Enhanced Extremity Dosimetry in Nuclear Medicine through Advanced Monte Carlo Simulations

Francisca Abbey Blay[1,2,ADEG], *Joanna Domienik-Andrzejewska*[1,FH], *Filip Vanhavere*[2,ADFH], *Pasquale Lombardo*[2,A], *Mateusz Mirowski*[1,F]

[1] Nofer Institute of Occupational Medicine (NIOM), 8 Sw. Teresy, Str., 91-348 Łódź, Poland

[2] Belgian Nuclear Research Centre (SCK•CEN), Boeretang 200, BE-2400 Mol, Belgium

Funding: PIANOFORTE project funded from the European Union's "EURATOM" research and innovation programme under the number 101061037 grant agreement.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Abstract

Nuclear medicine is a clinical discipline characterized by the use of radiopharmaceuticals with high activities, resulting in significant occupational exposure to the extremities of personnel involved in the preparation and administration of radionuclides. Current extremity dosimetry methods, based on ring and wrist dosemeters, exhibit limited capability to reliably assessing the equivalent skin dose Hp(0.07). This limitation arises primarily from their energy and angular dependence, as well as the inability to determine the actual location of the maximum dose on the skin surface. Consequently, these methods frequently lead to systematic underestimation of exposure, particularly in situations where the highest doses occur at the fingertips rather than at the standard dosimeter placement sites.

To address these limitations, a prototype extremity dosimetry system has been developed, integrating advanced Monte Carlo simulations, computer vision techniques and artificial intelligence algorithms. The system enables threedimensional tracking of hand movements during radiopharmaceutical preparation and administration, followed by automated reconstruction of the exposure geometry. This approach allows for the generation of spatially resolved Hp(0.07) dose maps that incorporate both the energy and angular distribution of the radiation field. Preliminary results demonstrate the feasibility of identifying highdose regions and determining maximum doses within a 1 cm² area, in accordance with regulatory skin dose limits.

The ongoing project includes the development of highfidelity digital twins of clinical procedures, the integration of Monte Carlo methods with AIbased optimisation, and the validation of the system under real clinical conditions using physical dosemeters. The ultimate objective is to establish a tool capable of providing rapid, individualized extremity dose assessments, thereby supporting radiological protection optimisation, improving clinical practice and enhancing staff training in accordance with the ALARA principle.

Key words: extremity dosimetry, Hp(0.07), nuclear medicine, Monte Carlo simulations, artificial intelligence, computer vision, digital twin, radiation protection, ALARA

Introduction

Nuclear Medicine (NM) is a modality that has been tremendously helpful in the field of medicine. The combination of radioisotopes and biologically active molecules in what is known as radiolabelling, this specialty diagnoses and treat a wide range of diseases from malignant to benign conditions. However, with use of such radionuclides comes serious radiation protection considerations such as adequate exposure monitoring of the staff handling the radionuclides either in the preparation from the hot labs or in the administration to the patients. Even with protective personal equipment (PPE), the hands are in close proximity to a source of radiation typically in the range of a few thousands megabecquerels[1,2], putting them at risk of receiving doses to the skin of their hands that exceeds the recommended limit of 500 mSv per year as some studies have shown. Current

Medicine Physicist & Engineer 1/2026 vol. 1

received: 16.02.2026; corrected: 04.03.2026; accepted: 11.03.2026

Author Contributions:
A – Conceptualization, B – Validation, C – Formal analysis, D – Resources, E – Writing—original draft preparation, F – Writing—review and editing, G – Visualization, H – Supervision.
All authors have read and agreed to the published version of the manuscript.

methods of estimating doses to the extremities based on single point measurements with ring or wrist dosimeter have shown to really underestimate the doses that staff in nuclear medicine departments receive due to the inherent limitations of such traditional passive dosimeters. Prominent amongst them is the energy and angular dependence, and the fact that the position of the maximum dose is not known in advance. In most cases the dosimeter is worn on the base of the finger whereas the fingertip has been shown to receive the highest amount of doses in most cases. The dose estimation might be even more inaccurate when using wrist dosimeter.

Material and Methods

A more comprehensive approach to solve the limitations of conventional extremity dosimeters is the use of advanced computational methods since it has the potential to overcome the limitations of conventional methods. This could be done with the use of advanced Monte Carlo simulations, 3-D camera tracking, computer vision and artificial intelligence (AI). A first prototype of this method of extremity dosimetry using computational methods has been developed with preliminary results already demonstrating the feasibility. The system developed was able to track the hands of a nuclear medicine worker during the preparation and dispensing of a radiopharmaceutical using a 3-D camera. The position of the hands and source are obtained from the video feed, with detection algorithms detecting the hands and source of radiation (syringe). The results are then passed unto an animation software that generates the geometry needed to run Monte Carlo simulations generating 3-D dose maps of the dose distribution to the hands of the worker. This computational system can take into account the energy and the angular distribution of the source and would allow 3-D dose maps to indicate which regions of the hands have hot spots. It can look for the maximum dose in a $1 cm^2$ surface to compare with the dose limits. The goal would be to obtain a similar or even better accuracy than passive dosemeters, which cannot do better than a factor of 2 for such point measurements. It could even be envisaged to go towards real time dose estimations or active dose monitoring. This would help in training nuclear medicine staff and would help implementing the ALARA principle. Some validation exercises were conducted and it showed that there are a still number of limitations present that need improving upon as well as some additions[3,4].

Preliminary Results, Further Work, and System Development

The scope of the current project being undertaken first task will be to develop precise digital twins of clinical procedures, incorporating staff hand movements and source manipulations using advanced computer vision. AI algorithms and MC methods will then be combined to optimize simulation parameters,

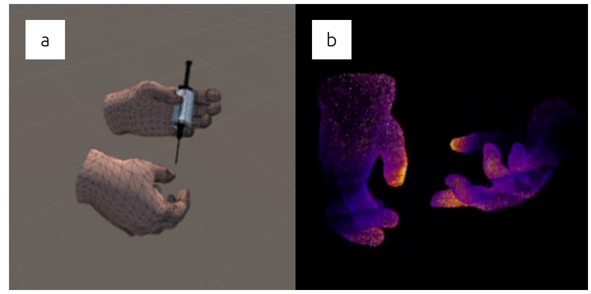

Fig. 1. Preliminary results from prototype developed: a)3D model deformation. b) Dose assessment and visualization from Monte Carlo Simulation[3]

enabling real-time dose estimation with reduced computational demands. Followed by the creation of an AI-driven system to detect radiological spills and contamination using input from environmental radiation monitors. Then finally, rigorous benchmarking will be conducted through MC simulations of realistic clinical scenarios, and validation of the methodologies against measurements from physical dosimeters during actual clinical practices for a range of radionuclides used in NM.

Conclusions

The end goal is to provide rapid, individualized extremity and skin dose estimates for nuclear medicine staff, improving dosimetry accuracy and providing an additional functionality for optimisation and training. In conclusion, with the current limitations of traditional dosimetry methods and the new possibilities offered by the methods integrating Monte Carlo simulations, artificial intelligence and computer vision technologies, the fusion of both passive with computational approaches is our best bet to improving extremity dosimetry in nuclear medicine.

Acknowledgements

The authors are thankful to the European Partnership for Radiation Protection Research (PIANOFORTE) and the Nofer Institute of Occupational Medicine (NIOM) for providing funding for this project.

References

1. Vanhavere F, Berus D, Buls N, Covens P. The use of extremity dosemeters in a hospital environment. *Radiation Protection Dosimetry*. 2006;118(2):190-195. doi:10.1093/rpd/ncl017
2. Vanhavere F, Carinou E, Donadille L, et al. An overview on extremity dosimetry in medical applications. *Radiat Prot Dosimetry*. 2008;129(1-3):350-355. doi:10.1093/rpd/ncn149
3. Rondón DS, Lombardo P, Abdelrahman M, Struelens L, Vanhavere F, Bergans N. Object and person tracking systems to enable extremity dosimetry in nuclear medicine using computational methods. *J Radiol Prot*. 2024;44(2):021524. doi:10.1088/1361-6498/ad53d5
4. Santiago Rondón D, Lombardo P, Abdelrahman M, et al. Computational system for extremity dosimetry in nuclear medicine. *J Radiol Prot*. 2025;45(4):041502. doi:10.1088/1361-6498/ae0a5b