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The Biological Survival Mechanisms Behind the World's Most Radioresistant Bacterium

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ABSTRACT

Deinococcus radiodurans is an extremely radioresistant bacterium that has captured the interest of researchers in pursuit of innovations in radioresistant technology and potential applications for bioremediation. The following paper provides an overview of the bacterium's unique biological mechanisms that enable it to maintain such resilience to ionizing radiation. Genetic redundancies and genomic copies play a considerable role in withstanding radiation-induced mutations and DNA damage. Similarly, antioxidant systems, including both enzymatic and non-enzymatic ones, counteract the effects of radiation by removing radiation-induced reactive oxygen species that harm the bacterium's proteome and genome. Lastly, highly efficient DNA repair mechanisms ensure a speedy recovery from DNA damage.

Keywords: *Deinococcus radiodurans*, Radioresistant Bacteria, Manganese Antioxidant Systems, Extreme DNA Repair Mechanisms, Ionizing Radiation, Biological Mechanisms of *D. radiodurans*.

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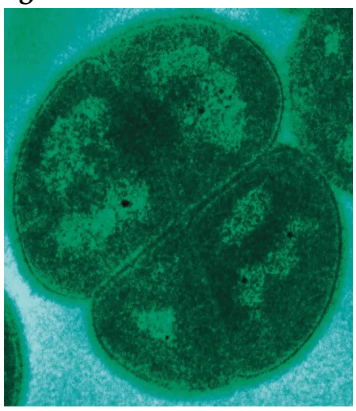
INTRODUCTION

In 1956, researcher Arthur Anderson isolated a vegetative bacterium from canned ground meat that had been γ-irradiated at 4,000 Gray (Gy), a dose approximately 250 times higher than that typically used to kill *Escherichia coli* (Cox et al., 2005). Often cited as the world's toughest bacterium, Anderson had discovered *Deinococcus radiodurans*. As of 2020, the species was the most radiation-resistant bacterium ever known (Agrawal, 2020), rightfully earning its spot in the *Guinness Book of World Records* (Guinness World Records, 1998).

Deinococcus radiodurans is a mesophilic, non-spore-forming, non-motile, spherical bacterium that forms pairs and tetrads in rich liquid media (Battista et al., 1999; Cox et al., 2005). While they thrive in temperatures between 30 and 37°C, *D. radiodurans* can survive in a variety of conditions, including extreme radioactivity and ultraviolet radiation, genotoxic chemicals, heat, dessication, and severe acceleration and deceleration forces, which are lethal to almost all other cellular species (Cox et al., 2005; Rew 2003). The species is often cited as the most radiation-resistant and DNA damage-resistant bacterium, capable of withstanding extremely high doses of radiation, approximately 5000 Gy of gamma irradiation (Sundar et al., 2023). Estimates suggest they can tolerate approximately 30 times more DNA double-strand breaks compared to E. Coli K12 before succumbing to damage (Cox et al., 2005), a 200-fold higher radiation dose than most other bacteria (Timmins et al., 2016), and a 1000-fold higher dose than most vertebrates (Munteanu et al., 2015). The evolutionary origins of radioresistance are a curious topic for biologists, given the absence of any naturally occurring environments exceeding 400 mGy per year (Cox et al., 2005), which makes the possibility of radioresistance resulting from natural selection unusual. Studying the proteome and pathways involved in *D. radiodurans* could possibly provide more clues.

Figure 1.



Note. A photograph of a tetrad of D. radiodurans, a commonly observed formation that the spherical bacteria take up in rich liquid media. Reprinted from Deinococcus Radiodurans by Michael Daly, Uniformed Services

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University, Bethesda, MD, USA, In The Microbial Menagerie, March 16, 2017., Retrieved December 30, 2025, from https://microbialmenagerie.com/meet-a-microbe-deinococcus-radiodurans/.

Current studies suggest that the species endures radiation through a robust physiology and a complement of repair enzymes. Rather than protecting its genome, the organisms utilize extensive DNA repair and a highly resistant proteome in response to DNA damage, without losing viability or exhibiting evidence of induced mutation (Battista, 1997). Through DNA repair machinery, consisting of base excision repair (BER), nucleotide excision repair (NER), and recombinational repair pathways (Timmins et al., 2016).

Table 1.

Species	D10 value (Gy)	Reference
Escherichia coli	1,000	(Chiasson et al., 2005)
Acinetobacter radioresistens	2,000	(Cox et al., 2005)
Hymenobacter actinosclerus	3,500	(Cox et al., 2005)
Rubrobacter xylanophilus	5,500	(Cox et al., 2005)
Deinococcus radiodurans	10,000	(Sundar et al., 2023; Battista et al., 1999)

The table compares the radioresistance of different species, measured by D10, which is defined as the dose of radiation required to eradicate 90% of the population.

The following literature review aims to examine the biological mechanisms that contribute to *D. radiodurans'* unique radioresistance. Research on the radioresistant mechanisms has become increasingly more important for the development of radioprotective agents and the prevention and reduction of radiation-induced injury and mortality (Peana et al., 2016). Direct applications of *D. radiodurans* have become more promising as researchers consider using the bacteria for the direct adsorption of uranium in wastewater and the transformation of other genes into the bacteria to engineer them for specific genetic functions (Li et al., 2021).

METHODOLOGY

This review utilized various peer-reviewed research papers from the databases Google Scholar, ScienceDirect, and NIH. Keywords used to identify articles included "*Deinococcus radiodurans*", "Biological

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mechanisms of *D. radiodurans*", "The role of manganese in *D. radiodurans*", "DNA repair mechanisms in *D. radiodurans*", and "Proteome of *D. radiodurans*".

GENETIC REDUNDANCIES AND GENOME COPIES

The *D. radiodurans* genome, comprising chromosome 1 (2,648,615 base pairs (bp)), chromosome 2 (412,340 bp), a megaplasmid (177,466 bp), and a plasmid (45,702 bp), exhibits a high level of redundancy in DNA repair genes. The average repeat content of base pairs in the genome was around 3.8% (White et al., 1999), while repeat base pairs made up 2% of the genome of E. coli (Romero et al., 1999). Many such redundant genes promote radioresistance, as mutations in a few redundant genes do not impair the corresponding function (Liu, 2023).

Furthermore, an increased number of genome copies has been theorized to produce a significant decrease in the probability of a gene being inactivated (Cox et al., 2005). Genome copies are necessary in radioresistance, as more than one genome is required to repair DNA double-strand breaks. As a result, *D. radiodurans* typically contains 8 to 10 haploid genome copies during exponential growth and 4 copies during the stationary phase (Marakova et al., 2001). However, a direct correlation between genome multiplicity and radioresistance does not exist, as cells containing 4 copies presented the same survival rates as those with 10 copies, suggesting that 5 or fewer copies are sufficient (Harsojo, 1981).

ANTIOXIDANT SYSTEMS

In a study by Daly and colleagues to investigate the effects of manganese (Mn(II)) on the radioresistance of *D. radiodurans*, the researchers found that cultures of *D. radiodurans* were less resistant to ionizing radiation when starved of Mn(II). Additionally, Mn(II) is necessary for post-irradiation recovery, as 10-kGY-irradiated *D. radiodurans* cells incubated without Mn display a 1,000-fold reduction in cell survival compared to cells recovered under normal conditions (Daly et al., 2004). However, the number of DNA double-strand breaks remained the same, suggesting that Mn(II) had no part in preventing DNA damage.

The prevailing theory for the phenomenon, and one proposed by Daly, is that Mn(II) protects proteins from reactive oxygen species (ROS), molecules including superoxide, hydrogen peroxide, and hydroxyl radicals formed by the radiation-induced breakdown of water molecules, which can damage DNA, proteins, and lipids (Zheng et al., 2023). In eight bacteria and one archaeon, a positive correlation was observed between radioresistance and the ratio of intracellular Mn(II) to Fe(II) concentrations due to manganese complexes scavenging ROS that are formed by iron through the Fenton reaction. *D. radiodurans* has a manganese-to-iron ratio of 0.24, which is significantly higher than that of more radiation-sensitive bacteria such as S. oneidensis, with a ratio of 0.0005 (Daly, 2009), while having a D10 value of 70 Gy (Sweet, 2023). When the

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manganese-to-iron ratio of cells was decreased from 0.24 to 0.04, the *D. radiodurans* cells became highly sensitive to radiation and highly susceptible to radiation-induced protein oxidation (Daly, 2009).

D. radiodurans possesses two known Mn(II) transporters: one from the natural resistance-associated macrophage (Nramp) family and one from the ATP-dependent ABC-type transporter family (Daly, 2009). Consequently, the bacterium has an exceptionally high intracellular manganese content of 0.2 to 4 nM (Slade et al., 2011), which is mostly present in small complexes with orthophosphate and peptides that scavenge superoxide and hydrogen peroxide, thereby protecting proteins from oxidative stress at a rate significantly more efficient than enzymatic ROS-scavenging systems. In a study, researchers used a sample decapeptide, DEHGTAVMLK (DP1), and its random scrambled version, THMVLAKGED (DP2), as they contained the most prevalent amino acids present in *D. radiodurans*, to study their interactions with Mn(II). They found that such peptides bind Mn(II) to create antioxidant complexes. These complexes act with phosphate to protect proteins from ROS generated by radiation (Peana et al., 2016).

Other antioxidants include proteins that prevent the effects of ROS, such as superoxide dismutase and catalase, which convert ROS into harmless molecules. Such proteins, including SodA and SodC, along with KatE1 and KatE2, appear to be equivalent to those in E. coli; however, the ROS scavenging activities of the proteins were significantly higher in *D. radiodurans* (Jung et al., 2017), suggesting they have a considerable contribution.

EFFICIENT DNA REPAIR MECHANISMS

Ionising radiation often induces DNA damage in the form of DNA double-strand breaks, bulky lesion cross-links, and single-strand breaks and damage (Liu, 2023). *D. radiodurans*, instead of directly preventing such damage, has evolved sophisticated DNA repair pathways to counteract such effects.

BASE EXCISION REPAIR

Base excision repair (BER) is primarily used to repair single-strand breaks and single-base damage induced by harmful chemicals, consisting mostly of AP endonucleases and exonucleases, which cleave nucleotides, and DNA glycosylases, which mainly excise damaged bases (Liu, 2023). BER is initiated by uracil-DNA glycosylases (UDG), which display specificity for a subset of damaged bases. This was evident by the significant reduction in radiation survival of UDG-deficient *D. radiodurans* (Liu, 2023). After recognizing a damaged base, the enzymes hydrolyze the N-glycosidic bond between the base and the sugar phosphate backbone, creating an abasic site (AP-site) and storing the base in its catalytic pocket. For monofunctional glycolases, an AP-endonuclease takes over the site, which cleaves the DNA. The 5'-overhang is removed by the

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dRP lyase activity of DNA polymerase, creating a 5' end, which allows the polymerase to reinstate a correct base. The gap is then sealed by DNA ligase (Timmins, 2016).

NUCLEOTIDE EXCISION REPAIR

Nucleotide excision repair (NER) is a universal DNA repair pathway in prokaryotes and eukaryotes (Liu, 2023). Bacterial NER is initiated by UvrA and UvrB, which act together as a dimer to recognize DNA damage. UvrA exits the site, and UvrB forms a stable complex by recruiting UvrC. UvrC is responsible for the 3' incision and the 5' incision of the site, yielding a 12- to 13-nucleotide fragment containing the damaged base. This fragment is released from the DNA duplex by the DNA helicase, UvrD. The gap is filled and sealed with the aid of DNA polymerase 1 and DNA ligase (Seck et al., 2022).

RECOMBINATION REPAIR

Recombination repair is the most important repair pathway in *D. radiodurans*, as it repairs double-strand breaks, the most severe form of DNA damage. Forms of recombinational repair include single-strand annealing (SSA), synthesis-dependent strand annealing (SDSA), extended synthesis-dependent strand annealing (ESDSA), and nonhomologous end joining (NHEJ) (Liu et al., 2023).

SSA begins when the protein Ssb binds to a single-strand DNA break, protecting the DNA from further degradation. The pathway then uses the multicopy genome as a template for annealing pairing between homologous single strands. DNA polymerase A and DNA polymerase 1 perform replication and extension, while DNA ligase completes the repair (Liu et al., 2023). SDSA, on the other hand, utilizes DdrA to form ring-like oligomers and bind to single-stranded DNA ends, thereby protecting them from degradation. *D. radiodurans* with low RecA expression, a protein crucial for other repair pathways, saw a reduction in IR resistance when ddrA was knocked out (Liu et al., 2023). A second protein, DdrB, then binds to the DNA to perform DNA annealing. ESDSA enables the use of chromosomes with homologous overlapping fragments as both primers and templates for DNA repair. NHEJ, a less-understood pathway, involves the PprA protein that binds specifically to damaged double-stranded DNA, as knocking out the pprA gene notably increases radiosensitivity of *D. radiodurans* (Kota et al., 2014).

CONCLUSION

Research on *D. radiodurans* and their radioresistant mechanisms allows for many further paths of innovation and development. The bacterium's DNA repair pathways and antioxidant systems, for example, provide many crucial insights for cancer therapies, which often involve sensitizing cancer cells to radiation while enhancing radioresistance among healthy human cells. Other advances include improving genetic engineering by

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mimicking the genetic makeup of *D. radiodurans*. The bacteria also have many direct practical uses, such as their aforementioned potential to clean up nuclear waste in radioactive environments and their transmission of DNA repair genes to other life forms. Furthermore, radioresistant bacteria support theories of life's potential on Mars and other planets due to their resilience to radiation, desiccation, and vacuum that characterize many extraterrestrial environments. The study of the curious bacterium's means of survival is a topic that warrants significantly more research.

REFERENCES

Agrawal, Dr. S. N., Satpathy, S., & Samal, D. (2020). Deinococcus Radiodurans: The World's Toughest Bacterium. A Review. *Global Journal of Medical Research*, *20*(2), 1–4. https://doi.org/10.34257/gjmrcvol20is2pg1

Battista, J. R. (1997). AGAINST ALL ODDS:The Survival Strategies of Deinococcus radiodurans. *Annual Review of Microbiology*, *51*(1), 203–224. https://doi.org/10.1146/annurev.micro.51.1.203

Chiasson, F., Borsa, J., & Lacroix, M. (2005). Combined Effect of Carvacrol and Packaging Conditions on Radiosensitivity of Escherichia coli and Salmonella Typhi in Ground Beef. *Journal of Food Protection*, *68*(12), 2567–2570. https://doi.org/10.4315/0362-028x-68.12.2567

Cox, M. M., & Battista, J. R. (2005). Deinococcus radiodurans — the consummate survivor. *Nature Reviews Microbiology*, *3*(11), 882–892. https://doi.org/10.1038/nrmicro1264

Daly, M. J. (2009). A new perspective on radiation resistance based on Deinococcus radiodurans. *Nature Reviews Microbiology*, *7*(3), 237–245. https://doi.org/10.1038/nrmicro2073

Daly, M. J., Gaidamakova, E. K., Matrosova, V. Y., Vasilenko, A., Zhai, M., Venkateswaran, A., Hess, M., Omelchenko, M. V., Kostandarithes, H. M., Makarova, K. S., Wackett, L. P., Fredrickson, J. K., & Ghosal, D. (2004). Accumulation of Mn(II) in Deinococcus radiodurans Facilitates Gamma-Radiation Resistance. *Science*, *306*(5698), 1025–1028. https://doi.org/10.1126/science.1103185

Harsojo, null, Kitayama, S., & Matsuyama, A. (1981). Genome multiplicity and radiation resistance in Micrococcus radiodurans. *Journal of Biochemistry*, *90*(3), 877–880. https://doi.org/10.1093/oxfordjournals.jbchem.a133544

Jung, K.-W., Lim, S., & Bahn, Y.-S. (2017). Microbial radiation-resistance mechanisms. *Journal of Microbiology*, *55*(7), 499–507. https://doi.org/10.1007/s12275-017-7242-5

Kota, S., Vijaya Kumar Charaka, & Misra, H. S. (2014). PprA, a pleiotropic protein for radioresistance, works through DNA gyrase and shows cellular dynamics during postirradiation recovery in Deinococcus radiodurans. *Journal of Genetics*, *93*(2), 349–354. https://doi.org/10.1007/s12041-014-0382-z

Liu, F., Li, N., & Zhang, Y. (2023). The radioresistant and survival mechanisms of Deinococcus radiodurans. *Radiation Medicine and Protection*, *4*(2). https://doi.org/10.1016/j.radmp.2023.03.001

Makarova, K. S., Aravind, L., Wolf, Y. I., Tatusov, R. L., Minton, K. W., Koonin, E. V., & Daly, M. J. (2001). Genome of the Extremely Radiation-Resistant Bacterium Deinococcus radiodurans Viewed from the

SCHOLARLY REVIEW JOURNAL

E-ISSN: 2996-8380
Published by Leadership & Innovation Lab

WINTER 2025/2026

Perspective of Comparative Genomics. *Microbiology and Molecular Biology Reviews*, *65*(1), 44–79. https://doi.org/10.1128/mmbr.65.1.44-79.2001

Minton, K. W. (1994). DNA repair in the extremely radioresistant bacterium Deinococcus radiodurans. *Molecular Microbiology*, *13*(1), 9–15. https://doi.org/10.1111/j.1365-2958.1994.tb00397.x

Most radiation-resistant lifeform. (n.d.). Guinness World Records. https://www.guinnessworldrecords.com/world-records/most-radiation-resistant-lifeform

Munteanu, A. - C., Uivarosi, V., & Andries, A. (2015). Recent progress in understanding the molecular mechanisms of radioresistance in Deinococcus bacteria. *Extremophiles*, *19*(4), 707–719. https://doi.org/10.1007/s00792-015-0759-9

Peana, M., Medici, S., Pangburn, H. A., Lamkin, T. J., Ostrowska, M., Gumienna-Kontecka, E., & Zoroddu, M. A. (2016). Manganese binding to antioxidant peptides involved in extreme radiation resistance in Deinococcus radiodurans. *Journal of Inorganic Biochemistry*, *164*(164), 49–58. https://doi.org/10.1016/j.jinorgbio.2016.08.012

Rew, D. A. (2003). Deinococcus radiodurans. *European Journal of Surgical Oncology*, *29*(6), 557–558. https://doi.org/10.1016/s0748-7983(03)00080-5

Romero, D., Martínez-Salazar, J., Ortiz, E., Rodríguez, C., & Valencia-Morales, E. (1999). Repeated sequences in bacterial chromosomes and plasmids: a glimpse from sequenced genomes. *Research in Microbiology*, *150*(9-10), 735–743. https://doi.org/10.1016/s0923-2508(99)00119-9

Seck, A., Salvatore De Bonis, Saint-Pierre, C., Didier Gasparutto, Jean-Luc Ravanat, & Timmins, J. (2022). In vitro reconstitution of an efficient nucleotide excision repair system using mesophilic enzymes from Deinococcus radiodurans. *Communications Biology*, *5*(1). https://doi.org/10.1038/s42003-022-03064-x

Sundar, H., Shree Padmini, & Parthiban Brindha Devi. (2023). Bioremediation of nuclear waste effluent using different communities of microbes. *Elsevier EBooks*, 403–444. https://doi.org/10.1016/b978-0-323-96113-4.00007-x

Sweet, P., Blacutt, J., Gordon, V., & Contreras, L. (2023). Exposure of Shewanella oneidensis MR-1 to Sublethal Doses of Ionizing Radiation Triggers Short-Term SOS Activation and Longer-Term Prophage Activation. *Applied and Environmental Microbiology*, *89*(3). https://doi.org/10.1128/aem.01716-22

Timmins, J., & Moe, E. (2016). A Decade of Biochemical and Structural Studies of the DNA Repair Machinery of Deinococcus radiodurans: Major Findings, Functional and Mechanistic Insight and Challenges. *Computational and Structural Biotechnology Journal*, *14*, 168–176. https://doi.org/10.1016/j.csbj.2016.04.001

Tsang, J. (2017, March 16). Meet a microbe: Deinococcus radiodurans. The Microbial Menagerie. https://microbialmenagerie.com/meet-a-microbe-deinococcus-radiodurans/

White, O. (1999). Genome Sequence of the Radioresistant Bacterium Deinococcus radiodurans R1. *Science*, *286*(5444), 1571–1577. https://doi.org/10.1126/science.286.5444.1571

SCHOLARLY REVIEW

SCHOLARLY REVIEW JOURNAL

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Zheng, Z., Su, J., Bao, X., Wang, H., Bian, C., Zhao, Q., & Jiang, X. (2023). Mechanisms and applications of radiation-induced oxidative stress in regulating cancer immunotherapy. *Frontiers in Immunology*, *14*. https://doi.org/10.3389/fimmu.2023.1247268