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Radiation Dosimetry: Methods for Measurement and Dose Assessment in Healthcare

[1]Bablu Malhotra, [2]Dr. Owais Zargar, [3]Dr. Ayat Albina, [4]Dr. Nashrah Ashraf
[1]Student, [2,4]Assistant Professor, [3]Senior Resident,
[2]Department of Surgery, [3]Department of Gynecology & Obstetrics,
[4]Department of Anesthesia,
[2,3,4]ASCOMS Jammu.
[1]Department of Biotechnology, NIMS UNIVERSITY, Jaipur,Rajasthan.

***Corresponding Author:**
Bablu Malhotra
Student, Department of Biotechnology, NIMS UNIVERSITY, Jaipur,Rajasthan

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Abstract

The speedy increase of diagnostic and therapeutic applications of ionizing radiation in the field of medicine has significantly increase the concerns related to radiation exposure among patients and healthcare professionals. Computed tomography, interventional radiology, and radiotherapy are the procedures that significantly contribute to the collective radiation dose, assessment of dose and optimization a critical needs. In this article, radiation dosimetry serves as the fundamental scientific framework for measuring, calculating, and interpreting the absorbed dose delivered to biological tissues, thereby enabling evaluation of potential short- and long-term biological effects. Radiation dosimetry relies on well-defined dosimetric quantities, including absorbed dose, equivalent dose, and effective dose, which are essential for both clinical decision-making and radiation protection. Accurate measurement of these quantities is particularly important in medical imaging and radiotherapy, where precise dose delivery directly influences image quality, treatment effectiveness, and patient safety. Various dosimetric techniques have been developed to meet these requirements, ranging from passive to active detectors, each offering distinct advantages depending on the clinical application. Furthermore, the increasing emphasis on personalized medicine has highlighted limitations in conventional dosimetry approaches, which often rely on standardized phantoms and population-averaged dose estimates. Current research efforts are therefore directed toward patient-specific and real-time dosimetry, incorporating advanced computational models and imaging-based dose calculations. These emerging trends aim to improve dose accuracy, enhance radiation safety, and support individualized risk assessment, underscoring the evolving role of radiation dosimetry in contemporary medical practice.

Keywords: Radiation dosimetry, Absorbed dose, Thermoluminescent dosimeter, Optically stimulated luminescence, Medical imaging, Radiotherapy, Radiation safety

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Introduction

The use of ionizing radiation in medicine has increased significantly over the past few decades, particularly in diagnostic imaging and radiotherapy. While radiation plays an essential role in disease diagnosis and treatment, excessive or uncontrolled exposure may lead to adverse biological effects. Radiation dosimetry is the scientific discipline concerned with the measurement and evaluation of radiation dose absorbed by matter, especially human tissues. Accurate dosimetry is fundamental for radiation protection, quality assurance, and treatment planning. In medical applications, dosimetry helps in optimizing radiation doses to achieve diagnostic or therapeutic objectives while minimizing risks to patients and healthcare workers. This paper reviews the principles, techniques, and applications of radiation dosimetry in medical practice.

The science of determining the absorbed dosage (or dose rate) in materials subjected to ionising radiation is known as radiation dosimetry. It is a vast field that includes calculations and measurements of both internal and exterior radiation. A radiation dosimeter is a device, instrument, or system that measures or assesses exposure, kerma, absorbed dose, equivalent dose, or their temporal derivatives (rates) or related quantities of ionising radiation, either directly or indirectly. A dosimetry system consists of a dosimeter and its reader. The science of determining radiation dose through measurement, computation, or a combination of both is known as "dosimetry." "Absorbed dose" is the technical term for radiation dosage, which is calculated by dividing the quantity of radiation energy deposited in tissue by its mass. The most significant physical factor influencing how tumours and the rest of the body react to radiation is the absorbed dosage. Radiation dosimetry provides a scientific framework to quantify absorbed dose, assess biological risk, and ensure compliance with radiation safety standards. Accurate dosimetric assessment is critical to balance diagnostic or therapeutic benefits with potential adverse effects. It is also essential for quality assurance, treatment planning, and occupational monitoring.

Dosimetric Quantities

The quantitative physical and radiobiological characteristics that characterise the energy deposited in matter by ionising radiation are the foundation of radiation dosimetry. The three main quantities absorbed dose, equivalent dose, and effective dose offer a foundation for radiation protection as well as clinical applications. To guarantee patient safety, maximise treatment results, and adhere to global safety regulations such those established by the International Commission on Radiological Protection (ICRP), precise measurement of these quantities is crucial.

2.1 Absorbed Dose (D)

The average energy that ionising radiation imparts to a unit mass of tissue or material is called the absorbed dose. It is the most basic dosimetry quantity and serves as the foundation for additional radiological risk assessment. In mathematical terms, it may be written as:

$$D = \frac{dE}{dm}$$

where:

D = absorbed dose (Gray, Gy)

dE= mean energy imparted by ionizing radiation (joules, J)

dm = mass of the tissue or material (kg)

1 Gy is equivalent to 1 joule of energy absorbed per kilogram of tissue. Absorbed dose is particularly important in radiotherapy, where it determines the tumoricidal effect on cancer cells while minimizing damage to surrounding healthy tissues. In diagnostic imaging, absorbed dose is used to estimate patient exposure, especially in procedures like CT and interventional radiology.

2.2 Dosage Equivalent (H)

The biological efficacy of various radiation types is not taken into consideration by absorbed dosage, even though it measures energy deposition. To account for variations in biological damage between radiation types including X-rays, gamma rays, alpha particles, and neutrons, the equivalent dose (H) includes a radiation weighting factor (WR):

$$H_{T} = \sum W_{R} \cdot D_{T,R}$$

H_T = equivalent dose to tissue T (Sievert, Sv)

W_R = radiation weighting factor for radiation type R

$D_{T,R}$ = absorbed dose in tissue T due to radiation type R (Gy)

The weighting factor WRWR reflects the relative biological effectiveness (RBE) of the radiation. For example, alpha particles have a higher WRWR (≈20) compared to X-rays (WR=1WR=1), reflecting their greater potential for causing biological damage. Equivalent dose is widely used in occupational monitoring and radiation protection, allowing assessment of potential stochastic effects such as cancer risk in exposed individuals.

2.3 Effective Dose (E)

A key idea in radiation dosimetry, especially in radiation protection and medical applications, is the effective dose (E), which offers a single metric to measure the total stochastic risk of radiation exposure to the human body. Effective dose takes into consideration the varying vulnerability of various organs and tissues to radiation-induced stochastic consequences, such as cancer and genetic changes, in contrast to equivalent dose, which takes into account the kind of radiation, and absorbed dose, which measures energy deposition.

Mathematically, effective dose is defined as:

$$E = \sum W_T \cdot H_T$$

Where:

1. E = effective dose (Sievert, Sv)
2. HT= equivalent dose received by tissue or organ TT (Sv)
3. WT = tissue weighting factor representing the relative radiosensitivity of tissue T

The tissue weighting factors (W_T) are recommended by the International Commission on Radiological Protection (ICRP) and reflect the probability that a dose to a specific organ contributes to the overall risk of stochastic effects. For example, radiosensitive tissues such as the bone marrow, breast, and thyroid are assigned higher weighting factors, whereas less radiosensitive tissues, like skin or muscle, have lower factors.

3. Radiation Dosimetry Measurement Techniques

Ensuring patient safety, treatment effectiveness, and regulatory compliance all depend on accurate radiation dose quantification. Radiation dosimetry is used in medical applications to measure absorbed dosage, confirm treatment regimens, and track occupational exposure using a range of physical and computational methods. These techniques can be roughly divided into ionisation chambers, film dosimetry, thermoluminescent dosimeters, optically stimulated luminescence dosimeters, and computational techniques.

3.1 Thermo Luminescent Dosimeters (Tlds)

In both clinical and occupational radiation monitoring, thermoluminescent dosimeters (TLDs) are commonly used. They are made up of crystalline substances like calcium fluoride and lithium fluoride that, when exposed to ionising radiation, trap electrons in lattice flaws. These trapped electrons are released when heated, releasing light in proportion to the dose absorbed. TLDs are able to give extremely sensitive and precise dose measurements because of this feature. They are especially useful for patient dosimetry in radiation and diagnostic imaging due to their near tissue-equivalent response. TLDs must be handled carefully and annealed before being used again because each readout is unique. They continue to be a trustworthy benchmark for environmental and personal monitoring in spite of these drawbacks.

3.2 Optically Stimulated Luminescence Dosimeters (Oslds)

Similar to TLDs, optically stimulated luminescence dosimeters work by releasing stored energy through optical stimulation rather than thermal heating. OSLDs have a number of benefits, such as long-term signal stability, high sensitivity at low doses, and numerous readings. They are frequently employed in occupational exposure assessment, environmental radiation assessments, and patient dosage monitoring. In clinical situations like paediatric CT imaging or long-term staff monitoring, where low-dose monitoring is crucial or recurrent dosage verification is required, OSLDs are becoming more and more popular.

3.3 Film Dosimetry

Radiographic or radiochromic films, which darken in proportion to the radiation dose absorbed, are used in film dosimetry. When mapping two-dimensional dosage distributions with great spatial precision, this method is especially helpful. Film dosimetry is widely used in radiation to verify and ensure the quality of complicated treatment plans, such as volumetric modulated arc therapy (VMAT) and intensity-modulated radiotherapy (IMRT). Film dosimetry has drawbacks despite its high resolution, including sensitivity to handling and processing conditions and the need for meticulous calibration to guarantee precise dosage measurement.

3.4 Ionization Chambers

Ionization chambers are considered the gold standard for absolute dose measurement in radiation dosimetry. They operate by measuring the ionization produced in a gas-filled chamber, which generates an electrical current proportional to the absorbed dose. Ionization chambers are widely used for beam calibration, equipment verification, and reference dosimetry in radiotherapy. While they provide high accuracy and immediate readout, they are relatively bulky and not suitable for direct patient measurements. Their primary role remains in standardizing dose delivery and ensuring compliance with dosimetric protocols.

3.5 Computational And Monte Carlo Dosimetry

Modern radiation dosimetry increasingly relies on computational approaches, particularly Monte Carlo simulations, which model photon and particle interactions at a microscopic level. These simulations provide highly accurate dose calculations in complex geometries and heterogeneous tissues, making them indispensable for personalized dosimetry and advanced radiotherapy planning. Monte Carlo methods are used to optimize treatment plans in CT, PET, and radiotherapy, as well as to calculate organ-specific doses in patients. While computational methods require significant computational resources and detailed input data, their accuracy and flexibility make them an essential component of modern dosimetry.

4. Applications Of Radiation Dosimetry

A key component of contemporary medicine is radiation dosimetry, which offers the mathematical framework required to assess, track, and maximise exposure to ionising radiation. In addition to occupational radiation protection, therapeutic radiology, and diagnostic imaging, its uses are expanding into advanced computer modelling and personalised medicine. Precise dosimetry guarantees that healthcare workers stay within specified occupational dose limits and that patients get therapeutically or diagnostically adequate doses while minimising biological risks.

4.1 Diagnostic Imaging

Radiation dosimetry is essential for determining patient exposure, maximising scan parameters, and guaranteeing radiation protection in diagnostic imaging. Patients are exposed to varied degrees of ionising radiation through common modalities such nuclear medicine scans, computed tomography (CT), fluoroscopy, mammography, and traditional radiography. For instance, a whole-body CT scan can produce doses greater than 20–30 mSv, but a typical chest X-ray may deliver an effective dosage of about 0.1 mSv. Significant cumulative exposure might result from repeated imaging, especially in the management of chronic diseases or in paediatric patients.

In diagnostic imaging, dosimetry measures exposure using entrance skin dose (ESD), dose-area product (DAP), and dose-length product (DLP) metrics. By ensuring that picture quality is adequate for diagnosis while maintaining dosages as low as practically possible, these measurements are essential for protocol optimisation (ALARA principle). In order to optimise CT scanning parameters including tube voltage (kVp), tube current (mA), and scan length, personalised dosimetry based on patient size and anatomy is being used more and more. Additionally, precise organ-specific dosimetry is necessary for dose monitoring in nuclear medicine, which uses radiopharmaceuticals like Technetium-99m or F-18 FDG to prevent excessive radiation to radiosensitive organs like the thyroid, bone marrow, or gonads.

4.2 Radiotherapy

Radiation dosimetry is fundamentally important in therapeutic applications, where the goal is to deliver a precisely prescribed dose to tumors while minimizing damage to adjacent healthy tissue. Modern radiotherapy techniques, including external beam radiotherapy (EBRT), intensity-modulated radiotherapy (IMRT), volumetric modulated arc therapy (VMAT), stereotactic radiosurgery (SRS), and brachytherapy, depend heavily on dosimetric planning and verification.

In EBRT, three-dimensional treatment planning systems calculate dose distributions in complex anatomical structures using patient imaging datasets. In vivo dosimetry using TLDs, OSLDs, or semiconductor detectors is often employed to verify delivered doses, ensuring compliance with planned treatment. In brachytherapy, precise dosimetry ensures optimal dose delivery to the tumor while protecting organs at risk such as the bladder, rectum, and spinal cord. Moreover, fractionated radiotherapy protocols rely on accurate dose measurements and dose-rate calculations to exploit differences in tumor and normal tissue radiobiology, maximizing therapeutic efficacy and reducing late effects.

4.3 Occupational Radiation Protection

Medical professionals are frequently exposed to ionising radiation when performing diagnostic, therapeutic, and interventional treatments. Dosimetry is essential for tracking and reducing occupational exposure. Personal dosimeters, such as TLD badges or OSLDs, are used by personnel in radiology, nuclear medicine, and interventional cardiology departments to track cumulative exposure over weeks or months. The International Commission on Radiological Protection (ICRP) recommends 20 mSv annually on average over five years, with a maximum of 50 mSv in a single year. Occupational dosimetry enables organisations to guarantee that employees stay within international regulatory limits. Frequent dose monitoring also makes it possible to optimise workflow, shielding, and procedural methods to reduce exposure, especially in high-dose procedures like radionuclide therapy or fluoroscopically guided interventions.

4.4 Emerging Applications

Recent advancements have expanded the applications of dosimetry beyond traditional clinical roles. Computational dosimetry, using Monte Carlo simulations and patient-specific 3D modeling, allows highly accurate dose calculations in complex geometries, accounting for tissue heterogeneity and patient anatomy. Real-time in vivo dosimetry, using miniature detectors or electronic portal imaging devices (EPIDs), provides immediate feedback on delivered doses during therapy, enhancing treatment safety.

Artificial intelligence (AI) and machine learning are now being integrated with dosimetric workflows to predict patient-specific doses, optimize imaging and treatment protocols, and minimize unnecessary exposure. For instance, AI algorithms can adjust CT scan parameters automatically based on patient size or predict cumulative radiation doses from multiple imaging procedures, reducing long-term stochastic risk. These emerging approaches mark a shift toward precision and personalized dosimetry, where radiation is tailored not just to the disease, but to the individual patient’s anatomy and risk profile.

4.5 Clinical Significance

The clinical significance of radiation dosimetry cannot be overstated. It ensures patient safety, treatment effectiveness, and occupational protection, while providing quantitative data for risk assessment and regulatory compliance. In diagnostic imaging, it guides protocol optimization to reduce unnecessary exposure; in therapy, it ensures that tumor doses are accurate and organs at risk are protected; and in occupational settings, it monitors cumulative exposure to minimize stochastic effects. With the integration of computational, real-time, and AI-assisted approaches, radiation dosimetry continues to evolve into a more precise, predictive, and patient-centered discipline.

5. Challenges And Future Trends In Radiation Dosimetry

The accuracy and consistency of dose assessment in medical applications are still limited by a number of technological, biological, and clinical issues, despite notable advancements in radiation dosimetry. Accurately estimating the patient-specific absorbed dose is one of the main hurdles, especially in complex anatomical locations and heterogeneous tissues. It is challenging to completely account for errors introduced by variations in patient size, organ geometry, tissue composition, and motion during imaging or therapy using traditional dosimetric models. In high-dosage procedures like advanced radiation and interventional radiology, where even slight variations in dose distribution can have major biological repercussions, these uncertainties become extremely important.

The conversion of physical dose measures into estimates of biological risk is another significant difficulty. Individual radiosensitivity may not be correctly reflected by dosimetric variables like absorbed dose and effective dose since they are based on population-averaged weighting factors. Although they affect radiation sensitivity, factors like age, sex, genetic predisposition, and pre-existing medical disorders are not frequently taken into account in traditional dosimetric calculations. This restriction is especially important for diagnostic imaging, as low-dose exposures may include stochastic dangers that are challenging to accurately measure.

Dosimeter technological constraints continue to be a problem. Despite their widespread use, devices like TLDs and OSLDs can be impacted by energy dependence, angular response, fading, and environmental factors, which could result in measurement mistakes if improperly addressed. It is still difficult to get high spatial precision in dose assessments in radiotherapy, particularly for small fields employed in stereotactic techniques. Further standardisation is still needed in the area of integrating dosimetric data from various imaging and treatment sessions to evaluate cumulative exposure.

As we look to the future, radiation dosimetry is moving towards more individualised and flexible methods. Monte Carlo-based dose calculations, which describe radiation transport at the microscopic level and produce extremely accurate, patient-specific dose distributions, are now widely used because to advances in computing capacity. In order to reduce uncertainty in complicated clinical circumstances, these techniques are being progressively integrated into diagnostic dosage estimating tools and clinical treatment planning systems.

It is anticipated that new technologies like real-time and in vivo dosimetry will be essential to enhancing therapy safety and dose verification. Electronic dosimeters and tiny detectors make it possible to continuously monitor radiation exposure during procedures, allowing for quick remedial action in the event that planned doses are not met. Because dynamic changes in patient location or anatomy might impact dose distribution, this capacity is especially useful in image-guided radiation and interventional procedures.

The future of radiation dosimetry is likewise being shaped by machine learning and artificial intelligence. Large datasets can be analysed by AI-based models to assess cumulative exposure over time, optimise imaging techniques, and forecast patient-specific doses. By automating dosage optimisation while preserving therapeutic or diagnostic quality, these techniques may reduce needless radiation exposure. In the long run, risk-adaptive dosimetry where dose decisions are informed by both physical measurements and individual biological sensitivity may be made possible by integrating dosimetry with biological markers of radiation response.

Conclusion

A key element of the safe and efficient application of ionising radiation in medical practice is radiation dosimetry. Accurate dose measurement and assessment are now crucial for weighing clinical benefit against possible biological harm due to the growing reliance on radiation-based diagnostic and therapeutic treatments. The scientific foundation for measuring radiation exposure, improving imaging and treatment procedures, and guaranteeing adherence to global radiation protection regulations is provided by dosimetric quantities and measurement methods. The complexity of dose delivery has greatly risen due to developments in medical imaging and radiation, underscoring the shortcomings of conventional, population-based dosimetric methods. The accuracy of dose calculation and treatment verification have been improved through the combination of computer modelling, real-time dose monitoring, and patient-specific data. These advancements are especially crucial for frequent diagnostic imaging and high-dose radiation therapy, when minor errors can have serious long-term consequences. In the future, the development of radiation dosimetry towards customised and flexible approaches is a crucial development in contemporary healthcare. It is anticipated that the use of biological risk modelling, artificial intelligence, and Monte Carlo simulations will lower uncertainty and enhance individual risk assessment. To improve patient safety, improve dosimetric accuracy, and encourage the responsible use of ionising radiation in medicine, more research and technology advancements will be necessary. In the end, radiation dosimetry will continue to be essential for attaining the best possible clinical results while upholding the strictest radiation protection regulations.

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