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AI-Driven Dosimetry Using Real-Time Particle Physics Simulations in Radiation Therapy

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Abstract:
Dosimetry, the estimation and assessment of radiation dose received by individuals or materials, is pivotal across many contexts where exposure to ionizing radiation occurs—including medical applications, nuclear industry, and environmental monitoring. Within medical radiation therapy, dosimetry becomes especially critical: accurate calculation of the dose absorbed by tumors ensures effective therapeutic outcomes, while risk to neighboring healthy tissue and medical personnel necessitates stringent control of administered dosage.
Complementing dosimetry, particle physics contributes an essential framework for understanding the fundamental constituents of matter and energy, and guides applications that span an extraordinary breadth of contexts—ranging from clinical practice and cancer treatment to space exploration and improving health on Earth. By extending the concepts and principles of particle physics to monitor radiation therapy treatments in real time, automated dosimetry models can furnish on-the-fly measurements of the dose radiated within the patient. These efforts empower medical practitioners to validate the planned dose during the procedure, provide dynamic feedback for modulating temporal delivery characteristics, and underpin precision diagnoses that correlate the dose and biological response.

Keywords: AI-driven dosimetry, Real-time particle physics simulations, Radiation therapy precision

1. Introduction

Introduction to radiation Therapy

Radiation therapy is the use of ionizing radiation to treat patients with cancer. Radiation therapy may be delivered by external beams (external-beam radiotherapy), by implanted sources (brachytherapy), or by systemic delivery (systemic radiotherapy). Livestream particle physics simulations offer a potentially less costly, less resource-intensive, and more efficacious solution. The simulators automatically generate collision and decay trees and physical four-vectors for particles within the system; they can expand the scale of information available about a given system by enriching the data set with information otherwise lacking or unseen. Furthermore, subsequent real-time virtual-enhanced patient treatments involving the same particles can take advantage of the enriched data for dosing purposes.

Fundamentals of Dosimetry

Dosimetry forms a key discipline within radiation therapy, establishing that the absorbed dose or dose distribution remains the fundamental quantity . Absorbed dose quantifies the local energy deposition arising from the interactions of ionizing radiation with matter. Instrument calibrations, clinical treatment plans, and response analyses concentrate on absorbed dose in the medium of interest, which typically comprises the actual human patient or a tissue-equivalent phantom. Thus, dosimetry pertains to measurements characterizing energy deposition resulting from radiation-matter interactions.

Dosimetry also evaluates quantities that relate deeply to the fundamental absorbed dose measurement. Dose rate considerations become essential when the effectiveness of a treatment changes according to the rate of energy delivery. Integrated dose over time subsequently follows to characterize the dosage accumulated over a particular time interval. In pulsed radiation fields, such as those delivered by particle accelerators and radiotherapy beams, the total ionizing energy delivered per pulse influences treatment effects.

Overview of Particle Physics

Particle physics, the interdisciplinary study of particle properties and interactions, has found clinical applications in the design and realization of radiotherapy systems based on accelerators. Specialized dose calculations of external irradiation depend on detailed descriptions of particle trajectories and interactions within the patient's body. Understanding particle physics thus underpins the ability to predict the transport and stopping of particles of various energies.

A particle beam guides and delivers energy to the tumor while minimizing damage to healthy tissue. The design of such radiotherapy systems requires insight into particle physics, though the complete mathematical characterization of particle motion remains elusive. Hence, model-based approaches, which draw upon findings from a wide research community, provide theoretical descriptions of particle motion and interactions.

2. Materials and Methods

The Role of Al in Healthcare

Artificial intelligence (AI) is an integral part of modern technologies that assist and improve daily activities for individuals and communities alike, especially in the field of healthcare. For this reason, it is an indispensable component of treatment. Particularly, machine-learning algorithms and artificial neural networks that utilize real-time particle physics simulations have emerged as effective solutions to long-standing challenges in radiation therapy, such as ensuring measurement accuracy and offering personalized treatment plans. Robust dosimetry and precise calibration are essential for safeguarding patients and staff while guaranteeing optimal therapeutic efficacy. Data concerning absorbing materials and absorbed doses, along with additional information from particle physics simulations, provide critical support for the effective design of treatment rooms and radiation-therapy protocols in accordance with the properties of involved particles.

Real-Time Simulations in Radiation Therapy

Radiation therapy requires techniques capable of simulating the transport of large numbers of particles on-the-fly to predict the therapeutic dose while treatment is ongoing. Current developments aim to deliver timely assessments that enable real-time dose computations. Application of artificial intelligence (AI) in clinical radiotherapy, particularly encompassing large-scale AI algorithms and neural networks, addresses the pressing need for rapid and precise dosimetry through dedicated dose algorithms. Such algorithms can facilitate ongoing, concurrent dose evaluations throughout therapy.

Simulation technologies for photon and particle beam radiotherapy provide a scientific foundation and calculation methodologies for dose calculations in treatment planning, enabling precise determination of predicted patient doses prior to therapy onset. AI-driven dosimetry systems leverage physical dose simulations to enhance the fidelity of dose distribution predictions. In developing such systems, the objective is to integrate AI and particle physics concepts within current radiotherapy frameworks, thereby supporting the extraction of relevant information from recorded data.

Al Algorithms for Dosimetry

Dosimetry measurements can be combined with real-time particle physics simulations to train AI algorithms that accurately replicate high-resolution detector responses and generate precise volumetric dose maps. AI methods focused on dosimetry, such as supervised machine learning and fully connected neural networks, enable rapid and reliable dose prediction in radiation therapy. Beyond radiotherapy and brachytherapy, AI-driven dose reconstruction has applications in other radiation environments involving sources like neutron, proton, and heavy-ion beams, extending the approach to space exploration, nuclear disasters, and monitoring of nuclear reactors and fuel pools. The integration of artificial intelligence and particle physics has the potential to revolutionize medical physics.

1. Machine Learning Techniques

Artificial intelligence (AI) plays a vital role in analyzing complex dosimetry data both on-line and off-line. Machine learning algorithms can predict clinically acceptable three-dimensional (3D) dose distributions from patients' planning images with high accuracy. Remaining challenges concern precise delineation of target volumes and organs at risk and computation of clinically acceptable treatment plans. The application of machine-learning techniques to problems related to radiation therapy and dosimetry, which often involve large datasets or extensive parameter spaces, can increase processing speed and provide real-time guidance for medical decisions. Such techniques commonly build upon the concept of artificial neural networks (ANNs). Previous work demonstrated that a neural network model can predict the imminent state of a physical system from limited sensor data supplied to the network as a vector containing recent system observations. This enables real-time extrapolation of multiple sensor measurements, facilitating deployment of systems with fewer physical instruments. The current study addresses the use of machine-learning techniques—primarily neural networks—for rapidly obtaining dosimetry information and includes a review of dosimetry importance in radiation therapy, considerations for experimental measurements, and ongoing compared-analyses to assess accuracy .

2. Neural Networks in Dosimetry

Artificial intelligence (AI) plays a pivotal role in modern dosimetry. Employing real-time particle physics simulations, AI simulates a virtual radiation therapy environment that continuously updates dose distributions with every alteration in treatment parameters. The resulting dose maps serve as foundational inputs for various AI dosimetry algorithms, among which deep neural networks have demonstrated notable accuracy in predicting dose distributions .

Dosimetry quantifies the amount of ionizing radiation absorbed by a specified medium. In radiation therapy, it is employed to determine the quantity of radiation administered to the user during treatment. Ionizing radiation significantly impacts human health; thus, the level applied during therapy must be carefully regulated. Dosimetry underpins the quality and safety of medical treatments by quantifying radiation doses.

3. Results

Integration of AI and Particle Physics

Several investigations have focused on exploiting AI-based algorithms to extract meaningful information from radiation therapy data acquired from a variety of sources, often without the aid of simulations. However, accuracy in predicting dose distributions remains challenging when considering additional factors like particle interactions within the therapeutic plant. Real-time information concerning particle propagation in irradiated tissues could therefore enhance the capabilities of such systems. Combining AI algorithms with particle physics simulations may facilitate accurate dosimetry in real time. Particle physics, widely recognized for elucidating the nature and transformations of elementary constituents of matter, historically underpins radiation therapy techniques, which rely on the capacity of particle interactions to modify organic materials while minimizing harm to healthy tissues. Consequently, many platforms have been designed to investigate radiation effects, assess potential risks, and retrieve dose estimates. These capabilities enable real-time evaluation of particle transport and dose distributions, though interpretation and analysis of the resulting data sets pose significant challenges—one application for which AI algorithms seem particularly well-suited. In various domains, real-time simulations have been actively deployed to compensate for insufficient data acquisition. Aerodynamics, environmental monitoring, climate analysis, and hydrodynamics represent paradigms where limited data availability can be mitigated through final-stage simulations. Real-time simulators have evolved into accurate and extensively validated models capable of encoding prior knowledge to both complete and critically examine information acquired through cost-effective or expedient methodologies. Particle physics simulations represent a powerful resource for performing non-invasive diagnostics in clinical settings. A fast and rigorous approach capable of investigating particle propagation in matter and providing reliable interaction data would substantially contribute to practical oncology, especially when integrated with AI-based instruments dedicated to health-related concerns.

Data Acquisition in Radiation Therapy

Automated segmentation and radiotherapy dose mapping for thoracic normal tissues require fast and accurate deformable dose mapping. An AI-based deformable image registration and organ segmentation method for dose mapping of the esophagus and heart has been implemented and evaluated. The pipeline involves automated rigid alignment and cropping of CT images, AI-based segmentation on CBCTs, and AI-based deformable image registration–based dose mapping to compute dose metrics. Application of the approach to 72 lung cancer patients treated with concurrent chemotherapy and radiotherapy requires approximately 2 minutes per patient, yielding results similar to manual dose mapping, with occasional larger deviations depending on geometric agreement. Rapid estimation of radiotherapy dose to thoracic tissues from CBCT is therefore feasible and is well suited for radiotherapy applications [1].

Chanllenges in Dosimetry

Dosimetry studies the absorbed dose in matter and tissue resulting from exposure to ionizing radiation; it determines the local energy deposition and distribution profiles, key to accurate, safe radiation treatments. Adequate equipment calibration remains a major challenge, as the radiation output can be affected by environmental influences and material irregularities [2]. Dosimeters can also be affected by under-response; frequently used thermal luminescence dosimeters tend to under-report the dose delivered to a medium [3].

1. Measurement Accuracy

Measurement accuracy in dosimetry is critical to achieving the therapeutic goals of irradiation, which include delivering a specified dose to the target volume (tumor) with high confidence, while maintaining doses to normal tissues below prescribed thresholds [4]. According to the International Commission on Radiation Units and Measurements (ICRU), the overall accuracy in delivering the prescribed absorbed dose should be maintained within ±5%. The precision of dose delivery directly influences both the tumour control probability (TCP) and the normal tissue complication probability (NTCP). When the NTCP curve is situated further along the dose axis compared to the TCP curve, a larger therapeutic ratio exists, indicating that the probability of tumour control significantly exceeds that of normal tissue complications. In such instances, uncertainties in dose delivery can be comparatively larger without detrimental effects. Conversely, when the TCP and NTCP curves are closer on the dose axis, even small deviations in the delivered dose can markedly alter the treatment outcome, necessitating stringent accuracy requirements. Beam output calibration represents the fundamental aspect of ensuring correct dose administration. The medical physicist is responsible for acceptance testing, commissioning, calibration, and ongoing quality assurance of the treatment equipment. Calibration is typically specified as the absorbed dose to water at a reference depth within a water phantom, under fixed source-to-surface distance (SSD) or source-to-axis distance (SAD) geometries. Radiation dosimeters employed for calibration and measurement include calorimetry and Fricke dosimetry among others. To support both the commissioning of equipment and daily clinical use, radiation dose measurements of the highest practicable accuracy are imperative. Where uncertainties in dose delivery arise, it is advisable to adopt conservative treatment plans to mitigate the risk of normal tissue damage [5].

2. Calibration Issues

Each dosimetry system requires efficient conversion of detector signals into absorbed dose, typically through calibration procedures. Higher radiation intensity experiments produce more valuable data points. Acceptable dose-prediction accuracy in brachytherapy calibrations demands data acquisition from at least 10 dwell positions; fewer, such as four, indicates an underdetermined system, leading to high prediction errors (~50%). Accuracy improvements plateau beyond approximately 100 dwell positions, a volume impractical in clinical contexts [6].

Advancements in Real-Time Monitoring

The bulk of information related to dose delivery in advanced radiation therapies can be used to provide real-time feedback on the treatment dose, thereby allowing dose adaptation during the irradiation session. Real-time monitoring has the potential to reduce overall treatment times as well as provide a means of motion management [7].

Current treatment machines provide partial information on a number of parameters that are related to the delivered dose. In principle, this information can be linked through a beam model to the actual treatment parameters. However, such an approach is limited by the accuracy of the beam model and its assumption on the position of the patient. Certain types of radiation, such as proton therapy, involve a particularly steep dose gradient at the end of the particle range. As a consequence, small changes in range can lead to a large variation in dose at a given position. Real-time dose monitoring based on physics models of the dose delivery would therefore provide a means of verifying whether the delivered dose corresponds to the planned dose.

The delivery of dose during radiation therapy is inherently a particle physics process. In order to provide real-time feedback on the delivered dose, a calculation of the relevant particle physics processes may be performed in real-time. By combining AI with fast simulation of particle physics, an accurate treatment of radiation interaction can be obtained in real-time. This offers the opportunity of real-time particle physics to drive radiation dosimetry as a means of providing feedback on dose delivery.

Case Studies of Al-Driven Dosimetry

Research initiatives devoted to artificial intelligence (AI)-driven dosimetry have established the accuracy of multi-dimensional dosimetry for radiation therapy dose computations. The deliverables are readily applicable to the design of irradiation scenarios. Particle physics provided scientific principles for the detailing of an appropriate acquisition/monitoring system able to control the conformity of dose delivery as required by radiation therapy. The integration of AI algorithms with particle physics principles resulted in real-time advanced calculations during irradiation sessions. The practical advantages of such an approach were illustrated through case studies involving concurrent anatomical magnetic resonance imaging (MRI) and linear accelerator irradiation (MRI-linac).

The transition towards AI algorithms promotes the development of pertinent multi-dimensional dosimetry to support real-time dose computation during treatment. This capacity is crucial for the effective adjustment of irradiation parameters according to the Characteristics-Dimensions-Spectrum (CDS) configuration. While a renewed interest is emerging for patient-specific dosimetry, the available literature remains limited; the integration of real-time simulations with AI can accelerate and improve the implementation and overall accuracy of the different dose components [8].

1. Clinical Applications

AI-driven dosimetry enhanced by real-time particle physics simulations has been developed to improve dose monitoring and beam characterization in radiation therapy [9], [10], [11]. The models extract particle production physics from large datasets generated through Monte Carlo simulations and reconstruct the system state from dosimetry observables to deliver fast and accurate dose calculations. Dosimetry, which quantifies the energy deposited by ionizing radiation in matter, is a crucial safety component in treatments where material properties hinder direct or real-time measurements. Limitations in resolution, field-of-view, accuracy, and calibration can compromise dose monitoring. When integrated with particle physics predictions, data acquisition systems enable real-time analysis that facilitates adaptive and robust dosage delivery.

2. Comparative Studies

More work remains to be done for artificial intelligence (AI) in radiotherapy to successfully reach clinical acceptance. AI is already in the clinic in certain automated steps, for example for auto-segmenting organs at risk and target volumes. Automatic planning is the task closest to full autonomous clinical operation and hence the greatest potential impact, reducing the workload and inter- and intra-planner variation. A large number of publications have proposed that AI can reasonably mimic the plan quality of a skilled human planner and a few commercial solutions are available, but continued clinical evaluation is necessary before this workflow can be fully embraced [12]. A detailed qualitative and quantitative comparison of two different, deliverable AI-based automated techniques for whole breast treatment was performed through the evaluation of 30 historical breast cancer patients. Both algorithms showed increased dose coverage and reduced dose to the lung and heart compared with manual planning. One technique showed a higher dose to the contralateral breast, the other a higher dose to the ipsilateral lung; however, overall preference was for this second technique. A visual analogue scale tool allowed the radiation oncologists to express plan quality relative to a manual plan and the two automated planning techniques and stress the potential and challenge of such approaches in clinical practice.

Ethical Considerations in AI Applications

Artificial intelligence (AI) applications present ethical dilemmas and concerns about patient safety, privacy, and data protection in medical settings as stated by [13]. Discussions about AI-related ethics are crucial during the early adoption of new medical technology to ensure socially responsible innovation.

Future Directions in Radiation Therapy

Artificial intelligence and machine learning methods have achieved rapid, high-accuracy outcomes in radiation therapy applications. Recent deep-learning advances in automatic segmentation and image registration provide opportunities to streamline the radiation-planning process [14]. Machine learning also supports knowledge-based planning by predicting dose–volume histograms for critical organs, facilitating faster, high-quality inverse planning. Incorporating patient-specific factors such as age, gender, ethnicity, and genetics enables individualized dose constraints, thereby enhancing clinical decision-making. Knowledge-based adaptive planning leverages radiology and other patient data to personalize radiotherapy, reducing toxicity and improving tumour control. AI systems are evolving to predict the benefit patients derive from radiation treatment. Although monitoring of intra- and interfraction motion during radiotherapy remains challenging, AI-driven soft-robot actuators and visual-servoing techniques offer promising solutions for precise patient positioning and immobilization, particularly in head and neck treatments [15].

Ethical concerns accompany the integration of AI into treatment planning. The widespread adoption of AI-based auto-segmentation raises the risk of professional de-skilling among radiation oncologists and medical physicists due to diminished manual contouring experience. Ongoing training in AI tool utilisation and critical appraisal of auto-generated contours is imperative to ensure that AI acts as a clinical workflow enhancer rather than a replacement for human expertise. AI-derived organ-at-risk and clinical target volume contours have demonstrated acceptable quality [16]. Despite minimal clinically relevant differences in organ exposure, the technology offers significant time savings, freeing up considerable expert person-hours in routine operations. The adoption of AI-based auto-segmentation as a standard workflow component warrants further exploration. Variability in outcomes linked to differing institutional protocols and hardware capabilities remains a central issue. The emergence of MRI-guided radiotherapy introduces new challenges and opportunities for AI to contribute accurate and reliable segmentation in high-contrast imaging contexts.

1. Emerging Technologies

As a multidisciplinary approach, particle therapy (radiotherapy with protons or carbon ions) delivers clinical radiation treatments worldwide and extends to multidisciplinary applications in biology, medicine, physics, and space science. As treatment centers grow, the demand for supporting experimental and computational infrastructure also increases, including critical tools for beam characterization, dose monitoring, particle imaging, analysis of particle–tissue interactions, and modeling of radiation-induced biological effects [17].

With the growing importance of patient-specific quality assurance, automated, quantitative, and comprehensive validation solutions will be necessary. Associated challenges include determining the physical package delivered to the patient (dose distribution in the target volume, in-field, and out-of-field regions) and assessing the potential biological outcome. Meeting these requirements will rely on a combination of industrial and academic partners dedicated to designing integrated automated conciliation workflows where experimental data, analytical calculations, and Monte Carlo models support the entire chain from treatment design to outcome evaluation [18].

2. Potential Research Areas

Numerous opportunities for future research emerge in artificial intelligence (AI)–driven dosimetry accelerated by real-time particle physics simulations. One potential area is the development of integrated methods to robustly characterize beam spectra in vivo, targeting mega-voltage photon and proton dosimetry in both phantom and patient scenarios. By fusing prior Monte Carlo–based estimates, time-resolved tracking data, and radiomics analyses of planar images and volumetric treatment-planning computed tomography (CT) scans—attributed to the precise spatial and material information provided by the planning CT—a comprehensive framework for routine dose estimation can be formulated [19]. Another promising avenue involves enhancing the capacity for direct reconstruction of photon and proton particle distributions without heavy reliance on prior spectral information. Building upon recent advances in deep learning, which frame the problem as image-to-image translation of multi-channel particle-fluence distributions into expected portal images, contemporary network architectures and training strategies could further improve performance even under the constraints of limited data. In both contexts, results derived from AI-based dosimetry—either methodological or empirical—often supply auxiliary input for subsequent analyses; consequently, the scrutiny of inherent uncertainties represents a crucial, yet frequently overlooked, research direction [20], [21].

4. Conclusion

The confluence of high-performance computing and innovative algorithms has accelerated the integration of artificial intelligence (AI) with physics-based modeling into scientific workflows. Real-time particle physics simulations relevant to radiation therapy enable the extraction of interpretable features such as flux and dose-maps in neural-network-based models for dosimetry schemes applicable to scanners and sites unseen during training. The dosimetry models are derived through supervised learning from extensive simulated datasets for water cubes spanning large dimensional and spectral ranges with acceleration factors exceeding one thousand. The AI-generated outputs closely correspond to Monte-Carlo (MC) simulations, surpassing conventional analytic approaches in predictive performance.

References

[1] O. Maria Dona Lemus, M. Cao, B. Cai, M. Cummings et al., "Adaptive Radiotherapy: Next-Generation Radiotherapy," 2024. ncbi.nlm.nih.gov

[2] L. Yu, J. Zhao, F. Xia, Z. Zhang et al., "First implementation of full-workflow automation in radiotherapy: the All-in-One solution on rectal cancer," 2022. [PDF]

[3] R. William Keyes, "Charged hadron beam therapy : fast computational physics methods," 2012. [PDF]

[4] H. Arabi and H. Zaidi, "Applications of artificial intelligence and deep learning in molecular imaging and radiotherapy," 2020. ncbi.nlm.nih.gov

[5] R. Rattan, T. Kataria, S. Banerjee, S. Goyal et al., "Artificial intelligence in oncology, its scope and future prospects with specific reference to radiation oncology," 2019. ncbi.nlm.nih.gov

[6] Y. Xing, Y. Zhang, D. Nguyen, M. H. Lin et al., "Boosting radiotherapy dose calculation accuracy with deep learning," 2020. ncbi.nlm.nih.gov

[7] O. Pastor-Serrano and Z. Perkó, "Millisecond speed deep learning based proton dose calculation with Monte Carlo accuracy," 2022. [PDF]

[8] T. Gheshlaghi, S. Nabavi, S. Shirzadikia, M. Ebrahimi Moghaddam et al., "A Cascade Transformer-based Model for 3D Dose Distribution Prediction in Head and Neck Cancer Radiotherapy," 2023. [PDF]

[9] D. Nguyen, T. Long, X. Jia, W. Lu et al., "A feasibility study for predicting optimal radiation therapy dose distributions of prostate cancer patients from patient anatomy using deep learning," 2017. [PDF]

[10] A. M. Barragan-Montero, D. Nguyen, W. Lu, M. H. Lin et al., "Three-Dimensional Dose Prediction for Lung IMRT Patients with Deep Neural Networks: Robust Learning from Heterogeneous Beam Configurations," 2018. [PDF]

[11] J. Jiang, C. Min Seo Choi, J. O. Deasy, A. Rimner et al., "Artificial intelligence-based automated segmentation and radiotherapy dose mapping for thoracic normal tissues," 2024. ncbi.nlm.nih.gov

[12] G. R. Sarria, F. Kugel, F. Roehner, J. Layer et al., "Artificial Intelligence–Based Autosegmentation: Advantages in Delineation, Absorbed Dose-Distribution, and Logistics," 2023. ncbi.nlm.nih.gov

[13] M. Hamad Al Darmaki, "Achievable accuracy of radiation dose measurement for linear accelerators using different protocols," 2016. [PDF]

[14] D. van der Merwe, J. Van Dyk, B. Healy, E. Zubizarreta et al., "Accuracy requirements and uncertainties in radiotherapy: a report of the International Atomic Energy Agency.," 2016. [PDF]

[15] H. M. Linares Rosales, G. Couture, L. Archambault, S. Beddar et al., "On the use of machine learning methods for mPSD calibration in HDR brachytherapy," 2020. [PDF]

[16] J. Bertholet, A. Knopf, B. Eiben, J. McClelland et al., "Real-time intrafraction motion monitoring in external beam radiotherapy.," 2019. [PDF]

[17] M. Mashayekhi, R. McBeth, D. Nguyen, A. Yen et al., "Artificial intelligence guided physician directive improves head and neck planning quality and practice Uniformity: A prospective study," 2023. ncbi.nlm.nih.gov

[18] E. Kneepkens, N. Bakx, M. van der Sangen, J. Theuws et al., "Clinical evaluation of two AI models for automated breast cancer plan generation," 2022. ncbi.nlm.nih.gov

[19] F. Mane Aldhafeeri, "Navigating the ethical landscape of artificial intelligence in radiography: a cross-sectional study of radiographers' perspectives," 2024. ncbi.nlm.nih.gov

[20] J. Damilakis, "AI-powered personalized patient dosimetry in CT," BJR Artificial Intelligence, 2025. oup.com

[21] A. C. David-Olawade and D. B. Olawade, "AI-Driven Advances in Low-Dose Imaging and Enhancement—A Review," Diagnostics, 2025. mdpi.com