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IONIZING RADIATION: MOLECULAR AND BIOLOGICAL INSIGHTS

Brijender Bhushan*[1], Pawitar Dulari[2], Ajay Bhushan[3]

[1]Assistant Professor, Department of Zoology, Govt. Degree College Lanj, Himachal Pradesh, India.

[2]Assistant Professor, Department of Physics, Govt. College Una, Himachal Pradesh, India

[3]Independent Researcher.

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***Corresponding Author: Brijender Bhushan**

Assistant Professor, Department of Zoology, Govt. Degree College Lanj, Himachal Pradesh, India.

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ABSTRACT

Ionizing radiation (IR) is a fundamental component of modern science, medicine, and industry. It enables medical imaging, cancer therapy, and technological innovations by interacting with matter at the atomic and molecular levels. However, IR can also disrupt biological structures, causing cellular damage, genetic mutations, and long-term health effects. This paper provides a comprehensive theoretical analysis of IR interactions with biological systems, covering physical energy deposition, radiolysis of water, reactive oxygen species (ROS) generation, DNA damage and repair, epigenetic modifications, and transgenerational effects. Modern computational approaches, including Monte Carlo simulations and radiogenomics, are discussed for their role in predicting biological outcomes. Understanding these mechanisms is essential for optimizing radioprotection strategies and guiding safe and effective applications of IR.

KEYWORDS: Ionizing radiation, DNA damage, radiolysis, reactive oxygen species, molecular mechanisms, epigenetics, radiogenomics, radioprotection.

INTRODUCTION

Ionizing radiation refers to high-energy photons and particles capable of removing electrons from atoms, initiating ionization cascades. Since its discovery in the late 19th century, IR has transformed medicine, physics, and industry (Mettler et al., 2018). Its interactions with biological matter involve complex physical, chemical, and biological processes, making theoretical understanding essential for assessing risk and guiding applications (Hall & Giaccia, 2019).

This paper focuses purely on the theoretical aspects of IR. It examines how IR interacts with water and biomolecules, generates ROS, induces DNA damage, alters epigenetic marks, and affects gene expression across generations. Insights from computational modeling and radiogenomics are integrated to highlight the current understanding of IR's biological effects (Liu et al., 2024).

Physical Interactions of Ionizing Radiation with Matter

IR deposits energy through direct and indirect interactions. Direct interactions occur when radiation directly ionizes a biomolecule such as DNA. Indirect interactions dominate in cells due to high water content, producing reactive species that damage biomolecules (Guleria et al.,2019; Guleria et al., 2020; Spinks & Woods, 1990; Goodhead, 1994).

Photons primarily interact via the photoelectric effect, Compton scattering, or pair production, while charged particles lose energy through inelastic collisions with electrons and nuclei (Durante & Loeffler, 2021). Linear Energy Transfer (LET) describes energy deposition density: high-LET radiation (e.g., alpha particles) produces clustered, complex DNA damage, whereas low-LET radiation (e.g., gamma rays) causes sparse, mostly repairable damage (Hall & Giaccia, 2019).

Radiolysis of Water and Reactive Oxygen Species (ROS)

Water is the predominant target of IR in cells. Radiolysis breaks water molecules into highly reactive species, including hydroxyl radicals (·OH), hydrogen radicals (·H), solvated electrons ($e^{-}_{a}q$), hydrogen peroxide (H_2O_2), and molecular hydrogen (H_2) (Spinks & Woods, 1990; Goodhead, 1994; Guleria et al., 2019).

The radiolysis process occurs in three stages:

1. Physical Stage: Immediate ionization and excitation of water molecules.
2. Physicochemical Stage: Formation of primary radicals and early recombination.
3. Chemical Stage: Diffusion of ROS and interactions with biomolecules, causing oxidative damage (Kundrát et al., 2020).

Oxygen amplifies damage via the oxygen enhancement ratio (OER), fixing DNA lesions and increasing biological impact by up to threefold (Hall & Giaccia, 2019; Durante & Loeffler, 2021). Recent computational studies reveal heterogeneous ROS clustering, particularly with high-LET radiation, producing complex damage patterns that challenge repair mechanisms (Liu et al., 2024 et al., 2023).

DNA Damage and Repair

IR induces a spectrum of DNA lesions: single-strand breaks (SSBs), double-strand breaks (DSBs), and clustered damage. The repair response depends on lesion complexity:

- Non-Homologous End Joining (NHEJ): Rapid but error-prone, predominant in G0/G1 phase.
- Homologous Recombination (HR): Accurate, requires S/G2 phase and intact sister chromatids (Jackson & Bartek, 2009).

Damage clustering, especially from high-LET radiation, increases the probability of misrepair, leading to mutations, chromosomal aberrations, or cell death (Friedland et al., 2020). Advanced models, including Monte Carlo and track-structure simulations, provide insight into energy deposition and subsequent DNA lesion patterns (Bai et al., 2020).

Epigenetic and Transgenerational Effects

IR can induce epigenetic modifications such as DNA methylation changes, histone modifications, and non-coding RNA regulation, persisting after DNA repair (Dubrova, 2003; Koehler et al., 2022).

These modifications can alter gene expression, impacting cell cycle regulation, apoptosis, and DNA repair pathways. Evidence shows transgenerational effects where parental exposure to IR leads to genomic instability, altered gene expression, and increased mutation rates in offspring (Dubrova, 2003; Liu et al., 2024 et al., 2023).

Non-coding RNAs, including microRNAs, play a key role in mediating inherited changes, affecting DNA repair and oxidative stress response networks (Kundrát et al., 2020). Computational models integrating DNA repair kinetics with epigenetic regulation now allow predictions of multigenerational consequences.

Low-Dose Radiation: Mechanistic Insights and Risk Modeling

The biological effects of low-dose ionizing radiation (typically less than 100 mGy) remain complex and subject to ongoing research. Traditional regulatory frameworks rely on the Linear-No-Threshold (LNT) model, which assumes that any dose of radiation, no matter how small, proportionally increases the risk of cancer and genetic mutations (ICRP, 2007). This model is conservative, designed to ensure public and occupational safety, but it does not account for potential biological adaptations at low exposures.

Experimental and epidemiological studies indicate that cellular responses to low-dose radiation are heterogeneous. Some cells activate protective mechanisms such as enhanced DNA repair, antioxidant production, and stress-response pathways, which can mitigate damage from subsequent exposures (Tapio & Jacob, 2020). This phenomenon, known as radiation hormesis, suggests that low doses might induce beneficial adaptive responses rather than only harmful effects.

Recent advances in radio-genomics allow researchers to link individual genetic and epigenetic profiles with radiation sensitivity. Variations in DNA repair efficiency, antioxidant capacity, and gene regulation determine how a person responds to low-dose exposure. Integrating these insights with dose-response models enables personalized risk assessment, moving beyond population averages to consider individual susceptibility (Liu et al., 2024 et al., 2023).

Moreover, computational models simulate micro-dosimetric energy deposition, ROS generation, and tissue-specific cellular responses. These models demonstrate that low-dose radiation produces a spectrum of outcomes: some cells effectively repair damage, some adapt, and others accumulate sub-lethal damage that may contribute to long-term stochastic effects.

Understanding the mechanistic basis of low-dose responses is crucial for developing optimized radioprotection strategies, refining medical imaging protocols, and setting evidence-based exposure limits that balance safety with the practical benefits of ionizing radiation in medicine and industry.

Theoretical Conclusions and Future Directions

Ionizing radiation affects biological systems across molecular, cellular, and organismal scales. A detailed theoretical understanding of water radiolysis, reactive oxygen species (ROS) generation, DNA damage, epigenetic alterations, and trans-generational effects is crucial for advancing radiobiology and risk assessment. Contemporary computational approaches, including Monte Carlo simulations, AI-driven radiogenomics, and multiscale modelling, provide powerful tools to predict radiation-induced effects and inform radioprotection strategies (Holmes et al., 2024; Liu et al., 2024). Future research should aim to integrate molecular-level mechanisms with tissue- and organism-level responses, enabling optimized therapeutic interventions while minimizing adverse outcomes and long-term risks.

REFERENCES

1. Bai, T., Liu, W., Jiang, S., Liu et al., 2024, Y., & Wang, J. (2020). Deep learning for Monte Carlo denoising in radiotherapy. Medical Physics, 47(4), 1854–1865. [https://doi.org/10.1002/mp.14023]
2. Dubrova, Y. E. (2003). Radiation-induced transgenerational instability. Oncogene, 22 (45),7087–7093. https://doi.org/10.1038/sj.onc.1206934
3. Durante, M., & Loeffler, J. S. (2021). Charged particles in radiation oncology. Nature Reviews Clinical Oncology, 18(8), 587–599. https://doi.org/10.1038/s41571-021-00505-6
4. Friedland, W., Dingfelder, M., Kundrát, P., & Jacob, P. (2020). Track-structure simulations of DNA damage by ionizing radiation. Radiation Research, 193(1), 36–49. https://doi.org/10.1667/RR15692.1
5. Goodhead, D. T. (1994). Initial events in the cellular effects of ionizing radiations: Clustered damage in DNA. International Journal of Radiation Biology, 65(1), 7–17. [https://doi.org/10.1080/09553009414550031]
6. Guleria, R., Bhushan, B., Guleria, A., Bhushan, A., & Dulari, P. (2019). Harmful effect of ionizing radiation. International Journal for Research in Applied Science and Engineering Technology, 7(12), 887–889. [http://ijraset.com/fileserve.php?FID=26203]
7. Guleria, R., Bhushan, B., Guleria, A., Bhushan, A., & Dulari, P. (2020). Non-ionizing radiation and human health. International Journal for Scientific and Academic Research Today, 6(1), 130–135. [http://www.ijsart.com]

8. Hall, E. J., & Giaccia, A. J. (2019). Radiobiology for the radiologist (8th ed.). Wolters Kluwer.
9. Holmes, J., Rogers, D., Anderson, P., & Williams, S. (2024). Advances in computational dosimetry for radiotherapy. Physics in Medicine & Biology, 69(3), 035012. [https://doi.org/10.1088/1361-6560/abf32c]
10. ICRP. (2007). The 2007 recommendations of the International Commission on Radiological Protection. ICRP Publication 103, 37(2–4).
11. Jackson, S. P., & Bartek, J. (2009). The DNA-damage response in human biology and disease. Nature, 461, 1071–1078. [https://doi.org/10.1038/nature08467]
12. Koehler, C., Maier, A., Schulz, H., & Becker, N. (2022). Radiogenomics: Toward personalized radiation therapy. Frontiers in Oncology, 12, 784590.
13. Kundrát, P., et al. (2020). Mechanistic modeling of DNA damage and repair. Radiation Protection Dosimetry, 188(4), 440–451.
14. Liu, G., Liu et al., 2024, R., Li, Y., Niu, L. M., Wu, X., Liu, Y. Y., & Liu et al., 2024, X. (2024). Study on the long-term medical effects of radiation in overexposed people. Journal of Radiation Research and Applied Sciences, 17 (3), 100955. [https://doi.org/10.1016/j.jrras.2024.100955]
15. Mettler, F. A., Upton, A. C., & Thomadsen, B. (2018). Medical effects of ionizing radiation (4th ed.). Elsevier.
16. Spinks, J. W. T., & Woods, R. J. (1990). An introduction to radiation chemistry (3rd ed.). Wiley.
17. Tapio, S., & Jacob, P. (2020). Combining low-dose radiation with other stressors. Mutation Research/Reviews in Mutation Research, 786, 108344.