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Biodosimeters: Advancements in Radiation Detection and Monitoring

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ÖZ

Bu çalışma, biyolojik tepkileri ölçen biodosimetrelere derinlemesine bir bakış sunarak, insan sağlığı ve çevre için radyasyon maruziyetinin ciddi bir sorun olduğunu ve etkili radyasyon tespit ve izleme sistemlerine ihtiyaç duyulduğunu vurgulamaktadır. İlk bölümde biodosimetrelere ve radyasyon tespitinde ve izlenmesindeki kullanımlarına değinilmektedir. Güvenilir maruziyet seviyesi göstergeleri olarak kabul edilirler ve radyasyon güvenliğinde önemli bir rol oynarlar. Araştırma, kan bileşenlerini ve kromozomal değişiklikleri analiz eden hematolojik ve sitogenetik bioduyarlı sensörler gibi diğer biodosimetre türlerine de odaklanmaktadır. Takip eden bölümler, biodosimetrelere ilişkin işleyiş ve kullanımlara daha detaylı bir bakış sunmaktadır. Biodosimetrelere, radyasyon maruziyetinin gerçek zamanlı izlenmesine izin verdiği gibi sağlık sorunlarının erken tespitine de olanak tanır. Ayrıca, biodosimetrelere, tıbbi tedavilerde ve çevresel araştırmalarda hassas doz tahmini yapmada yardımcı olarak, radyasyon olayları sonrası çalışmaları mümkün kılar. Biodosimetrelere, işyeri radyasyon maruziyet izleme, radyoterapi, nükleer tıp ve çevresel radyasyon izleme gibi alanlarda, ekosistemler üzerindeki radyasyon etkisini incelemek için geniş ölçüde başvurulmaktadır. Son dönemdeki gelişmeler, onların doğruluğunu ve duyarlılığını artırarak, onları giyilebilir cihazlar ve IoT platformları ile entegre ederek basit ve gerçek zamanlı izleme imkanı sunmuştur. Rapor ayrıca, düşük maliyetli, yüksek duyarlılıkta radyasyon tespiti sağlayan bakteriyel bioduyarlı sensörlerin tanıtımına da vurgu yapmaktadır. Biodosimetre teknolojisinin ilerlemesi, özelleştirilmiş radyasyon maruziyet izleme ve uzay keşfi koruması için umut vaat etmektedir. Son olarak, biodosimetreler, geniş bir endüstri yelpazesini kapsayan radyasyon güvenliğinde kritik varlıklar olup, insan sağlığı ve çevre için daha güvenli ve daha güvenli bir gelecek sağlayarak gerçek zamanlı izleme ve erken risk tespiti sağlar.

Anahtar Kelimeler: *Biyodosimetreler; radyasyon; biyoduyarlar; hematoloji; tarama.*

Biodosimeters: Advancements in Radiation Detection and Monitoring

ABSTRACT

Radiation exposure is a serious problem for both human health and the environment, needing effective radiation detection and monitoring systems. Biodosimeters, which measure biological reactions to radiation, have emerged as cutting-edge technologies in this sector. This study takes an in-depth look at biodosimeters and their uses. The first section discusses biodosimeters and their use in radiation detection and monitoring. They are considered as dependable exposure level indicators and serve an important role in radiation safety. The research then looks into other forms of biodosimeters, such as hematological and cytogenetic biodosensors, which analyze blood components and chromosomal changes, respectively. The sections that follow go into the functioning and uses of biodosimeters in greater detail. They allow for real-time monitoring of radiation exposure as well as early detection of health problems. Furthermore, biodosimeters help with precise dose estimation in medical treatments and environmental investigations, allowing for post-radiation event study. Biodosimeters are widely used to examine the impact of radiation on ecosystems in occupational radiation exposure monitoring, radiotherapy, nuclear medicine, and environmental radiation monitoring. Recent advances have improved their accuracy and sensitivity, allowing them to be integrated with wearable devices and IoT platforms for simple and real-time monitoring. The report also emphasizes the introduction of bacterial biodosensors, which provide low-cost, high-sensitivity radiation detection options. The advancement of biodosimeter technology holds promise for tailored radiation exposure monitoring and space exploration protection. Finally, biodosimeters are critical assets in radiation safety, with applications covering a wide range of industries. They provide real-time monitoring and early risk detection, resulting in a safer and more secure future for human health and the environment.

Keywords: biodosimeters; radiation; biodosensors; hematology; screening.

1. Introduction

Biodosimeters are indispensable tools used for measuring radiation exposure levels and assessing its impact on biological systems. Their significance in radiation detection and monitoring is widely recognized, making them vital instruments in various fields. These innovative devices play a crucial role in ensuring radiation safety and protecting human health. At their core, biodosimeters are designed to detect and quantify radiation exposure [1]. They provide valuable insights into the amount of radiation absorbed by living organisms, including humans [2,3]. By utilizing different biological and physical markers, biodosimeters enable scientists and medical professionals to assess radiation doses accurately and monitor exposure over time. In this section, we will explore the different types of biodosimeters and their respective functions [4,5]. The variations in biodosimeters cater to specific applications, offering diverse approaches to radiation detection and monitoring. Biological biodosimeters, for instance, focus on analyzing biological materials, such as blood components or chromosomal alterations, to gauge radiation exposure levels. On the other hand, physical biodosimeters, such as thermoluminescent biodosimeters (TLD) and optically stimulated luminescence biodosimeters (OSL), rely on the measurement of luminescence to assess accumulated radiation doses [6,7].

The introduction of biodosimeters revolutionized radiation safety, especially in fields where exposure is a concern. They enable real-time monitoring of radiation levels, facilitating early identification of potential health risks [8]. Furthermore, biodosimeters have proven to be invaluable in post-radiation incident analysis, aiding in assessing the extent of exposure after radiological emergencies or accidents. Throughout this article, we will delve deeper into the functions and applications of biodosimeters in diverse settings. From occupational radiation exposure monitoring to their use in medical and clinical environments, biodosimeters have become indispensable tools for ensuring safe radiation practices [9,3]. Advancements in biodosimeter technology have further enhanced their accuracy and sensitivity, paving the way for integration with wearable devices and Internet of Things (IoT) platforms. These developments promise convenient and real-time monitoring of radiation exposure, making biodosimeters even more versatile and accessible in various scenarios. Looking ahead, the potential areas of research and development in biodosimeter technology are vast [4]. From exploring novel applications in personalized radiation exposure monitoring to their role in space exploration, biodosimeters continue to hold promising prospects for advancing radiation safety measures and protecting human health. Throughout this article, we will explore the intricacies of biodosimeters, their wide-ranging functions, and the exciting possibilities they hold for the future [10].

Biodosimeters are sophisticated devices used in radiation science to measure the level of radiation exposure and evaluate its impact on biological systems. These innovative tools play a vital role in the field of radiation detection and monitoring, providing valuable insights into the amount of radiation absorbed by living organisms, including humans [1,5]. The principle behind biodosimeters lies in their ability to analyze specific biomarkers and cellular changes that occur in response to radiation exposure. When ionizing radiation interacts with biological tissues, it can cause various alterations, such as DNA damage or changes in cellular function. Biodosimeters are designed to detect and quantify these changes, thereby offering a means to estimate the absorbed radiation dose accurately [11]. One of the essential applications of biodosimeters is in the field of personnel monitoring, especially for individuals working in environments where radiation exposure is a concern, such as nuclear power plants, radiological research facilities, and medical facilities utilizing ionizing radiation in treatments [12]. By regularly monitoring the radiation exposure levels of workers, employers can ensure that safety regulations are adhered to, and employees are protected from excessive radiation doses. Furthermore, biodosimeters have proven to be invaluable in assessing the potential health risks associated with radiation exposure. By analyzing biological samples and cellular responses, scientists and medical professionals can identify early signs of radiation-induced health issues, allowing for timely interventions and appropriate medical care [12, 13].

Biodosimeters play a critical role in ensuring radiation safety across various applications and industries. By providing real-time data on radiation exposure, these devices enable professionals to take proactive measures to minimize potential health risks and prevent overexposure to radiation. In occupational settings, where workers are regularly exposed to radiation, biodosimeters are extensively used for personnel monitoring. By wearing biodosimeters, employees can have their radiation exposure levels continuously monitored, ensuring that they remain within safe limits prescribed by regulatory agencies. This monitoring not only protects workers' health but also assists in compliance with safety standards [14]. In medical and clinical settings, biodosimeters are indispensable in radiotherapy treatments. Precise and accurate monitoring of radiation doses during treatments is crucial to effectively target cancerous cells while minimizing damage to healthy tissues. Biodosimeters assist medical practitioners in optimizing treatment plans and ensuring that the radiation dose delivered is within the therapeutic range [15]. Environmental radiation monitoring is another significant application of biodosimeters. By measuring radiation levels in the environment, scientists can study the impact of radiation on ecosystems and wildlife. This data aids in understanding the potential risks to the environment and supports conservation efforts. With advancements in technology, biodosimeters are becoming more user-friendly and convenient. Integration with wearable devices and IoT platforms allows for continuous and real-time monitoring of radiation exposure. This integration enhances radiation safety practices in various industries, including emergency response and disaster management, where rapid assessment of radiation exposure is crucial. Overall, biodosimeters play a vital role in safeguarding human health, protecting the environment, and ensuring that radiation is used safely and responsibly in various applications. Their contributions in monitoring and assessing radiation exposure levels are instrumental in promoting radiation safety and mitigating potential health risks [16, 17].

2. Importance in Radiation Detection And Monitoring

Biodosimeters play a crucial role in the field of radiation detection and monitoring, offering significant benefits in various environments where radiation exposure is a concern [15,18]. These advanced devices have revolutionized the way we assess and manage radiation exposure, providing valuable data to ensure radiation safety and protect human health [7,10].

Biodosimeters serve as invaluable tools for detecting and quantifying radiation exposure levels across diverse settings. From nuclear power plants to radiological research facilities and medical institutions, biodosimeters are at the forefront of radiation monitoring [19]. The ability to analyze biological and physical markers allows biodosimeters to offer accurate and reliable assessments of radiation doses absorbed by individuals. In occupational environments, where workers may face routine exposure to radiation, biodosimeters play a crucial role in personnel monitoring [3]. By wearing biodosimeters, employees can have their radiation exposure continuously monitored, providing crucial data to ensure they remain within safe exposure limits. This not only safeguards workers' health but also helps employers comply with safety standards and regulatory requirements. In the context of emergency response and disaster management, biodosimeters are vital assets. In the aftermath of radiological incidents or accidents, biodosimeters enable rapid and precise assessment of radiation exposure in affected individuals. This data allows authorities to respond promptly and provide appropriate medical care to those in need [20, 21, 22].

Real-time monitoring is a critical aspect of radiation safety, especially in high-risk environments. Biodosimeters offer the advantage of continuous monitoring, providing immediate feedback on radiation exposure levels. This real-time data empowers workers, emergency responders, and medical personnel to take necessary precautions if exposure levels approach or exceed safety thresholds, thus preventing potential health risks [23]. Moreover, one of the most significant contributions of biodosimeters lies in their ability to facilitate early identification of potential health risks associated with radiation exposure. By analyzing biological samples and detecting changes at a cellular level, biodosimeters can alert medical professionals to early signs of radiation-induced health issues. Timely identification of such risks can lead to early intervention and appropriate medical care, improving treatment outcomes and minimizing potential health complications. Beyond the immediate benefits in radiation safety, biodosimeters also contribute to ongoing research and development in radiation science [24]. The data collected by these devices helps scientists better understand the effects of radiation on the human body and contributes to advancements in radiation protection and medical treatments. In conclusion, biodosimeters have become indispensable instruments in radiation detection and monitoring. Their ability to detect and quantify radiation exposure in diverse environments, coupled with real-time monitoring capabilities and early identification of health risks, makes them essential tools for ensuring radiation safety and protecting human health [25]. As technology continues to advance, biodosimeters hold promise for even greater precision and expanded applications, further advancing our understanding and management of radiation exposure [26, 27].

3. Significance of Biodosimeters in Radiation Detection and Monitoring

Biodosimeters hold immense significance in radiation detection and monitoring, garnering widespread recognition as reliable indicators of radiation exposure levels. These advanced devices have revolutionized the field of radiation science, playing a pivotal role in safeguarding human health and contributing to radiation safety across various applications [28, 29].

Biodosimeters have gained global acknowledgment and trust as accurate tools for measuring radiation exposure. Their ability to analyze specific biomarkers and cellular changes in response to radiation makes them highly reliable indicators of absorbed radiation doses. The scientific community, regulatory agencies, and industries alike have embraced biodosimeters as essential instruments for ensuring radiation safety [30,31]. The versatility of biodosimeters allows for their application in a wide range of scenarios. From routine personnel monitoring in nuclear power plants to emergency response situations, biodosimeters have proven their effectiveness in providing real-time data on radiation exposure levels. As a result, they have become instrumental in both planned radiation activities and unforeseen radiological incidents, aiding in efficient emergency management and response [32,33].

The role of biodosimeters in contributing to radiation safety cannot be overstated. By providing accurate and timely information on radiation exposure levels, biodosimeters empower individuals and organizations to make informed decisions that minimize potential health risks associated with radiation. In occupational settings, where workers may encounter radiation as part of their daily tasks, biodosimeters offer a proactive approach to personnel monitoring.

Through continuous and real-time monitoring, employers can ensure that radiation exposure remains within safe limits, fostering a safe working environment and protecting the health of their workforce [3, 34]. Additionally, biodosimeters play a critical role in medical and clinical applications, particularly in radiotherapy treatments. The precise monitoring of radiation doses during medical procedures ensures that cancer patients receive optimal treatment while minimizing damage to surrounding healthy tissues. This not only enhances treatment effectiveness but also reduces the risk of long-term side effects. Moreover, biodosimeters contribute to the broader field of radiation research, aiding in understanding the effects of radiation on biological systems. The data collected by biodosimeters allows scientists to improve radiation protection measures and develop innovative medical treatments [35]. As technology continues to advance, biodosimeters hold even greater promise for the future. Integration with wearable devices and IoT platforms enables convenient and continuous monitoring of radiation exposure, further enhancing radiation safety practices across diverse industries. In conclusion, biodosimeters have emerged as essential and reliable tools in radiation detection and monitoring. Their wide recognition as accurate indicators of radiation exposure levels, coupled with their contribution to radiation safety and the protection of human health, solidifies their significance in the field of radiation science. With ongoing research and technological advancements, biodosimeters will continue to play a vital role in ensuring safe and responsible use of radiation, ultimately contributing to the well-being of individuals and the environment [36].

4. TYPES OF BIODOSIMETERS

When it comes to biodosimeters, there are several types that cater to different aspects of radiation detection and monitoring. Each type has its unique characteristics and applications, making them valuable tools in diverse scenarios. Hematological biodosimeters focus on analyzing blood components to assess radiation exposure levels. By studying specific biomarkers in blood samples, such as micronuclei or chromosomal aberrations, these biodosimeters provide valuable insights into the absorbed radiation dose. They are particularly useful in medical settings, research facilities, and even emergency response situations [37,38]. Cytogenetic biodosimeters evaluate radiation-induced chromosomal alterations, providing information about the extent of radiation exposure. These biodosimeters are instrumental in understanding the biological effects of radiation and are frequently used in research and medical fields. Each type of biodosimeter has its strengths and applications, and the selection depends on specific requirements, such as the type of radiation, the environment, and the purpose of monitoring [2,4]. The continuous advancements in biodosimeter technology promise even greater precision and capabilities in the future, further enhancing our ability to detect and monitor radiation exposure levels effectively. As we delve deeper into each type of biodosimeter, we will discover their unique functions and the essential role they play in radiation safety and protection [39,40].

Biological biodosimeters encompass a range of techniques that rely on biological materials to assess radiation exposure levels. Two common types of biological biodosimeters are the hair biodosimeter and the DNA comet assay, each offering valuable insights into radiation-induced changes in biological systems[41,42].

4.1. Hair Biodosimeter

The hair biodosimeter involves analyzing hair samples to estimate radiation exposure levels. Hair has the unique property of preserving a chronological record of exposure to ionizing radiation, making it a convenient and non-invasive tool for retrospective dosimetry. As hair grows, it incorporates stable isotopes of certain elements, such as carbon and oxygen, which can serve as radiation exposure markers[43]. By analyzing the isotopic composition of hair strands, scientists can approximate the cumulative radiation dose received over a specific period. Hair biodosimeters are particularly useful in situations where other biological samples might not be readily available or when assessing long-term exposure over several months or years. They have found applications in retrospective dosimetry for individuals exposed to radiation due to medical treatments, occupational settings, or radiological incidents [4, 44].

4.2. DNA Comet Assay

The DNA comet assay, also known as the single-cell gel electrophoresis assay, is a sensitive technique used to evaluate DNA damage caused by radiation exposure. In this assay, individual cells are embedded in agarose gel, subjected to electrophoresis, and then stained with a fluorescent dye[45]. When viewed under a microscope, the DNA fragments resemble a "comet" shape, with the extent of "comet tail" indicating the level of DNA damage. The comet assay is highly versatile, allowing scientists to assess DNA damage in various cell types and tissues. It is particularly valuable in biodosimetry for detecting acute radiation exposure and assessing the effectiveness of radiation protection measures. The comet assay is commonly used in research, emergency response scenarios, and environmental radiation monitoring[46,47]. Both hair biodosimeters and the DNA comet assay play essential roles in assessing radiation exposure levels and understanding its impact on biological systems[48]. These biological biodosimeters complement other techniques, such as cytogenetic biodosimeters and hematological biodosimeters, in providing a comprehensive assessment of radiation exposure. By combining multiple biodosimetric approaches, we gain a better understanding of radiation effects, enabling us to enhance radiation safety practices and protect human health effectively [49, 50, 51].

4.3. Hematological Biodosimeters

Hematological biodosimeters are specialized tools used to assess radiation exposure levels by analyzing blood components. These biodosimeters rely on changes in blood cells and their characteristics, induced by exposure to ionizing radiation, to estimate the absorbed radiation dose [1, 52]. Hematological biodosimeters are based on the principle that ionizing radiation can cause alterations in blood cell populations and their properties. When the body is exposed to radiation, it can lead to various changes in blood cells, which can be detected and quantified through hematological biodosimetry [2,5]. Blood samples are collected from individuals exposed to radiation, and specific blood components are analyzed to determine the extent of radiation exposure. The advantage of hematological biodosimetry lies in its non-invasive nature, as blood samples are relatively easy to obtain and analyze. Hematological biodosimeters utilize several biomarkers to assess the effects of radiation on blood cells. Two common biomarkers used in hematological biodosimetry are micronuclei and chromosomal aberrations [53, 54].

4.3.1. Micronuclei

Micronuclei are small, additional nuclei that may form in cells after exposure to radiation or genotoxic agents. These micronuclei arise due to chromosomal fragments or whole chromosomes that are not incorporated into the main nucleus during cell division [55, 56]. In hematological biodosimetry, the presence and frequency of micronuclei in blood cells, such as lymphocytes or erythrocytes, are analyzed. The number of micronuclei is directly proportional to the absorbed radiation dose, making them valuable indicators of radiation exposure levels [57, 58].

4.3.2. Chromosomal Aberrations

Chromosomal aberrations refer to structural changes or abnormalities in chromosomes that result from exposure to ionizing radiation. Such changes may include breaks, deletions, translocations, or inversions of chromosomal segments [59]. Hematological biodosimetry involves analyzing blood cells for these chromosomal aberrations, particularly in lymphocytes. The frequency and types of chromosomal aberrations observed in the blood cells provide valuable information about the magnitude of radiation exposure [37,60]. By analyzing these hematological biomarkers, scientists and medical professionals can estimate the absorbed radiation dose accurately. Hematological biodosimeters are particularly valuable in emergency response situations, where rapid assessment of radiation exposure is crucial, as well as in long-term monitoring of individuals exposed to radiation due to medical treatments or occupational settings [61, 62]. The data obtained through hematological biodosimetry aids in medical decision-making, ensuring the safety of individuals exposed to radiation and contributing to better understanding and management of radiation-related risks [1, 63].

4.4. Cytogenetic Biodosimeters

Cytogenetic biodosimeters are specialized tools used to evaluate radiation-induced chromosomal alterations as a means to estimate the absorbed radiation dose. These biodosimeters focus on the analysis of chromosomal changes that occur in response to ionizing radiation exposure, providing valuable insights into the extent of radiation damage. Cytogenetic biodosimeters are a subset of biodosimetry techniques that specifically target the effects of radiation on chromosomes. When cells are exposed to ionizing radiation, it can cause breaks or other structural changes in the DNA of chromosomes. Cytogenetic biodosimeters capitalize on these changes to assess the magnitude of radiation exposure [59]. The key biological material used in cytogenetic biodosimetry is usually lymphocytes, which are white blood cells that play a crucial role in the immune system. Lymphocytes are particularly sensitive to radiation and readily exhibit chromosomal alterations after exposure. By analyzing the chromosomal changes in lymphocytes, cytogenetic biodosimetry provides a reliable and accurate method for assessing the absorbed radiation dose. Cytogenetic biodosimeters quantitatively assess the absorbed radiation dose based on the frequency and types of chromosomal alterations observed in lymphocytes. The dose-response relationship between the absorbed radiation dose and the extent of chromosomal damage is well established, allowing for a precise estimation of the radiation dose received by an individual [3]. One of the primary chromosomal alterations detected by cytogenetic biodosimeters is the formation of dicentric chromosomes. Dicentric chromosomes result from the fusion of two damaged chromosomes and are highly specific to radiation exposure. The number of dicentric chromosomes observed in lymphocytes serves as a direct indicator of the absorbed radiation dose, even when exposure occurs in a short period. Cytogenetic biodosimeters are especially valuable in emergency situations, where a rapid and accurate assessment of radiation exposure is essential for medical decision-making and appropriate treatment. In the event of a radiological incident or accident, cytogenetic biodosimetry plays a crucial role in identifying individuals exposed to high levels of radiation and prioritizing their medical care[64]. Furthermore, cytogenetic biodosimetry is used in long-term monitoring of individuals with potential occupational radiation exposure or those receiving radiotherapy treatments. Regular monitoring of chromosomal changes in lymphocytes allows for the continuous evaluation of radiation doses received, ensuring safety and providing valuable data for the optimization of radiation treatments. In conclusion, cytogenetic biodosimeters are invaluable tools in radiation science, focusing on the evaluation of chromosomal alterations induced by radiation exposure. By quantifying the absorbed radiation dose through the analysis of chromosomal changes, these biodosimeters offer a reliable method for radiation dose assessment. Their applications range from emergency response situations to routine monitoring, contributing to radiation safety practices and the protection of human health in various contexts [64, 65].

4.5. Bacterial Biodosimeters

In recent years, bacterial biodosimeters have emerged as a novel and promising approach in the field of radiation detection and monitoring. These innovative biodosensors utilize the remarkable ability of certain bacteria to respond to radiation exposure by activating specific genes or undergoing morphological changes. This response can be measured and quantified, providing valuable data on the level of radiation exposure. Bacterial biodosimeters offer several advantages that make them attractive for various applications. Firstly, they are cost-effective and easy to use, making them suitable for large-scale monitoring in radiation-prone environments. Unlike traditional biodosimeters that may require complex processing and analysis, bacterial biodosensors can often provide rapid and straightforward readouts. Moreover, bacterial biodosimeters demonstrate high sensitivity to low levels of radiation, allowing for the detection of even subtle changes in exposure. This sensitivity is particularly valuable in environments where radiation levels might be relatively low but still pose potential health risks over extended periods. The versatility of bacterial biodosensors extends to different types of radiation, such as ionizing and non-ionizing radiation. This adaptability allows researchers and professionals to utilize bacterial biodosimeters in a wide range of radiation-related studies and applications [66,67]. One of the most significant advantages of bacterial biodosimeters is their potential for real-time monitoring. Due to their rapid response to radiation, these biodosensors can provide continuous data, enabling immediate assessment of radiation exposure levels. Real-time monitoring is especially valuable in emergency situations or high-risk environments where rapid decision-making is crucial for ensuring the safety of individuals [68]. Several types of bacteria have been used as biodosensors in bacterial biodosimeters. Some of the commonly used bacterial species include:

4.5.1. Escherichia coli (E. coli)

E. coli is a well-known bacterium that has been extensively used in biological research. It possesses various stress response genes that can be activated in response to radiation exposure, making it a popular choice for bacterial biodosensors [69].

4.5.2. Deinococcus radiodurans

Deinococcus radiodurans is a remarkable bacterium known for its extreme resistance to radiation. It can withstand very high doses of ionizing radiation and repair its damaged DNA efficiently. Due to its unique radiation resistance, *D. radiodurans* is often employed as a model organism for studying the effects of radiation and for developing biodosensors.

4.5.3. Pseudomonas putida

Pseudomonas putida is a versatile bacterium that can detect and respond to various environmental stresses, including radiation exposure. Researchers have explored its potential as a biodosensor in environmental monitoring and radiation studies [67].

4.5.4. Bacillus subtilis

Bacillus subtilis is another bacterium known for its ability to survive under extreme conditions, including exposure to ionizing radiation. It contains genes that respond to radiation-induced stress, making it a candidate for biodosensor development [66].

4.5.5. Shewanella oneidensis

Shewanella oneidensis is a bacterium that has been investigated for its ability to generate an electric current in response to radiation exposure. This unique property makes it a promising candidate for radiation biodosensors with potential applications in bioenergy and environmental monitoring.

The choice of bacterial species depends on the specific requirements of the biodosimeter application, the type of radiation being monitored, and the desired sensitivity and response characteristics. Researchers continue to explore different bacterial strains and their genetic responses to radiation exposure to optimize and expand the capabilities of bacterial biodosensors for various radiation monitoring purposes [70]. Although bacterial biodosimeters show great promise, ongoing research and development are still needed to further optimize their performance and reliability. This includes exploring different bacterial strains and their responses to various radiation types, as well as refining the methodologies for data collection and analysis. Bacterial biodosimeters represent an exciting advancement in the field of radiation detection and monitoring. Their cost-effectiveness, high sensitivity, and real-time monitoring potential make them valuable tools in various applications, including environmental radiation monitoring, occupational safety, and emergency response. As research in this area continues to progress, bacterial biodosensors hold great potential to contribute significantly to radiation safety and protection of human health and the environment [71, 72].

5. Functions of Biodosimeters

5.1. Real-time Monitoring of Radiation Exposure

Biodosimeters play a crucial role in facilitating real-time monitoring of radiation exposure, providing continuous and immediate feedback on the level of radiation to which an individual or a group of people are exposed [73]. This function is essential in various high-risk environments where radiation safety is paramount. Real-time monitoring with biodosimeters is made possible through their ability to rapidly analyze and assess changes in biological or physical markers in response to radiation exposure [74]. Depending on the type of biodosimeter used, this could involve analyzing blood components, detecting luminescence in crystals, or assessing DNA damage in cells. In occupational settings, wearable biodosimeters can be easily integrated into the daily attire of workers, allowing for continuous monitoring during their work shifts. These wearable devices provide immediate readings and can transmit data to a centralized monitoring system, enabling supervisors and safety personnel to keep a close watch on radiation exposure levels in real-time. For personnel working in environments with a risk of sudden radiological incidents, portable handheld biodosimeters offer rapid assessment capabilities. These handheld devices can be quickly deployed to assess radiation exposure levels during emergency response situations, providing crucial data for decision-making and emergency management.

In high-risk occupational settings, such as nuclear power plants, radiological research facilities, and medical institutions that utilize ionizing radiation, real-time monitoring with biodosimeters is of paramount importance [75,76]. Workers in these environments are regularly exposed to radiation, and continuous monitoring is essential to ensure their safety. In nuclear power plants, where workers handle radioactive materials and are exposed to various sources of radiation, wearable biodosimeters can provide real-time data on their radiation exposure levels. If exposure levels approach or exceed safety limits, immediate action can be taken to mitigate risks and protect workers from potential health hazards. Similarly, in medical settings where radiation is used for diagnostic or therapeutic purposes, such as in radiation oncology or interventional radiology, real-time monitoring is crucial. Biodosimeters can ensure that patients receive the prescribed radiation dose accurately and that medical staff is not exposed to excessive radiation during procedures [77]. Moreover, real-time monitoring with biodosimeters is valuable in emergency response scenarios, such as radiological accidents or nuclear incidents. Rapid assessment of radiation exposure levels in affected individuals allows emergency responders to prioritize medical care and allocate resources effectively. In conclusion, the real-time monitoring function of biodosimeters is a powerful tool for ensuring radiation safety in high-risk environments [78,79]. By providing continuous and immediate feedback on radiation exposure levels, biodosimeters empower individuals and organizations to take proactive measures, protecting human health and minimizing potential risks associated with radiation exposure. Whether in routine occupational monitoring or emergency response situations, real-time biodosimetry significantly contributes to radiation safety practices and the overall well-being of individuals in radiation-prone environments [80, 81].

5.2. Dose Assessment and Accumulated Exposure Measurement

Biodosimeters play a vital role in accurately assessing radiation doses and measuring cumulative exposure over time. These sophisticated instruments provide valuable data that enables professionals to make informed decisions about radiation safety in various fields, including medical treatments, environmental studies, and emergency response scenarios.

Biodosimeters employ various biological and physical markers to assess radiation doses accurately. In the case of biological biodosimeters, such as hematological and cytogenetic biodosimeters, changes in blood components or chromosomal alterations are analyzed to determine the extent of radiation exposure. These biomarkers respond to radiation in predictable ways, allowing for a direct correlation between the observed changes and the absorbed radiation dose.

Physical biodosimeters, like thermoluminescent and optically stimulated luminescence biodosimeters, work based on the principle of luminescence. When exposed to radiation, these biodosimeters absorb energy, which is later released as light when heated or stimulated with specific wavelengths of light [82]. The intensity of the emitted light is directly proportional to the absorbed radiation dose, making them reliable tools for dose assessment. Furthermore, biodosimeters enable the measurement of accumulated exposure over time. By monitoring radiation exposure continuously or through periodic assessments, biodosimeters allow for the determination of the total radiation dose received over a specific duration. This cumulative exposure data is valuable in assessing long-term effects, setting safety standards, and optimizing radiation protection measures. Dose assessment is of utmost significance in various fields where radiation exposure is a concern [83]. In medical treatments, such as radiotherapy for cancer patients, precise dose assessment is essential to deliver the correct amount of radiation to target cancer cells while minimizing damage to healthy tissues. Biodosimeters play a critical role in verifying that the prescribed radiation dose is accurately administered, ensuring the effectiveness and safety of the treatment. In environmental studies, biodosimeters aid in assessing the impact of radiation on ecosystems and wildlife. By measuring radiation exposure levels in environmental samples, researchers can study the effects on biodiversity, identify potential risks to the environment, and develop conservation strategies. In emergency response scenarios, such as radiological incidents or nuclear accidents, dose assessment is crucial in identifying exposed individuals and prioritizing medical care [84].

Biodosimeters offer rapid and accurate dose estimation, helping emergency responders make informed decisions and allocate resources effectively during the critical early stages of response. Moreover, accumulated exposure measurement through biodosimeters allows for long-term monitoring of radiation workers and individuals in high-risk environments. Regular assessment of cumulative exposure ensures that safety limits are not exceeded, minimizing the risk of adverse health effects, and protecting the well-being of those working with or around ionizing radiation. It can be said that biodosimeters' ability to accurately assess radiation doses and measure accumulated exposure over time is invaluable in medical treatments, environmental studies, and emergency response. By providing reliable dose data, biodosimeters enhance radiation safety practices, contribute to research and regulatory efforts, and ultimately safeguard human health and the environment from the potential risks associated with radiation exposure [85, 86].

5.3. Early Identification of Potential Health Risks

Biodosimeters play a crucial role in the early identification of potential health risks caused by radiation exposure. These sophisticated instruments allow for the detection of subtle biological changes and cellular responses that occur in response to radiation, enabling timely interventions and proactive health monitoring. Biodosimeters, especially cytogenetic and hematological biodosimeters, offer valuable insights into the effects of radiation on biological systems. For instance, cytogenetic biodosimeters can detect specific chromosomal aberrations in cells, while hematological biodosimeters analyze blood components for changes induced by radiation exposure. These alterations serve as biomarkers that indicate the body's response to radiation and potential health risks [87]. Early identification of such radiation-induced changes through biodosimeters allows medical professionals and researchers to recognize the initial signs of radiation-related health issues. Detecting these changes early can lead to further investigations and targeted health monitoring, facilitating timely interventions to prevent or minimize the progression of adverse health effects. The ability to identify potential health risks early based on biodosimeter data is of paramount importance in radiation safety and medical contexts. For individuals exposed to high radiation doses, prompt and appropriate medical care is crucial to mitigate the health impacts. By detecting early signs of radiation-induced damage through biodosimeters, healthcare providers can implement personalized treatment plans and closely monitor the individual's health to ensure optimal outcomes [88].

In occupational settings where workers may face routine radiation exposure, early identification of health risks through regular biodosimetry monitoring enables employers to take timely actions to protect their employees' well-being. Implementing safety measures and optimizing radiation protection practices can help prevent overexposure and long-term health complications. In addition to occupational settings, biodosimeters are vital tools for monitoring individuals undergoing medical treatments involving ionizing radiation. In cancer patients receiving radiotherapy, for example, biodosimeters can help assess the radiation dose delivered to healthy tissues surrounding the tumor[89]. By identifying any deviations from the planned dose, adjustments can be made to improve treatment accuracy and reduce the risk of adverse effects. Furthermore, in the context of emergency response to radiological incidents or nuclear accidents, biodosimeters are indispensable for triaging exposed individuals. Early identification of individuals with potentially high radiation doses ensures they receive priority medical attention, enabling timely interventions to minimize radiation-related health risks [90].

There is an obvious result that should be underlined, biodosimeter readings serve as early indicators of potential health risks caused by radiation exposure. By detecting subtle biological changes and cellular responses, biodosimeters enable timely interventions and health monitoring, ultimately contributing to radiation safety and protecting individuals from adverse health effects. The data obtained from biodosimeters plays a vital role in optimizing medical treatments, safeguarding radiation workers, and guiding emergency response efforts, highlighting their significance in ensuring the well-being of individuals exposed to ionizing radiation [91, 92].

5.4. Post-Radiation Incident Analysis

Biodosimeters play a crucial role in analyzing radiation exposure levels and evaluating the impact of radiological incidents or accidents. After such events, biodosimeters provide essential data that helps assess the extent of radiation exposure, understand its effects on individuals, and plan appropriate responses to ensure the safety and well-being of those affected. In the aftermath of a radiological incident or accident, one of the primary concerns is assessing the radiation exposure levels of individuals who may have been affected. [4] Biodosimeters are invaluable tools for this task, as they can quickly and accurately measure radiation doses absorbed by individuals during the incident. Emergency responders can rapidly collect biological samples, such as blood or tissue, from those involved in the incident. These samples are then analyzed using biodosimeters, such as cytogenetic biodosimeters or hematological biodosimeters, to detect specific biomarkers or chromosomal changes indicative of radiation exposure. By analyzing the biodosimeter data, authorities can identify individuals who have received high radiation doses and require immediate medical attention. This information allows for the prioritization of medical care and ensures that resources are allocated efficiently during the emergency response [93, 94]. Biodosimeters provide essential information for understanding the extent of radiation exposure and its potential health effects on affected individuals. The data obtained from biodosimeter readings allow experts to estimate the absorbed radiation dose and assess the severity of exposure. This understanding of the extent of exposure is crucial for planning appropriate responses and medical interventions. It helps healthcare professionals anticipate potential health risks and design targeted treatment strategies for individuals with high radiation doses. For those with lower exposure levels, health monitoring and follow-up care can be tailored to address specific risks. Moreover, the biodosimeter data aids in determining the scope of the radiological incident and its impact on the environment. Environmental samples can also be analyzed using biodosimeters to assess radiation levels in affected areas and wildlife. With this comprehensive assessment of the incident's impact, authorities can implement effective safety measures and decontamination protocols to minimize further exposure risks [95]. Additionally, the biodosimeter data contributes to the ongoing research and development of radiation protection measures, ensuring that lessons learned from the incident are applied to enhance preparedness for future radiological events.

Finally, biodosimeters play a crucial role in post-radiation incident analysis by providing accurate and timely information on radiation exposure levels. This data is instrumental in understanding the extent of exposure, planning appropriate medical responses, and implementing safety measures. By enabling swift assessment and response, biodosimeters contribute significantly to emergency management efforts and help safeguard the health and well-being of individuals affected by radiological incidents or accidents [3].

6. Applications of Biodosimeters

Biodosimeters find diverse applications in various fields, including occupational radiation exposure monitoring, medical and clinical settings, as well as environmental radiation monitoring [96, 97]. These advanced instruments play a crucial role in ensuring radiation safety, optimizing medical treatments, and assessing radiation's impact on the environment, including in CBRN (Chemical, Biological, Radiological, and Nuclear) contexts [98, 99].

6.1. Occupational Radiation Exposure Monitoring

In occupational settings where workers may encounter radiation as part of their daily tasks, biodosimeters are extensively used to monitor radiation exposure. These settings include nuclear power plants, research facilities, industrial radiography, and other industries dealing with radioactive materials. Biodosimeters provide continuous or periodic monitoring, enabling employers to track and manage radiation doses received by workers accurately[11, 3].

Regulatory agencies and guidelines often mandate occupational radiation monitoring programs to ensure worker safety. Biodosimeters play a crucial role in complying with these regulations, providing precise data on radiation exposure. Employers implement biodosimeter-based monitoring programs to assess compliance with safety standards, identify potential overexposure, and take appropriate measures to protect workers' health[100, 101].

6.2. Medical and Clinical Settings

6.2.1. Radiotherapy

In radiotherapy, where radiation is used to treat cancer, biodosimeters play a crucial role in ensuring accurate and safe radiation doses to patients. Biodosimeters are employed to verify the delivered radiation dose during treatments, enabling radiation oncologists to adjust treatment plans and optimize dose distribution for better tumor targeting and sparing of healthy tissues [102]. Advancements in biodosimetry techniques have revolutionized radiotherapy planning and optimization. Biodosimeters allow for personalized treatment plans based on individual patient responses to radiation. This approach, known as "biologically guided radiotherapy," enhances treatment efficacy and reduces the risk of radiation-induced side effects[103, 104].

6.2.2. Nuclear Medicine

Biodosimeters have valuable applications in nuclear medicine, where radioactive materials are used for diagnostic and therapeutic procedures. Biodosimeters enable patient-specific dose monitoring, ensuring that the administered dose is appropriate for effective diagnosis and treatment while minimizing unnecessary radiation exposure. In diagnostic nuclear medicine, biodosimeters aid in optimizing imaging procedures to achieve accurate diagnostic information with the least possible radiation dose to patients. In therapeutic nuclear medicine, biodosimeters assist in monitoring and adjusting the radiation dose during treatments, optimizing treatment outcomes while protecting healthy tissues[105, 106].

6.3. Environmental Radiation Monitoring

Biodosimeters are valuable tools for environmental radiation monitoring, allowing researchers to assess radiation levels in the environment accurately. By analyzing biodosimeter responses in plants, animals, or environmental samples, scientists gain insights into the level of radiation present in specific ecosystems [107]. Environmental studies utilizing biodosimeters help understand radiation's impact on ecosystems and wildlife. Researchers can assess how radiation exposure affects organisms' health and behavior, providing valuable data for conservation efforts and ecosystem management [108].

In conclusion, biodosimeters have diverse applications in occupational, medical, and environmental settings, providing crucial data for radiation safety, medical treatments, and environmental studies. Their contribution is especially significant in CBRN contexts, where biodosimeters aid in monitoring and mitigating the impact of radiation, contributing to overall human and environmental well-being[109].

7. ADVANCEMENTS AND FUTURE PROSPECTS

Biodosimeters, as essential tools for radiation detection and monitoring, have witnessed significant technological advancements that promise to revolutionize various applications, including space exploration and personalized radiation exposure monitoring. These innovations aim to enhance accuracy, sensitivity, and convenience, making biodosimeters even more indispensable in diverse fields[4, 110].

Recent years have seen remarkable progress in biodosimeter technology. Researchers and engineers have focused on improving the sensitivity and precision of biodosimeters, enabling them to detect even lower levels of radiation exposure. New materials and sensor designs have been incorporated, enhancing the biodosimeters' capabilities to accurately assess radiation doses across various dose ranges. Advancements in data processing and analysis have led to faster and more efficient biodosimeter readouts. Automated biodosimeter systems are now capable of providing real-time data, facilitating rapid decision-making in critical situations. The improved accuracy and sensitivity of biodosimeters have opened up new opportunities, particularly in the realm of space exploration. Space missions expose astronauts to elevated levels of cosmic radiation, posing potential health risks. Advanced biodosimeters are being developed to precisely measure radiation exposure in space environments, ensuring the safety of astronauts during extended missions beyond Earth. Accurate biodosimetry in space is not only critical for astronaut health but also for developing strategies to protect future space travelers during long-duration missions to the moon, Mars, or beyond. By providing real-time radiation monitoring, biodosimeters contribute to designing safer spacecraft and developing adequate shielding measures [2, 111].

An emerging trend in biodosimeter technology is their integration into wearable devices and Internet of Things (IoT) platforms. Miniaturized biodosensors can now be seamlessly incorporated into wearable gadgets, such as smartwatches or badges, offering continuous, non-invasive monitoring of radiation exposure. IoT platforms allow biodosimeter data to be collected, analyzed, and transmitted in real-time, enabling centralized monitoring and data sharing. This integration enhances radiation safety, as individuals working in radiation-prone environments can receive instant alerts if exposure levels exceed safety limits [112, 113].

The integration of biodosimeters with wearable devices and IoT platforms holds tremendous potential for revolutionizing radiation exposure monitoring. Workers in high-risk occupational settings can have personalized biodosimeter wearables, empowering them to proactively manage their radiation exposure levels. In emergency response scenarios, first responders equipped with biodosimeter wearables can quickly assess their radiation exposure and take necessary precautions. Additionally, real-time monitoring with wearable biodosimeters aids in triaging exposed individuals during radiological incidents, ensuring that those with high radiation doses receive immediate medical attention. Future research in biodosimeter technology is likely to focus on enhancing its versatility and compatibility with different biological samples and radiation sources. Development of novel biodosensors based on advanced materials and nanotechnology may further improve sensitivity and accuracy[31].

Researchers may also explore multi-parametric biodosimeters, which simultaneously assess multiple biological responses to radiation, providing a comprehensive evaluation of radiation exposure and its effects. As biodosimeter technology advances, new applications in personalized radiation exposure monitoring may emerge. Personal biodosimeters tailored to an individual's genetic and physiological characteristics could provide personalized safety thresholds and recommendations for radiation exposure. In medical contexts, personalized biodosimeters could optimize radiotherapy treatments, adjusting radiation doses based on an individual's response to radiation. This approach, known as "precision radiation oncology," promises to enhance treatment outcomes while minimizing side effects. In conclusion, the advancements and future prospects in biodosimeters are promising for radiation safety, medical treatments, and space exploration[110]. The integration of biodosensors into wearable devices and IoT platforms opens new avenues for real-time monitoring and data-driven decision-making. Ongoing research and development in biodosimeter technology are likely to expand their applications, contributing to personalized radiation exposure monitoring and further enhancing radiation safety measures across various domains[113].

8. Conclusion

Biodosimeters stand as indispensable tools in the realm of radiation detection, monitoring, and safety. Throughout this article, we have explored the various aspects of biodosimeters, delving into their functions and applications in diverse fields. Recapitulating their importance and functionality reinforces their vital role in safeguarding individuals from the potential risks of radiation exposure. Biodosimeters play a critical role in assessing radiation exposure levels accurately. From biological biodosimeters, such as hematological and cytogenetic biodosimeters, to physical biodosimeters like thermoluminescent and optically stimulated luminescence biodosimeters, each type offers valuable insights into radiation's impact on biological systems and materials. By enabling real-time monitoring and early identification of potential health risks, biodosimeters contribute significantly to radiation safety. They aid in ensuring radiation workers are exposed within safe limits, optimizing medical treatments, and facilitating appropriate emergency responses in the event of radiological incidents. Biodosimeters find extensive applications in multiple sectors, each serving a unique purpose. In medical and clinical settings, biodosimeters provide invaluable data for accurate radiotherapy treatments, optimizing patient care and outcomes. In nuclear medicine, biodosimeters aid in patient dose monitoring, balancing effective diagnosis and treatment with minimizing radiation exposure. Environmental radiation monitoring is another critical area where biodosimeters prove their worth. They help researchers and authorities assess radiation levels in the environment, understand its impact on ecosystems, and develop strategies for conservation and environmental management. As technology advances, biodosimeters continue to improve in accuracy, sensitivity, and convenience. Recent developments have led to real-time monitoring capabilities, integration with wearable devices, and IoT platforms, enhancing their usability and application. The ongoing research and development in biodosimeter technology hold promising prospects for the future. Advancements may lead to novel biodosensors, multi-parametric biodosimeters, and personalized radiation exposure monitoring. These developments could further optimize radiation safety measures and broaden the scope of biodosimeter applications. The potential impact of biodosimeters on protecting human health and the environment cannot be overstated. By providing timely and accurate data, biodosimeters enable proactive measures to minimize health risks associated with radiation exposure. They facilitate precision radiation oncology, reducing treatment side effects and improving patient outcomes. In the environmental context, biodosimeters aid in assessing radiation's impact on ecosystems, ensuring the preservation of biodiversity and the sustainable management of natural resources. Furthermore, biodosimeters play a pivotal role in space exploration, safeguarding astronauts during extended missions and advancing humanity's journey into the cosmos.

To summarize and finalize, biodosimeters stand as indispensable tools in the realm of radiation detection, monitoring, and safety. Throughout this article, we have explored the various aspects of biodosimeters, delving into their functions and applications in diverse fields. Biodosimeters play a critical role in assessing radiation exposure levels accurately, whether through biological biodosimeters, such as hematological and cytogenetic biodosimeters, or physical biodosimeters like thermoluminescent and optically stimulated luminescence biodosimeters. Their ability to enable real-time monitoring and early identification of potential health risks reinforces their vital role in radiation safety, ensuring that radiation workers are exposed within safe limits, optimizing medical treatments, and facilitating appropriate emergency responses in the event of radiological incidents. The significance of biodosimeters extends across various sectors, making them invaluable assets in different applications. In medical and clinical settings, biodosimeters provide crucial data for accurate radiotherapy treatments, optimizing patient care and outcomes. They also aid in nuclear medicine procedures, monitoring patient doses for effective diagnosis and treatment while minimizing radiation exposure. Environmental radiation monitoring benefits from biodosimeters as well, helping researchers and authorities assess radiation levels in the environment, understand its impact on ecosystems, and develop strategies for conservation and environmental management. Looking to the future, biodosimeters hold promising prospects for advancing radiation safety measures. Recent technological advancements have led to improved accuracy, sensitivity, and convenience in biodosimeter development. Real-time monitoring capabilities, integration with wearable devices and IoT platforms, and ongoing research in biodosimeter technology indicate a bright future for their applications. The potential impact of biodosimeters is profound, as they enable proactive measures to minimize health risks associated with radiation exposure and pave the way for precision radiation oncology, reducing treatment side effects and improving patient outcomes. Additionally, biodosimeters play a pivotal role in space exploration, safeguarding astronauts during extended missions and advancing humanity's journey into the cosmos. As biodosimeter technology continues to progress, they will continue to be vital instruments in protecting human health and the environment, forging a safer and more secure path forward in the world of radiation science.

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