much faster F6 (fluence-based) tally can be as large as 60%. While this is somehow expected at higher energies, because of the buildup region, what is more surprising is that this discrepancy can be as large at lower energies (~0.1 MeV), where the buildup region is not as large. Further, it was found that for certain situations the F6 tally result underestimates the dose (the *F8 result) in the superficial layer. This is particularly worrisome as the F6 tally is the one customarily used to evaluate the dose in many routine calculations. It also stresses the importance of using the correct *F8 tally in calculating the absorbed dose to the skin.

## III. RESULTS AND DISCUSSION

The magnitude of the absorbed doses to the superficial layers of the fingers depends strongly on the geometry, i.e., the position of the finger (or phalanx of the finger) relative to the photon volumetric source, as well as on the energy of the photons emitted.

The highest dose per source photon is observed for skin areas that are closest to the syringe barrel containing the source of photons, such as the distal phalanx of the little finger in Fig. 1. The dose values for the other phalanges of the right hand in Fig. 1 can be one to two orders of magnitude smaller, for the same radionuclide (i.e., same energy of the emitted photons). This is to be expected because of the law of variation ($1/r^n$ with $n$ between 1 and 2) of the particle fluence with respect to the distance from the source.

The variation with respect to the energy of the emitted photons can also span more than one order of magnitude for the range of energies included in Table I.

As an example, for the right hand in Fig. 1 with a 3-ml syringe filled 25% with the radioactive solution, the absorbed dose can be as high as $1.4 \times 10^{-4}$ nGy/(Bq s)

for the distal phalanx of the little finger and $2.9 \times 10^{-6}$ nGy/(Bq s) for the middle phalanx of the index finger when the emitter is $^{18}$F. These values are $8.7 \times 10^{-6}$ nGy/(Bq s) and $4.8 \times 10^{-8}$ nGy/(Bq s), respectively, for the two phalanges when the radioisotope is $^{99m}$Tc. The statistical errors associated with these values are below 1% for $^{18}$F and below 5% for $^{99m}$Tc, which means that the variation is real, beyond any statistical uncertainty.

The Monte Carlo simulations conducted during the course of this work do not indicate a consistent relationship between the highest skin dose and the dose indicated by the ring dosimeter on the middle finger (the usual location in monitoring). The highest deviation in these readings was observed for geometry 1 (right hand in Fig. 1), where the distal phalanx of the little finger and the tip of the thumb are holding the barrel of the syringe as the cap is placed on its needle. The nuclide-specific dose rate coefficients for the distal phalange exceeded those indicated by the ring dosimeter on the middle finger by factors ranging from 13 to 44. In contrast, for the hand holding the cap, referred to as geometry 2, the skin dose rate exceeded that indicated by the dosimeter by factors ranging from 4 to 8. The skin dose rate exceeded that indicated by the dosimeter by factors ranging from 3 to 5 for the other exposure geometries considered.

The Monte Carlo simulations indicate that the most highly exposed parts of the hands are the tips of the fingers (index and little finger) and the thumb. This is, however, highly dependent on the position of the fingers and thus may be expected to vary with the techniques of individual technicians. Furthermore, it should be noted that we evaluated a limited set of procedures with fixed exposure geometries and did not consider the duration and number of procedures in the course of the technician's daily activities. Nevertheless, with the exception of geometry 1, the values observed in the simulations are in reasonable agreement with those reported in the literature. The extensive study of Wrzesien et al.[5] indicated that the "dose recorded by the ring dosimeter is on the average five times lower than the dose received by the fingertips of the three most highly exposed fingers." Their data further indicated that the doses to the tips of the index fingers exceeded those measured by a ring dosimeter by factors of $6.90 \pm 3.19$ and $5.32 \pm 2.07$ for the left and right hands, respectively.

The definition of the skin dose quantity itself makes the mathematical simulation and calibration of dosimeters difficult. Skin dose is the only radiation protection quantity that is not defined in terms of the energy deposition in a volume or mass. Skin dose is defined as the dose at a depth of 0.007 cm (70 $\mu$m) from the skin surface averaged over a 10-cm$^2$ area.[8] It is extremely difficult to compute this quantity as energy is deposited by events within a volume. Thus, Monte Carlo calculations of skin dose assume a layer of tissue centered on 70-$\mu$m depth. In our simulations this layer extended from the surface to 140 $\mu$m. Such calculations are further complicated by the fact that the number of secondary electrons (formed by photon interactions) entering this layer is different from that of the electrons exiting the layer—so-called charged-particle equilibrium is not achieved. This necessitates simulating the transport of both photons and secondary electrons (coupled photon-electron transport). The demanding nature of the radiation transport calculations needed to compute the skin dose requires that substantial computational hardware be available for this task.

## IV. CONCLUSIONS

Monte Carlo simulations of the dose to the skin of the hands were carried out for a series of geometries and syringes of various sizes and degrees of filling. Dose rate coefficients were tabulated for a selected set of radionuclides used in nuclear medicine, and the tables (many pages of data that will not be reproduced here) thus obtained were inspected to determine systematic trends. This effort is the first study employing detailed models of the hands, syringes, and vials in positions reflecting procedures in handling the radiopharmaceuticals. The simulations indicate that the most highly exposed parts of the hand are the tips of the fingers (index and little finger) and the thumb, and no fixed relationship was observed between the highest skin dose and the dose indicated by a ring dosimeter on the middle finger (the usual placement for monitoring purpose). Furthermore, no alternative placement of the dosimeter that might better serve to monitor the shallow dose equivalent was evident. Considering the range of exposure geometries involved as technicians carry out various tasks, a suitable multiplicative factor needs to be derived that reflects the manner of calibration of the ring dosimeter and other practices within the industry. The most recent study in this area (Wrzesien et al.[5]) recommended that a factor of 5 be applied to derive the average skin dose over the three most highly irradiated fingers and that a factor of 7 be applied for the most highly irradiated finger. Our simulations are consistent with the experimental results obtained lately.

We have demonstrated that mathematical simulations using Monte Carlo methods can be useful in understanding the distribution of the skin dose resulting from the manipulation of radiopharmaceuticals. Furthermore, the results of the simulations were found to be largely consistent with the limited measurements of the distribution of skin doses to the fingers reported in the literature.

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