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Pakistan Journal of Nuclear Medicine is the official journal of Pakistan Society of Nuclear Medicine

Comparison of dosimetric methods in nuclear medicine

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ABSTRACT

Historically, dosimetry has been conducted with varying degrees of sophistication. A broad and general approach involves computing organ-specific time-integrated activity multiplied by S-factors, as defined by the Medical Internal Radiation Dose (MIRD) Committee. This method uses a standard human body phantom as a reference for mass density distribution. More advanced methods, such as the voxel dose approach, estimate absorbed dose by linearly superimposing contributions from each voxel in the spatial activity distribution, treating each voxel as a radiation point source. The energy dose from a radiation point source with isotropic unit activity in an infinite homogeneous medium is known as a dose point kernel (DPK). Previously, DPKs were calculated using Monte Carlo techniques for tissues like bone, lung, soft tissue, and water, primarily for isotopes such as Iodine-131 and Yttrium-90. Later, continuous DPKs were discretized into DVKs that can be arbitrarily scaled. The absorbed dose distribution is then derived by convolving the time-integrated spatial activity distribution with the Monte Carlo-based DVK, based on the patient's anatomy. Due to the computational expense of this process, various methods have been explored to estimate approximate DVKs. The highest level of sophistication is achieved with full Monte Carlo simulations of radiation transport inside the patient's body, providing reference results for benchmarking other approaches. The network is trained with DVKs obtained from dedicated Monte Carlo simulations using equally sized kernels of specified tissue density and a specified radioisotope. This method is intermediate between the canonical MIRD protocol and deep neural network approaches that predict whole-body absorbed dose distributions from individual mass density and activity distributions. In this paper, we have discussed and compared all the commonly employed dosimetric methods along with new approaches using artificial intelligence.

Keywords: Dose voxel kernels, organ-specific time-integrated activity, Medical Internal Radiation Dose.

Received: 02 July 2024

Accepted: 25 July 2024

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Introduction

Personalized medicine holds great promise for improving healthcare outcomes and potentially reducing costs. This approach aims to move away from a generic "one-size-fits-all" strategy and tailor treatments to individual patients [1]. In the field of nuclear medicine, where managing radiation dose is crucial, personalized dose estimation plays a vital role. It allows for the optimization of treatment procedures while minimizing the risk of radiation-induced side effects. This integration of personalized medicine and precise dose calculation highlights the significant potential for nuclear medicine to contribute to this evolving healthcare paradigm [2].

Traditional dosimetry methods

Currently, most nuclear medicine practices rely on simplified models to estimate the radiation dose patients receive during treatment. One widely used system is the

Medical Internal Radiation Dose (MIRD) methodology. The MIRD system treats the body as a collection of organs and averages the radiation dose across each entire organ. While this approach provides a structured framework, it does not account for individual variations in body size and shape, which can lead to inaccurate dose estimations [3].

The MIRD schema defines source organs as those containing the administered radiopharmaceutical (such as I-131) and target organs as those receiving radiation exposure. It provides pre-calculated values representing the fraction of energy emitted by a source organ that is absorbed by a specific target organ per unit of activity in the source organ. Despite its widespread acceptance and utility, the MIRD approach relies on standardized models for organ uptake and clearance, which may not always reflect individual patient variations. Consequently, this can result in inaccuracies in dose estimations, particularly for complex anatomical structures.

Voxel-based dosimetry: a more advanced approach

Voxel-based dosimetry offers a more advanced and detailed approach compared to traditional simplified models like MIRD. This method leverages the power of 3D imaging and computational modeling, dividing the body into tiny volumetric elements called voxels. Each voxel represents a small volume of tissue, allowing for the calculation of the radiation dose absorbed in each voxel. This voxel-based approach provides a more detailed and accurate picture of dose distribution within the body, reflecting individual anatomical and physiological characteristics.

To implement voxel-based dosimetry, a CT scan of the patient is obtained to provide detailed anatomical information about the thyroid and surrounding structures. Nuclear medicine imaging techniques, such as SPECT or PET, are then used to measure the distribution of radiopharmaceuticals like I-131 within the patient's body. This information is used to determine the activity concentration in each voxel of the thyroid gland. Based on simulated interactions and known energy deposition patterns of I-131, the program calculates the absorbed dose in each voxel, resulting in a 3D map of the radiation dose distribution within the entire body, including the thyroid gland and surrounding organs [4].

Benefits of voxel-based dosimetry

By considering the radiation dose absorbed in each small volume of tissue, voxel-based dosimetry offers a highly detailed and accurate assessment of dose distribution. This precision is crucial for tailoring treatments to the specific needs of each patient, potentially improving therapeutic outcomes and reducing side effects.

Voxel-based dosimetry supports the development of personalized treatment plans by accounting for individual variations in body size, shape, and tissue composition. This approach aligns with the broader goals of personalized medicine, which aims to provide treatments specifically suited to each patient's unique characteristics [5].

The ability to generate detailed 3D dose maps allows for the optimization of radiation therapy by identifying areas that receive higher or lower doses than intended. This information can be used to adjust treatment protocols, ensuring that target tissues receive the optimal dose while minimizing exposure to surrounding healthy tissues.

Voxel-based dosimetry allows for a thorough analysis of dose distribution within complex anatomical structures. This capability is particularly important for organs with heterogeneous tissue composition, such as the thyroid gland, where accurate dosimetry is crucial for effective treatment [6].

Deep neural networks in thyroid dosimetry: emerging potential

The field of thyroid dosimetry is constantly evolving, and deep neural networks (DNNs) are emerging as a

promising tool with the potential to revolutionize how we estimate radiation dose distribution. Here is a look at the potential role of DNNs in this domain:

DNNs are a type of artificial intelligence that mimics the structure and function of the human brain. They consist of interconnected layers of artificial neurons, progressively extracting complex patterns from large datasets. In the context of thyroid dosimetry, DNNs could be trained on data containing: CT scans for anatomical information and nuclear medicine images (SPECT/PET) showing I-131 distribution within the body [7]. Existing data from MIRD-based calculations or voxel-based dosimetry for absorbed dose estimations in the thyroid and other organs. DNNs could analyze patient-specific data (imaging, clinical history) and predict the absorbed dose distribution with greater accuracy than traditional methods, accounting for individual variations in anatomy and I-131 biodistribution. By learning from vast datasets of patient information, DNNs may help refine biokinetic models used in MIRD-based dosimetry, leading to more accurate estimations of residence times and ultimately, absorbed dose [8]. For voxel-based dosimetry, DNNs could potentially act as a surrogate for complex Monte Carlo simulations, significantly reducing the computational time required for dose calculations. DNNs could be integrated into treatment planning software, allowing for real-time adjustments to the I-131 activity based on predicted dose distribution and potential side effects.

Challenges and Future Directions

Despite its advantages, voxel-based dosimetry involves complex calculations, often requiring Monte Carlo (MC) simulations. While MC simulations are highly accurate and considered the gold standard for research applications, they are computationally expensive and time-consuming, making them impractical for routine clinical use. Researchers are exploring ways to bridge the gap between accuracy and efficiency, such as using tissue-specific dose point kernels, which offer a compromise by considering different tissue types for more realistic dose estimation with less computational power (6).

Advancements in computing power and software development are expected to streamline the workflow and enhance the efficiency of voxel-based dosimetry. Additionally, as theranostic agents (agents used for both diagnosis and therapy) gain traction, voxel-based dosimetry can be integrated into the treatment planning process for these agents. Machine learning algorithms also hold promise for further refining voxel-based dosimetry by analyzing large datasets of patient information and improving the accuracy of dose predictions.

Furthermore, Training DNNs requires large and high-quality datasets containing patient imaging, dosimetry data, and potential clinical outcomes. Access to such data and maintaining patient privacy are crucial

considerations. Rigorous validation is essential to ensure the accuracy and generalizability of DNN predictions. This involves testing the model on data not used for training and ensuring its performance remains reliable across diverse patient populations. Understanding how DNNs arrive at their predictions is crucial for building trust in their clinical application. Techniques for explaining the reasoning behind DNN outputs are needed for safe and effective implementation [5].

Tailoring DNN architectures specifically for thyroid dosimetry tasks can potentially enhance their performance and accuracy. DNNs could be employed to complement existing methods like MIRD or voxel-based dosimetry, leveraging their strengths while addressing limitations. Rigorous clinical trials are necessary to demonstrate the effectiveness and safety of DNN-based approaches in thyroid dosimetry before widespread clinical adoption.

Deep neural networks hold immense potential for revolutionizing thyroid dosimetry. Their ability to learn complex relationships from data offers opportunities for personalized dose predictions, improved biokinetic modeling, and streamlined treatment planning. However, addressing data availability, model validation, and explainability remains crucial for ensuring the safe and effective integration of DNNs into clinical practice. As research progresses, DNNs have the potential to become a powerful tool for optimizing patient outcomes and enhancing the safety and effectiveness of I-131 therapy for thyroid disorders [6].

Conclusion

Personalized medicine represents a transformative shift in healthcare, aiming to tailor treatments to individual patients to improve outcomes and reduce costs. In nuclear medicine, personalized dose estimation is critical for optimizing treatment procedures and minimizing radiation-induced side effects. Voxel-based dosimetry offers a more advanced and precise approach compared to traditional methods, providing detailed 3D dose maps that reflect individual patient anatomy and variations in radiopharmaceutical distribution.

While challenges remain, ongoing advancements in computational techniques and the integration of machine learning are poised to enhance the accuracy and efficiency of voxel-based dosimetry. This evolving approach underscores the significant potential for nuclear medicine to contribute to personalized healthcare, ultimately leading to better patient outcomes and more effective treatments.

Conflicts of interest

The authors declare that they have no conflict of interest regarding the publication of this article.

Funding

None.

Informed Consent

Not applicable.

Ethical approval

Ethical approval is not required at our institution to publish an anonymous case report.

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