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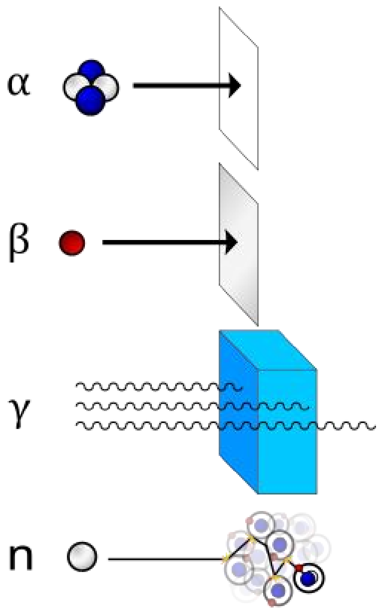
MECHANISMS OF IONIZING RADIATION-INDUCED DAMAGE TO CELLS AND DNA

Tashkent State Technical University
Department of Biomedical Engineering, Biophysics and Informatics
Assistant: **Kholmetov Shavkat Sherimatovich**
Fayziyeva Nodira Alisherovna
2nd Faculty of General Medicine, 1st-year student**: Orazbaev Nuraliy Amanaliyevich**
Rustamov Sanjar Rustam ugli
Pediatrics Program, 1st-year student: **Kudaibergenov Sultan Polatovich**

Abstract: This article analyzes the primary physical and biological effects of ionizing radiation on living cells. Radiation-induced DNA damage, disruption of cellular structures, and the mechanisms of their repair are explained based on scientific evidence. Additionally, risk factors associated with the use of radiation sources in medical practice and the main methods of radiation protection aimed at minimizing these risks are discussed. The results hold practical significance in the fields of biophysics, radiobiology, and medical diagnostics.

Keywords: Ionizing radiation, radiobiological effects, DNA damage, cellular processes, radiation dose, safety standards, X-ray, radiotherapy, mutagenesis, ionization process.

Relevance



Studying the effects of ionizing radiation on living organisms is especially important today, as radiological technologies widely used in medical diagnostics and treatment significantly increase the relevance of this topic. Understanding radiation-induced consequences at the cellular and molecular levels is essential for protecting patient health, ensuring medical staff safety, and promoting the safe use of modern medical equipment. Furthermore, global factors involving environmental radiation sources and nuclear technologies continue to increase the scientific and practical importance of this field.

Introduction

Ionizing radiation is a stream of high-energy electromagnetic waves or particles capable of disrupting the electrical balance of atoms and molecules by converting them into ions (Turner, 2007; Hall & Giaccia, 2018). Although natural radioactivity is constantly present in the environment, the use of artificial radiation sources has sharply increased in recent decades due to advances in medicine, industry, and technology (UNSCEAR, 2008). Modern diagnostic tools such as X-rays, CT, contrast radiology, and nuclear medicine procedures require the continuous use of radiation (Khan & Gibbons, 2014).

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The effects of ionizing radiation on living organisms involve multistage processes that begin with the breaking of chemical bonds in the cell, formation of free radicals, and structural alterations of DNA (Alberts et al., 2015; Sacher, 2017). These processes may lead to functional disorders or irreversible cellular damage. At the same time, controlled and targeted use of radiation in medicine—especially in cancer therapy—plays an essential role in treatment (Paganetti, 2012).

Studying these mechanisms is vital for understanding the safety of medical technologies, the nature of biophysical processes, and the principles of radiation protection. Knowledge of radiation effects on the human body is crucial for healthcare workers, radiologists, physicists, and industrial specialists to ensure safe working conditions and protect human health (ICRP, 2007; Hall & Giaccia, 2012).

Scientific Background of the Problem

Since 70–80% of the human body consists of water, radiation interacting with water molecules leads to the following reactions. **Radiolysis**:

$H_2O \rightarrow H^+ + OH^-$ or $H_2O \rightarrow H\bullet + OH\bullet$

Here, **OH• (hydroxyl radical)** is one of the most aggressive oxidizing radicals. It damages DNA bases, proteins, enzymes, and causes peroxidation of membrane lipids (Hall & Giaccia, 2018; Lindahl, Modrich & Sancar, 2000).

Ionizing radiation includes high-energy particles and waves capable of ejecting electrons from atoms. Its main types include alpha, beta, gamma radiation, neutrons, and protons. These differ in penetration power, ionization capability, and mechanisms of biological damage (Turner, 2007):

Alpha particles – high ionizing power, low penetration.

Beta particles – moderate ionizing ability.

Gamma rays – strong penetration depth; major external hazard.

Protons and heavy ions – high LET; used in radiotherapy (Paganetti, 2012).

Biological effects on DNA and cells

Radiation affects DNA either **directly** (breaking the DNA strands) or **indirectly** (via free radicals formed from water molecules) (Alberts et al., 2015; Sacher, 2017).

Major DNA damage types include:

Single-strand breaks (SSBs)

Double-strand breaks (DSBs)

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Oxidation and deamination of bases

Chromosomal aberrations

Double-strand breaks are the most dangerous and may lead to cancer development (Lindahl, Modrich & Sancar, 2000).

Cellular responses

Radiation exposure leads to:

slowing or cessation of cell division,

activation of apoptosis,

necrosis in high-damage conditions,

mutations in genetic material,

uncontrolled proliferation leading to tumor formation (Hall & Giaccia, 2018).

Rapidly dividing cells—blood cells, intestinal epithelium, reproductive cells—are the most radiosensitive.

Literature Review

Recent decades have seen significant growth in studies examining the biological effects of ionizing radiation. Research in radiobiology, molecular biology, and medical physics has mainly focused on analyzing the mechanisms of DNA damage and repair. Foundational studies by T. Lindahl, P. Modrich, and A. Sancar provided important insights into DNA repair pathways.

Reports by ICRP, UNSCEAR, and IAEA provide detailed information on radiation dose limits and safety standards. Medical literature covers the biological effects of X-ray diagnostics, CT imaging, and nuclear medicine procedures.

In radiotherapy-related studies, the effects of high-energy protons, gamma rays, and heavy ions on tumor tissues, as well as the significance of LET (Linear Energy Transfer), are widely discussed. Research on environmental radiation and nuclear accidents offers valuable data on long-term and low-dose radiation exposure.

Overall, the literature shows that the impact of ionizing radiation on living organisms is complex, multifactorial, and requires deep investigation.

Methodology

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This study analyzes the effects of ionizing radiation on living cells using the following methodological approaches:

1.Theoretical analysis of radiobiology, biophysics, and medical physics literature, including ICRP, UNSCEAR, and IAEA reports.

2.Comparative analysis of different radiation types (alpha, beta, gamma, neutron, proton, heavy ions) and their biological effects.

3.Structural-functional analysis of DNA and cellular damage, apoptosis, necrosis, and repair mechanisms.

4.Study of medical practice, including radiation sources used in diagnostics and therapy, and examination of safety standards.

Radiation Protection Principles

The main goal of radiation protection is to minimize the absorbed dose. Increasing the distance from the radiation source significantly reduces exposure; doubling the distance decreases dose by a factor of four. Different materials block different radiation types:

paper blocks alpha particles,

plastic or aluminum blocks beta particles,

lead and thick concrete block gamma and X-rays,

water or paraffin slows down neutron radiation.

Lead aprons, shields, and protective walls are widely used in medical settings.

Conclusion

Ionizing radiation has deep and multifaceted effects on living organisms. Its primary danger lies in its ability to ionize intracellular molecules, damage DNA, and disrupt normal cellular function. Low doses may be repaired by natural biological mechanisms, but high or prolonged exposure can lead to cell death, tissue damage, mutations, and cancer development.

The biological effects of radiation depend on radiation type, dose, organism sensitivity, and exposure duration. Children and embryos are more radiosensitive than adults. Understanding these mechanisms is essential for ensuring safety in medicine, industry, and environmental protection.

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