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BIOMEDICAL SCIENCES

Beyond the Badge: Bridging Physical and Biological Monitoring to Strengthen Occupational Radiation Safety

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Abstract: Cytogenetic dosimetry (CD) provides biological evidence of radiation exposure and is particularly valuable in emergencies. However, its routine use in occupational protection remains limited globally. This study examines the barriers to institutionalization of CD within Brazil's occupational health and safety (OHS) framework. A qualitative analysis was conducted through a critical examination of international standards, Brazilian regulations, and scientific literature. The study mapped national guidelines, identified regulatory gaps, and evaluated the implications for worker health surveillance, with a specific focus on the potential role of CD. Our analysis shows that cytogenetic dosimetry is a technically feasible, accessible, and cost-effective method for biological monitoring. Its implementation in Brazilian occupational settings is constrained by the absence of standardized protocols, a lack of professional training among OHS practitioners, and low awareness of its clinical applicability. The findings from the Brazilian context highlight the need for updated OHS policies that integrate physical dosimetry with the biological effects of radiation, providing broader insights for advancing evidence-based occupational health policies and promoting a stronger global culture of radiation protection.

Key words: Radiation Science, Biological dosimetry, Cytogenetic dosimetry, Occupational health, Radiation protection.

INTRODUCTION

Since its discovery, ionizing radiation (IR) has played a pivotal role in technological progress, underpinning advancements in various sectors, including medicine (diagnostics and therapeutic procedures), agriculture, industry, and other critical domains. Despite its societal benefits, IR poses potential health risks, whose severity depends on the absorbed dose and the duration of exposure (Amaral 2005, Jaksic et al. 2023). Therefore, all activities involving radiation must comply with the three core principles of radiological protection: Justification, which states that any exposure should only occur if the benefits outweigh the risks; Individual Dose Limitation, which establishes dose limits to protect individuals; and Optimization, which seeks to reduce exposure to the lowest reasonably achievable level, following ALARA (As Low As Reasonably Achievable) and ALARP (As Low As Reasonably Practicable) basic principles (ICRP 1991, Okuno 2013, Kotre 2022).

Absorbed dose, the energy deposited by radiation per unit mass, is the fundamental quantity for assessing biological risk. In routine

occupational monitoring, personnel dosimeters (so-called badges) are commonly worn to measure the highest expected absorbed dose in the trunk (Pinto & Amaral 2014, Obrador et al. 2020). However, in practice, individual dosimetry for occupational exposure has several limitations. Physical dosimeter readings can be misleading, especially if the badge is not correctly positioned or falls outside the radiation field during inhomogeneous or partial-body exposures. As a result, in many real-world scenarios, particularly in cases of accidental, unexpected, or suspected exposure, workers may not be wearing dosimeters or may lack reliable dose records, making direct assessment unfeasible. Moreover, dosimeters can sometimes be irradiated while not being worn, either inadvertently or intentionally, leading to misleading exposure readings (Montoro et al. 2009). In such situations, cytogenetic dosimetry offers a valuable complementary or alternative approach for estimating absorbed dose and verifying the authenticity of individual exposure records (Lemos Pinto et al. 2010, Herate & Sabatier 2020).

Cytogenetic dosimetry detects and quantifies chromosomal aberrations (CAs) in peripheral blood lymphocytes as biomarkers of radiation exposure. Internationally, it is recognized as a sensitive and reliable technique for retrospective dose assessment, emergency triage, and long-term health monitoring (Vinnikov & Belyakov 2022, Vinnikov 2024). Worldwide, however, the integration of cytogenetic dosimetry into occupational radiological safety practices remains limited. In Brazil, for instance, although the technique is formally mentioned in regulatory standards, its inclusion is only occasional and lacks detailed guidance, consistency, or reinforcement across the broader occupational health framework.

The Regulatory Standards (Normas Regulamentadoras – NRs) of the Brazilian Ministry of Labor (BML) establish mandatory occupational safety procedures, which are periodically updated to address emerging risks (Brasil 1978). In 2005, the BML approved Regulatory Standard No 32 (NR-32) dedicated to safety in healthcare services, which sets forth procedures to protect the physical and mental integrity of healthcare workers. Notably, NR-32 includes cytogenetic dosimetry as a recommended tool for individual monitoring, to be used at the discretion of a medical professional in cases of suspected or confirmed accidental exposure to ionizing radiation (Brasil 2022a). Despite this recommendation, the method is rarely applied in routine occupational practice, primarily due to limited awareness among Occupational Health and Safety (OHS) teams (Lemos-Pinto & Amaral 2011, Arbo et al. 2022).

On the other hand, while the BML recommends incorporating cytogenetic dosimetry into the occupational health framework for the investigation of radiological incidents, the current regulatory framework of the Comissão Nacional de Energia Nuclear (CNEN), the Brazilian federal authority responsible for regulating radiation protection in medical, industrial, and research applications, does not explicitly address this technique. Although CNEN is the primary institution overseeing radiological safety in Brazil, the absence of specific references to cytogenetic dosimetry in its guidelines suggests a potential area for future alignment with internationally recognized practices in biological dose assessment and radiological emergency preparedness (IAEA 2011, Escalona et al. 2022). This misalignment between regulatory bodies contributes to the underutilization of cytogenetic dosimetry and

delays its institutionalization as a standard tool in occupational radiation protection.

Based on the Brazilian experience in applying cytogenetic dosimetry for occupational radiological protection, this work contextualizes regulatory advancements, discusses current limitations, and outlines perspectives on institutionalizing cytogenetic dosimetry as a standard tool in occupational health and safety protocols.

MATERIALS AND METHODS

This study employs a qualitative narrative review grounded in a critical examination of normative frameworks and scientific literature to analyze the historical evolution and conceptual shifts in occupational radiation protection in Brazil. Given the regulatory, institutional, and interdisciplinary nature of the topic, a narrative design was adopted to enable contextual interpretation and conceptual synthesis rather than exhaustive or reproducible literature aggregation.

The investigation focused on documents and publications with recognized relevance to occupational radiation protection, including international radiation protection standards, Brazilian regulatory and institutional frameworks, and peer-reviewed scientific literature addressing occupational exposure, radiological protection practices, and the application of cytogenetic dosimetry in exposed workers. Document selection was guided by relevance, regulatory or scientific influence, and contribution to the understanding of physical and biological monitoring in occupational settings, with emphasis on key thematic areas at the interface of radiation science, biological dosimetry, cytogenetic dosimetry, occupational health, and radiation protection.

The analytical procedure followed an interpretative narrative logic. International standards were first examined to establish the global reference framework for occupational radiation protection, followed by a chronological and thematic analysis of key Brazilian regulatory milestones. The scientific literature was subsequently analyzed to contextualize regulatory practices, identify conceptual and methodological gaps, and examine the role of cytogenetic techniques in the biological monitoring of occupational exposure. The resulting synthesis integrated regulatory, technical, and conceptual perspectives, enabling the identification of structural challenges and opportunities to strengthen occupational radiation safety.

RESULTS AND DISCUSSION

Basis for physical and cytogenetic dosimetry in worker surveillance

Monitoring of occupational exposure

To ensure the effectiveness of radiological protection measures and prevent occupational exposure limits from being exceeded, the use of physical dosimeters, devices that record the accumulated dose of ionizing radiation absorbed by the environment and individuals occupationally exposed (IOE), has become essential (Brasil 2018).

The monitoring of IOEs is primarily carried out using various types of physical dosimeters, such as film, thermoluminescent (TL), optically stimulated luminescence (OSL), and electronic dosimeters with real-time readout (Yang et al. 2024). The choice and positioning of the dosimeter vary according to the nature of the occupational exposure. They can be worn on the chest (as a badge or pen), on the head (for monitoring the lens), on the wrist, or as a ring (Miller et al. 2010). These devices are typically evaluated and replaced every month.

At each monthly replacement, a report is issued containing the radiation doses recorded individually for each worker (Brasil 2025a).

All dosimeters share a fundamental limitation: in cases of whole-body exposure with an inhomogeneous radiation distribution, the absorbed dose may be inaccurately quantified, leading to either underestimation or overestimation of exposure (Lemos Pinto et al. 2010). In addition, the accuracy of dosimeter readings can be affected by several operational factors, such as partial-body exposure to radiation and incorrect or inadequate use of a dosimeter at the time of exposure (Amaral 2005). In parallel, there is the possibility of clinical exposures to which IOEs may be subjected during radiological examinations or nuclear medicine procedures. Since absorbed dose is cumulative, these factors affect the reliability of the measurements.

Figure 1 illustrates two hypothetical scenarios of ionizing radiation exposure: homogeneous (Fig. 1a), in which the radiation is uniformly distributed throughout the body; and partial-body exposure (Fig. 1b). These different exposure patterns significantly affect how the absorbed doses are (or are not) recorded and interpreted using physical dosimeters, potentially influencing dose estimation.

As illustrated in Figure 1a, homogeneous whole-body exposures are relatively well captured by dosimeters, but in realistic occupational scenarios, characterized by partial-body irradiation, oblique incidence, and scattered fields, the recorded dose may diverge significantly from the biologically relevant dose. This bias, expressed as (Reading – TrueDose)/TrueDose, tends to remain approximately constant across different source strengths, suggesting that underestimation is a structural rather than stochastic artifact of workplace conditions.

Considering these limitations, it becomes evident that physical dosimetry alone cannot provide a complete or always reliable picture of occupational exposure. The systematic underestimation observed across clinical practice (Lee et al. 2022, Munoz et al. 2022), organ-specific monitoring such as the eye lens (Silva et al. 2019), electronic dosimeter performance (Borowski et al. 2010, Hourdakis et al. 2010), epidemiological reconstructions

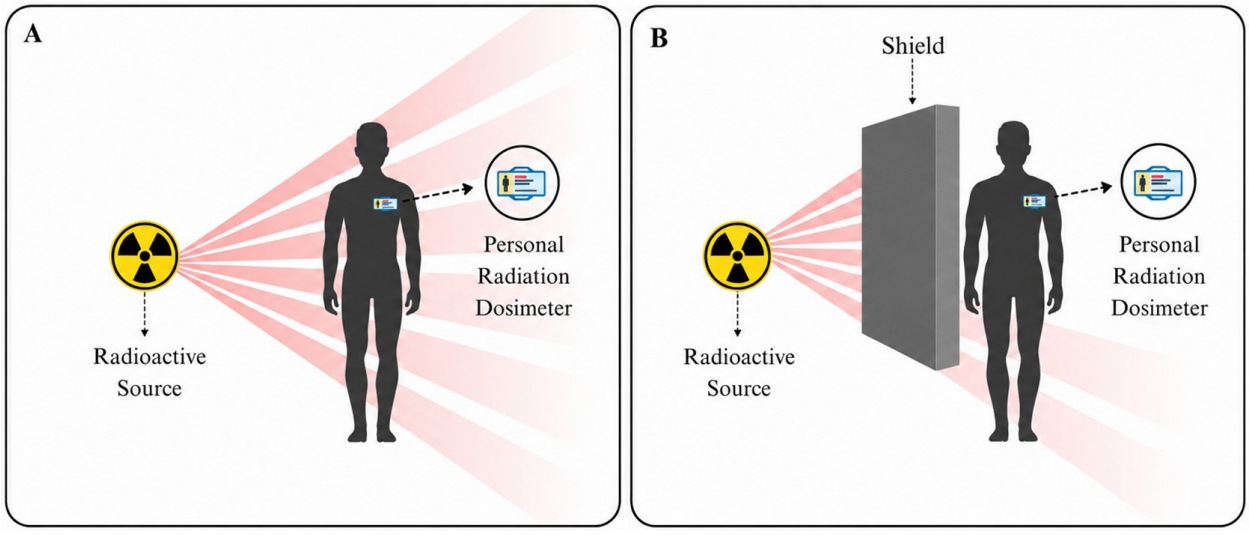

Figure 1. Comparison between homogeneous (a) and nonhomogeneous (b) ionizing radiation exposures, highlighting their distinct impacts on dose recording.

of large worker cohorts (Bellamy et al. 2025), and even algorithmic dose estimation under protective garments (Boetticher et al. 2008) all converge on the same conclusion: the "true" biological burden of radiation is often higher than what is recorded. This recognition has driven increasing interest in complementary approaches that directly measure biological effects rather than relying solely on physical proxies. Cytogenetic dosimetry, as emphasized by Piotrowski et al. (2021), offers precisely this advantage—providing sensitive, cell-based biomarkers of exposure that are independent of worker compliance, dosimeter placement, or gaps in historical records.

The following section, therefore, examines the principles, assays, and applications of cytogenetic dosimetry, highlighting its role as a critical complement to conventional monitoring in occupational radiation protection.

Cytogenetic dosimetry

Cytogenetic dosimetry, first investigated by Bender & Gooch (1962), uses cytogenetic biomarkers to quantitatively estimate the absorbed dose of ionizing radiation from acute or chronic exposures. The most established approach involves assessing unstable chromosomal aberrations (CA) and micronuclei in binucleated lymphocytes from human peripheral blood. When ionizing radiation interacts with these quiescent cells, DNA damage can be induced and remain undetected until the cells enter the replication phase. At this point, such lesions may be expressed as chromosomal abnormalities. To interpret CA scores in terms of radiation dose, a calibration curve is required (Lemos Pinto et al. 2010, IAEA 2011).

Among the available cellular models, fibroblasts and lymphocytes are the most widely studied for the analysis of CA (Lemos Pinto et al. 2010). Lymphocytes offer practical advantages, as they require shorter culture times, and they can be collected through minimally invasive procedures, such as venipuncture, whereas fibroblast isolation typically involves skin biopsies. Furthermore, because lymphocytes circulate systemically, they serve as more representative biomarkers of whole-body exposure, thereby enhancing their suitability for biodosimetric applications (Ferreira-Lucena et al. 2024).

The gold standard in biodosimetry, cytogenetic dosimetry has been used as a complementary methodology for determining absorbed dose in occupationally exposed professionals, and in investigations of accidental exposure to ionizing radiation (IAEA 2011). In addition to radiation-related exposures, cytogenetic biomarkers have also demonstrated efficacy in assessing environmental genotoxicity. This is supported by studies investigating the effects of occupational exposures, such as gasoline vapors among gas station attendants and pesticides among rural workers (Valente et al. 2017, Nogueira et al. 2020).

Human cells exhibit varying degrees of radiosensitivity throughout the cell cycle, being most sensitive during mitosis and most resistant during the late S phase. This variation influences their overall susceptibility to genotoxic agents, such as ionizing radiation and mutagenic substances, depending on the timing of exposure. These agents can induce chromosomal breaks and rearrangements, leading to CA during metaphase, when chromosomes are condensed and preparing to divide. These CA are classified as stable or unstable depending on their persistence through subsequent cell divisions (Bryant et al. 2010, Lemos Pinto et al. 2010).

Stable CAs, such as inversions, deletions, and balanced translocations, undergo normal chromosome segregation during mitosis and can be transmitted to daughter cells, persisting in

the body for long periods. In contrast, unstable CA, such as dicentric chromosomes and acentric fragments (Figure 2), impair mitotic stability and hinder cell division. These cells are typically eliminated through apoptosis or mitotic failure, leading to a gradual decline in the frequency of such aberrations over time (Lemos Pinto et al. 2010, Lemos-Pinto & Amaral 2011).

Dicentric chromosomes (DC), characterized by the presence of two centromeric regions, originate from the fusion of two distinct chromosomes. This phenomenon occurs when adjacent chromosomes are cleaved and, due to failures in the repair enzyme system, are joined asymmetrically. This leads to an altered structure with two centromeres and an acentric fragment, which may not be equally segregated during cell division (Agrawala et al. 2010, IAEA 2011, Herate & Sabatier 2020).

On the other hand, micronuclei (MN) are a kind of byproduct generated by the fragmentation or loss of chromosomes. These structures correspond to small cytoplasmic compartments, delimited by a nuclear membrane, that contain genetic material not incorporated into the real nucleus during cell division, as illustrated in Figure 3. These alterations typically occur in response to exposure to genotoxic agents, including ionizing radiation, chemical compounds, and heavy metals (Fenech 2020, Piotrowski et al. 2021, Lemos-Pinto & Amaral 2011, Herate & Sabatier 2020).

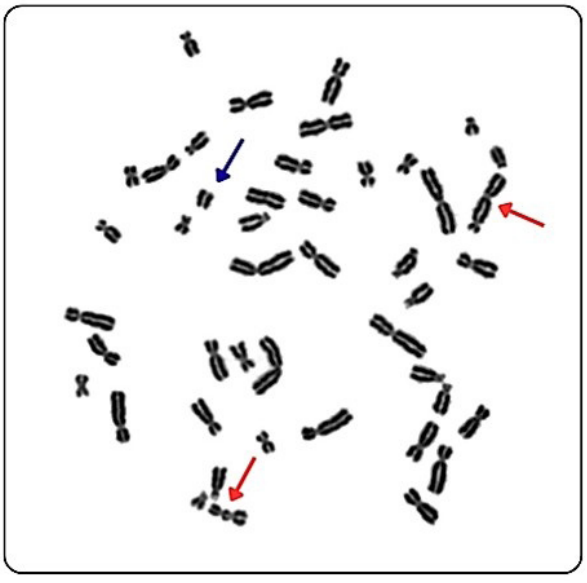

Figure 2. Unstable chromosomal aberrations observed in metaphase spreads of peripheral lymphocytes following ionizing radiation exposure. Dicentric chromosomes (red arrow) and acentric fragments (blue arrow). Source: Laboratory of Modeling and Applied Biodosimetry (Laboratório de Modelagem e Biodosimetria Aplicada-Lambda-DEN/UFPE) 2024.

Cytogenetic assays

Cytogenetic biomarkers form the basis for several assays in cytogenetic dosimetry, including the translocation assay, the cytokinesis-block micronucleus (CBMN) assay, the premature chromosome condensation (PCC) assay, and the dicentric chromosome assay, as summarized in Table I.

The cytogenetic assays presented in Table I, which are used in biological dosimetry

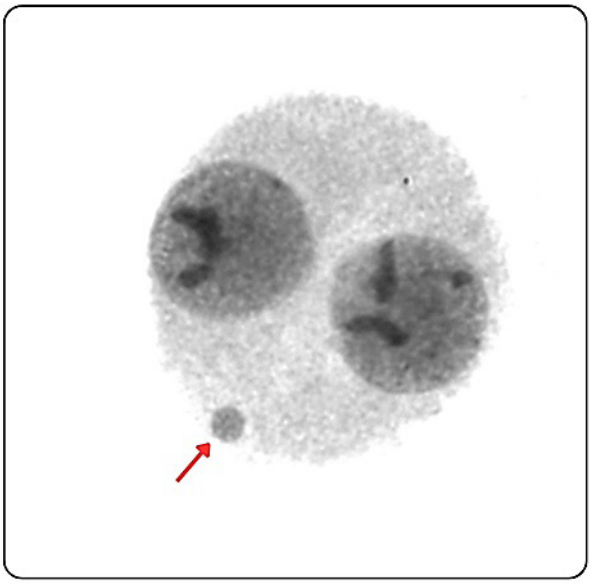

Figure 3. Binucleated lymphocyte cell with the presence of a labeled micronucleus by a red arrow. Source: Laboratory of Modeling and Applied Biodosimetry (Laboratório de Modelagem e Biodosimetria Aplicada-Lambda-DEN/UFPE) 2024.

to estimate the absorbed dose of ionizing radiation, have distinct characteristics that determine their applicability according to the level of exposure and the time elapsed since the event (Lemos-Pinto & Amaral 2011).

The translocation assay, for example, is most used for detecting old exposures, as these chromosomal alterations are stable and can remain detectable in peripheral blood lymphocytes for months or even years. However, its interpretation is compromised by the high natural frequency of translocations in unexposed individuals, as well as by factors such as aging, smoking, and exposure to chemical agents (Gnanasekaran 2021, Herate & Sabatier 2020).

The PCC assay is particularly useful for rapidly assessing radiation damage at high doses and is effective within the first few hours after exposure. Despite its agility, the application of this method is limited by the technical complexity, which involves the fusion of lymphocytes with cells in mitosis, requiring greater specialization and compromising its routine use (Lemos Pinto et al. 2010, Gnanasekaran 2021).

The dicentric chromosome assay is widely recognized as the gold standard for identifying acute exposures to ionizing radiation due to its high sensitivity and specificity. This method enables the detection of extremely low doses (> 0.1 Gy) and can identify exposures that occur from a few days to several weeks after the event, making it indispensable in both occupational exposure contexts and retrospective post-accident evaluations. Its application was fundamental in significant episodes of radiological contamination, such as the accidents in Chornobyl (Ukraine, 1986), Goiânia (Brazil, 1987), Tokaimura (Japan, 1999), and Fukushima (Japan, 2011) (Ramalho et al. 1995, Jamal et al. 2009, Sumption et al. 2011, Suto 2016, Sakamoto-Hojo 2018).

For the dicentric chromosome assay, precise dose quantification relies on a dose–response calibration curve, assuming that the biological effect is proportional to the radiation dose. In radiological emergencies, rapid assessment can be achieved by analyzing as few as 50 metaphases or 30 dicentric chromosomes. This

Table I. Characteristics of the main cytogenetic dosimetry assay for estimating the absorbed dose of ionizing radiation. Sources: Adapted from Lemos Pinto et al. (2010), Lemos-Pinto & Amaral (2011), and IAEA (2011).

Assay	Lower Limit	Culture Time	Analysis Time	Methods
Dicentric Chromosome	0.1 Gy	48-51 hours	4-5 days	Conventional Giemsa FPG C-banding FISH
CBMN*	0.3 Gy	72 hours	4 days	Conventional Giemsa C-banding FISH FPG
Translocation	0.25 Gy	72-75 hours	2-3 days	Conventional Giemsa C-banding FISH SKY
PCC**	4 Gy	3-4 hours	4-6 hours	Conventional Giemsa C-banding FISH

***CBMN: Cytokinesis-Block Micronucleus; **PCC: Premature Chromosome Condensation.**

expedited approach contrasts with standard protocols, which recommend evaluating 500 metaphases for suspected low-dose exposures (<1 Gy) or counting 100 dicentric chromosomes for higher doses, thereby improving accuracy and statistical reliability in dose estimation (Lemos Pinto et al. 2010, IAEA 2011).

The methodology of this assay involves a series of carefully standardized laboratory steps that begin with blood collection and proceed to the acquisition and cultivation of lymphocytes, the preparation of slides, the observation of cells in metaphase, and the identification of chromosomal aberrations under light microscopy. At the end of this process, the estimated dose is calculated based on the frequency of dicentrics observed. This entire procedure, although technically demanding, can be completed on average in 1 to 2 weeks, allowing for a relatively rapid response in contexts of suspected exposure (Lemos Pinto et al. 2010).

In situations that require large-scale screening or a faster response, the CBMN assay represents a viable alternative, as it has a detection period similar to that of the dicentric assay and requires less technical knowledge. However, it is essential to note that cytokinesis-block micronucleus (CBMN) is not specific to ionizing radiation, as micronuclei (MN) can be induced by various genotoxic agents, which limits its ability to attribute damage exclusively to IRs (Gnanasekaran 2021).

Historically, the primary limitation of cytogenetic dose estimation has been the highly labor-intensive nature of the process, which requires skilled personnel to dedicate extensive time to the microscopic analysis of sufficient metaphases to ensure statistically significant results with minimal uncertainty (IAEA 2011). This requirement becomes even more critical in scenarios involving low-dose exposures, where the frequency of chromosomal aberrations is reduced, and a larger number of cells must be analyzed to confirm the findings. Consequently, the operational costs and time constraints associated with cytogenetic assays limit their routine incorporation into annual medical surveillance programs for occupationally exposed workers. Therefore, even in countries with well-established biodosimetry laboratories, the application of this technique has historically been limited to cases of actual or suspected accidental overexposure.

However, more recently, advances in automated microscopy and pattern recognition algorithms have accelerated the analysis process, reducing both the time and labor costs of the assay. Currently, ongoing research on artificial intelligence applied to microscope-captured images shows promise for further improvements (M'Kacher et al. 2023). These advances now open up opportunities for wider implementation of the method in routine monitoring, and countries such as Brazil should recognize this potential and act accordingly.

Challenges in occupational cytogenetic monitoring

By design, occupational exposure to ionizing radiation is kept at low levels and considered safe under established protection standards. Nevertheless, the absence of immediate health effects does not eliminate potential risks, as cumulative or unmonitored exposures can compromise long-term well-being. Continuous dose monitoring is therefore essential for both verifying the effectiveness of radiological protection measures and establishing a biological record of a worker's exposure (Fernandes et al. 2006, Djokovic et al. 2023).

While international radiological protection bodies, such as the International Atomic Energy Agency (IAEA), recommend cytogenetic

assessment for individual dose evaluation, its incorporation into global occupational health frameworks remains limited. For instance, the Technical and Ethical Guidelines for Workers' Health Surveillance issued by the International Labor Organization establish principles for safeguarding the health of workers exposed to ionizing radiation. However, they do not refer to cytogenetic dosimetry (ILO 1998). This omission underscores the need to strengthen international regulations by incorporating more sensitive methodologies for early detection of radiation-induced biological effects in occupational settings. The importance of updating current guidelines is further supported by scientific evidence indicating risks from prolonged exposure, even at levels traditionally considered safe.

For example, Venneri et al. (2009) found that cardiac catheterization laboratory workers with higher levels of ionizing radiation exposure had an increased risk of developing neoplasms. Similarly, a study by Kim et al. (2022) among nuclear power plant workers in South Korea found that chromosomal damage can occur in individuals exposed to doses below permitted occupational limits, underscoring the need for more sensitive and comprehensive monitoring methods to ensure the health of these professionals. Another example is the work of Pinto & Amaral (2014), which emphasizes the relevance of cytogenetic dosimetry as a complementary tool to conventional physical dosimetry. By comparing cytogenetic analysis results from radiological workers with data from physical dosimeters, the authors identified significant discrepancies, indicating that chromosomal alterations can be detected even when physical dosimeters do not register meaningful dose levels. Their findings highlight the need for an integrated, up-to-date approach to monitoring occupational exposure to ionizing radiation, particularly in environments characterized by chronic low-dose exposure.

Radioprotection management in Brazil

In Brazil, radioprotection management began with the establishment of the Brazilian Nuclear Program in the 1950s. This program aimed to diversify the national energy matrix by introducing nuclear energy, thereby stimulating the country's technological and industrial development (Gonçalves 2009). As part of this effort, the Comissão Nacional de Energia Nuclear (CNEN) was created in 1956, the body responsible for establishing technical and safety guidelines in the sector, with the Instituto de Radioproteção e Dosimetria (IRD) as a technical reference for research, regulation, and monitoring of radioprotection in the country (Brasil 1956, Andrade & dos Santos 2013, Sakamoto-Hojo 2018, Souza et al. 2022).

The International Commission on Radiological Protection (ICRP) has been publishing recommendations on protection from ionizing radiation since 1928. Virtually all international standards and national regulations addressing radiological protection are based on the recommendations of this Commission. Based on the principles of the ICRP and the operational quantities established by the International Commission on Radiation Units and Measurements (ICRU), CNEN has created and updated the National Standards (NN) that regulate the safe use of IRs in Brazil. These standards establish the technical and administrative requirements necessary to ensure the protection of workers, patients, and the public (ICRP 1959, ICRU 1993, Souza et al. 2022).

NN 3.01 establishes the fundamental radiological protection requirements for exposure to ionizing radiation, covering activities related to the handling, production,

transport, storage, and disposal of radioactive materials and their waste. The standard applies to occupational, medical, and public exposures, stipulating protective measures both in daily and emergency situations through the Radioprotection Plan. Additionally, it provides the intervention protocols for chronic exposure scenarios and defines control strategies for natural sources of radiation (Brasil 2025a).

NN 3.02, in turn, regulates the implementation and operation of radioprotection services in nuclear and radiology installations, detailing the requirements for the structure, personnel, and equipment necessary for the proper functioning of these facilities. The standard specifies the qualifications required for technicians and assistants and defines control activities, such as monitoring workers, areas, and equipment, as well as waste management (Brasil 2018). Such activities are strictly supervised by radiological protection supervisors, in accordance with CNEN Resolution 340/25, which ensures that professionals involved in these activities have access to the necessary criteria for radiological safety at those installations (Brasil 2025b).

Finally, NN 3.05 specifically addresses nuclear medicine "*in vivo*", establishing the duties of responsible professionals and the operational requirements for radiological safety and protection, with emphasis on the handling of radiopharmaceuticals, waste management, exposure optimization, and contamination control (Brasil 2013).

Table II summarizes the main radioprotection standards in Brazil, highlighting the responsibilities, guidelines, and specific conditions applicable to various practices involving ionizing radiation.

Among its prerogatives, the CNEN has historically been responsible for overseeing activities involving ionizing radiation in Brazil. In certain areas, particularly in the medical and dental sectors, this supervisory role is also exercised by the National Health Surveillance Agency (ANVISA) (Souza et al. 2022). However, the establishment of the National Nuclear Safety Authority (ANSN) in 2021, driven by the need to separate regulatory and operational functions within the nuclear sector, marked a shift in this oversight structure. ANSN is now the designated authority for nuclear safety, and the gradual transfer of this responsibility from CNEN is underway. It is worth noting that ANVISA continues to fulfill its surveillance role within

Table II. National Radioprotection Standards established by CNEN. Source: Brasil (2013, 2018, 2025a).

Standards (NN)	Regulation	Applicability
3.01	Basic requirements for radioprotection and radiological safety of radiation sources (CNEN Resolution 344/25).	Establishes employers' responsibilities, annual dose limits for the exposed population, and criteria for monitoring, training, and control of exposure.
3.02	Radioprotection services.	It establishes the limits, requirements, and basic conditions for radiological protection in practices involving ionizing radiation.
3.05	Radiological safety and protection requirements for nuclear medicine services (CNEN Resolution 159/13).	Regulates the safety and radiological protection requirements for nuclear medicine services.

the specific areas for which it is responsible (Brasil 2021).

Limitations and gaps in Brazilian standards

Although cytogenetic dosimetry is formally referenced in Brazilian regulatory frameworks, as in Regulatory Standard NR-32 *Safety and Health in Healthcare Services*, its integration into routine occupational health practice remains limited. This gap may be largely attributable to the absence of detailed operational guidelines, such as standardized flowcharts and procedural protocols, as well as to the limited awareness and training of occupational health and safety professionals regarding its clinical applicability, methodological foundations, and practical implementation in real-world settings (Brasil 2022a).

In practice, the NR-7 guidelines for monitoring workers exposed to ionizing radiation primarily rely on hematological analyses, specially complete blood counts (Brasil 2022b). These assess lymphocytes, polymorphonuclear leukocytes, and platelets, nonspecific biomarkers whose variations can arise from numerous causes unrelated to radiological exposure, such as adverse environmental conditions or viral and bacterial infections (Brasil 2022b, Lemos Pinto et al. 2010). In the context of radiation, hematological changes typically occur only after acute exposures exceeding 1 Gy, as documented in radiological accidents (Awaad et al. 2017, Djokovic et al. 2023). This substantially limits the usefulness of such tests for detecting occupational exposures that are within, or only slightly above, regulatory dose limits.

Moreover, NR-7 not only mandates new medical evaluations when annual radiation dose limits are exceeded but also requires that health records be preserved for 30 years after the termination of employment. However, it does not include cytogenetic or other biological dosimetry techniques among the recommended tools for reassessing worker health. Consequently, the ability to detect genotoxic effects with greater sensitivity and specificity, which is essential for both short- and long-term health surveillance, is significantly compromised (Brasil 2022b).

Within the CNEN regulation framework, the latest revised edition of the standard NN 3.01 (Brasil 2025a) remains the primary regulatory instrument for occupational radiological protection in Brazil. However, it does not currently include specific references to cytogenetic dosimetry (Brasil 2025a). The only CNEN standard that refers to this technique is NN 3.05, which considers its use in exceptional cases where a worker receives an effective dose exceeding 100 mSv in a single month. Even in such situations, cytogenetic dosimetry is presented as a supplementary rather than a periodic component of occupational monitoring (Brasil 2013).

NR-32, in turn, allows for the use of cytogenetic dosimetry in acute exposure scenarios involving both sealed and unsealed sources, although its application is left to medical discretion. The absence of more detailed guidance, combined with the limited dissemination of cytogenetic techniques in medical education and training, may contribute to its underutilization, even in situations where it could offer clinical benefits. Furthermore, the regulation does not incorporate cytogenetic dosimetry into pre-employment, periodic, or termination medical evaluations for workers potentially exposed to ionizing radiation, which may limit the identification of prior exposures and the reconstruction of retrospective doses (Brasil 2022a).

Another challenge concerns the absence of clear regulatory definitions regarding which institutions are authorized to conduct cytogenetic dosimetry and the technical, methodological, or

infrastructural standards required to ensure the reliability of results. This lack of specification may lead to legal ambiguities, potentially hindering the recognition of occupational health claims and limiting the effectiveness of surveillance programs.

Ultimately, the absence of cytogenetic dosimetry in standard occupational monitoring protocols limits the ability of employers and OHS professionals to apply biologically based methods to estimate workers' cumulative radiation exposure. While physical dosimeters remain essential for dose tracking, they do not reflect biological effects or cumulative exposure, particularly in chronic low-dose radiation scenarios. These limitations underscore the need to revisit and, if necessary, update Brazilian occupational radiation protection frameworks to incorporate cytogenetic dosimetry into legally supported and operationally feasible health monitoring systems.

Challenges and perspectives for the implementation of cytogenetic dosimetry in Brazil

The timeline of radioprotection in Brazil, as presented in Figure 4, highlights significant

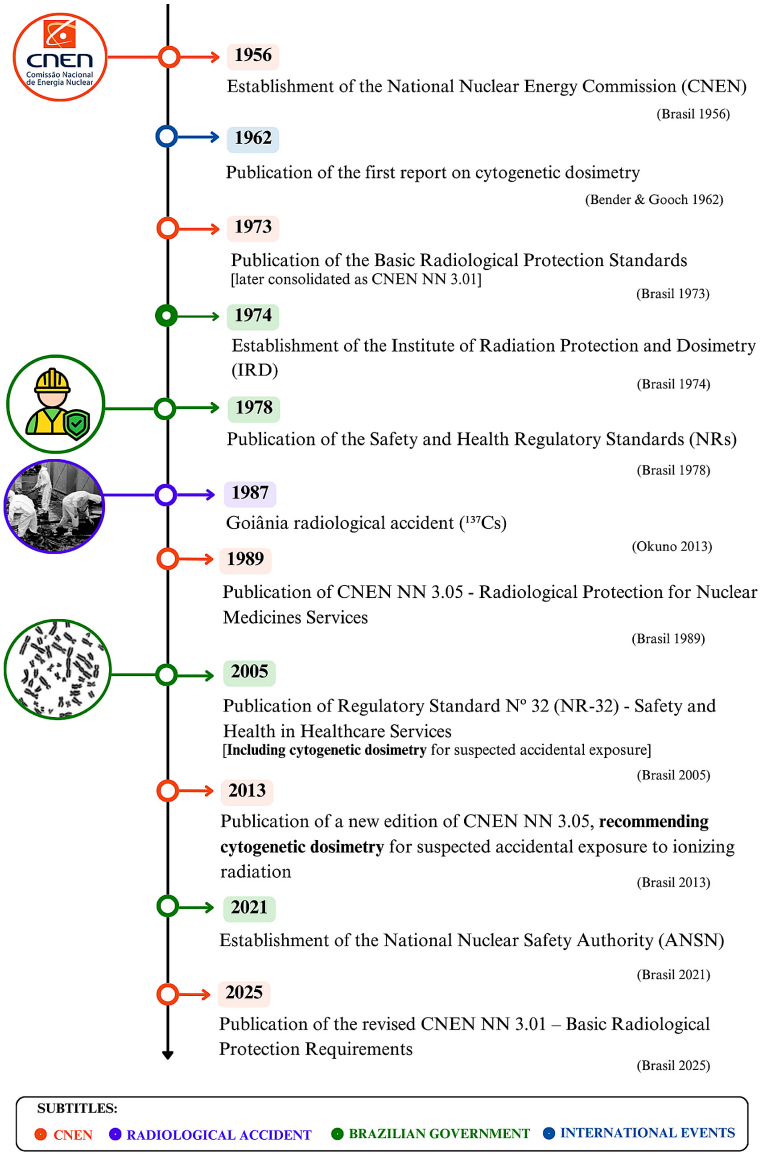

Figure 4. Timeline of landmarks in radioprotection management in Brazil.

landmarks in both the regulatory and institutional domains since the establishment of CNEN in 1956.

Throughout the process, the Basic Standards for Radiological Protection were published in 1973, along with the implementation of the Occupational Safety and Health Regulatory Standards (NRs) in 1978, followed a few years later by the radiological accident in Goiania, which occurred in 1987, triggering profound changes in the national response system to ionizing radiation exposure. Despite these critical milestones, the incorporation of cytogenetic dosimetry into the Brazilian regulatory framework has progressed at a slower rate compared to other areas of regulatory development in radiological protection.

Although cytogenetic dosimetry was initially proposed in 1962, it was not formally incorporated into Brazilian standards until 2005, through NR-32, in situations of suspected accidental exposure. This interval of more than four decades between the scientific recognition of the technique and its normative incorporation, even restricted, reflects persistent structural obstacles, such as the scarcity of trained laboratories, the lack of technical protocols in Portuguese, and the widespread lack of knowledge among OHS professionals about its applicability, indication, and interpretation of the results.

Even with the creation of the Institute of Radioprotection and Dosimetry-IRD in 1974, an institution linked to CNEN and equipped with a reference laboratory specialized in cytogenetic dosimetry for worker protection, the widespread and systematic implementation of this technique in Brazil remains limited. This situation reflects ongoing challenges in consolidating the technical and scientific infrastructure needed to effectively adopt cytogenetic dosimetry on a national scale.

Currently, cytogenetic dosimetry in Brazil is primarily performed by a limited number of specialized centers, generally affiliated with CNEN or public universities. This concentration of services restricts accessibility and poses challenges for large-scale applications, especially in emergencies or in occupational settings located far from major urban areas. Moreover, since the test requires a formal medical referral, as stipulated in NR-32, it is essential that physicians, especially those in occupational health, diagnostic imaging, radiotherapy, or nuclear medicine, are adequately informed about the clinical signs of radiation exposure and the appropriate indications for biological dosimetry.

Considering this scenario, the prospects for the expansion and consolidation of cytogenetic dosimetry in Brazil involve multiple interconnected strategies. The first of these is the systematic inclusion of content focused on the biological effects of ionizing radiation and on detection methods, such as cytogenetic dosimetry, in medical education. Such an insertion could contribute to more critical, interdisciplinary, and technically up-to-date medical training, enabling future professionals to act based on the principles of radioprotection, recognize potential exposures, and properly refer cases for specialized examinations.

At the same time, it is essential to promote the development and dissemination of a manual of cytogenetics dosimetry for OHS as well as for human cytogenetics laboratories. Many of these laboratories already have a basic structure for performing dicentric assays; however, they do not conduct the test due to a lack of standardization and training. The decentralization of dosimetry, through the qualification of laboratories across the country, is strategic for expanding coverage and enabling more agile responses to occupational or accidental exposures.

To advance effective occupational radiation protection, it is essential to establish standardized care protocols for both suspected exposure events and the periodic evaluation of workers routinely exposed to IR. These protocols should define clear and coordinated procedures for clinical screening, biological sample collection, case referral, and follow-up, ensuring alignment among radiation protection committees, occupational health services, and specialized laboratories. Importantly, no country needs to start from scratch: the international community has already developed a solid foundation of tools and best practices, including statistical methodologies for dose reconstruction—such as the BioDose platform of the European RENEB consortium—triage frameworks for radiological mass-casualty incidents (Wilkins et al. 2016), and ISO standards governing cytogenetic assays such as DC, MN, and FISH (Wilkins et al. 2025).

In the particular case of Brazil, the establishment of the National Nuclear Safety Authority (ANSN) in 2021 and the publication of the new edition of CNEN Standard NN 3.01 in 2025 create a favorable institutional environment for adopting these international models. Together, these milestones provide an opportunity to strengthen regulatory coherence, enhance coordination among technical and educational sectors, and promote a more integrated and proactive national system for occupational radiation safety.

The consolidation of cytogenetic dosimetry as a routine and effective component of occupational radiation protection will ultimately depend on building systemic capacity through enhanced medical training, expanded laboratory infrastructure, accessible technical materials, and the integration of health surveillance across institutional levels. Embedding cytogenetic dosimetry within such a coordinated framework would not only enhance preparedness and response to accidental or chronic exposures but also strengthen the country's overall ability to anticipate, manage, and learn from radiological events, thereby contributing to a more resilient and evidence-based safety culture.

CONCLUSIONS

The Brazilian experience has demonstrated that integrating cytogenetic dosimetry into routine occupational radiation protection is not simply a technical refinement; it represents a paradigm shift in how chronic and low-dose exposures are managed. By bridging the gap between physical dose measurements and the biological reality of cumulative exposure, this strategy enables earlier detection of harm, reinforces the scientific basis for decision-making, and strengthens long-term health surveillance.

Furthermore, as an accessible and cost-effective methodology, cytogenetic dosimetry has the potential to strengthen both the technical and perceptual dimensions of radiological protection. By making the biological consequences of exposure more tangible to workers and decision-makers, this methodology can improve subjective risk perception, recognizing that risk is not perceived in purely technical terms but is shaped by context, personal experience, and collective confidence in safety measures. This dual benefit reinforces the role of cytogenetic dosimetry as a strategic tool for promoting a stronger safety culture alongside measurable health protection outcomes.

Although shaped by Brazil's regulatory and institutional context, the conceptual approach discussed in this study addresses challenges common to many countries and can be adapted to diverse occupational settings. Its adoption worldwide could mark a pivotal improvement in radiation protection management by integrating

physical dosimetry with biological indicators of exposure, positioning cytogenetic dosimetry as a core element of modern occupational safety, and contributing to a stronger, evidence-based global culture of radiation protection.

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REFERENCES

AGRAWALA P, ADHIKARI JS & CHAUDHURY NK. 2010. Lymphocyte chromosomal aberration assay in radiation biodosimetry. J Pharm Bioallied Sci 2(3): 197-201. doi: 10.4103/0975-7406.68501.

AMARAL A. 2005. Physical and biological dosimetry for risk perception in radioprotection. Brazilian Arch Biol Technol 48: 229-234. https://doi.org/10.1590/S1516-89132005000700034.

ANDRADE AMR & DOS SANTOS TL. 2013. A dinâmica política da criação da Comissão Nacional de Energia Nuclear, 1956-1960. Bol Mus Para Emílio Goeldi 8: 113-128. https://doi.org/10.1590/S1981-81222013000100007.

ARBO MD, GARCIA SC, SARPA M, DA SILVA JUNIOR FMR, NASCIMENTO SN, GARCIA ALH & DA SILVA J. 2022. Brazilian workers occupationally exposed to different toxic agents: A systematic review on DNA damage. Mutat Res Toxicol Environ Mutagen 879-880: DOI: 10.1016/j.mrgentox.2022.503519.

AWAAD AE, KAMEL EA, KHASHABA EO & EL-DAHTORY FAM. 2017. Chromosomal aberrations and hematological alterations among radiation-exposed health care workers in Mansoura University Hospitals, Egypt. Egypt J Occup Med 41: 325-342.

BELLAMY MB, GROGAN HA, GIRARDI D, HOWARD SC, GOLDEN AP, SAMUELS CE & LAWRENCE TD. 2025. Reconstructing Handford Worker External Doses from Photons for Epidemology. J Radiol Prot 45(4): 041501. DOI: 10.1088/1361-6498/ae0a59.

BENDER MA & GOOCH PC. 1962. Persistent Chromosome Aberrations in Irradiated Human Subjects. Radiat Res 16: 44-53. https://doi.org/10.2307/3571128.

BOETTICHER H, LACHMUND J & HOFFMANN W. 2008. Effective dose estimation in diagnostic radiology with two dosimeters: Impact of the 2007 recommendations of the ICRP. Health Phys 95: 337-340. DOI: 10.1097/01.HP.0000318877.79131.08.

BOROWSKI M, POPPE B, LOOE HK & VON BOETTICHER H. 2010. Sind elektronische Personendosimeter in klinischen Expositionssituationen grundsätzlich nicht einsetzbar? RoFo Fortschr Auf Geb Rontgenstrahlen Bildgeb Verfahr 182: 773-779. DOI: 10.1055/s-0029-1245438.

BRASIL. 1956. Criação da Comissão Nacional de Energia Nuclear (CNEN) – Decreto n° 40.110, de 10 Out, 1956. Available at: https://www.planalto.gov.br/ccivil_03/decreto/1950-1969/d40110.htm.

BRASIL. 1973. Comissão Nacional de Energia Nuclear (CNEN): Criação das Normas Básicas de Radioproteção - atual 3.01, Resolução nº 6. Available at: https://memoria.cnen.gov.br/manut/ImprimeLeg.asp?Tipo=RES%20%20&Ano=1973&Numero=6.

BRASIL. 1974. Criação do Instituto de Radioproteção e Dosimetria (IRD) - Resolução n° 9, de 29 Jan. 1974. Available at: https://memoria.cnen.gov.br/manut/ImprimeCrono.asp?Ano=1974&seq=1&unidade=IRD.

BRASIL. 1978. Portaria n° 3.214, de 8 Jun, 1978. Aprova as Normas Regulamentadoras (NRs) relativas à segurança e medicina do trabalho. Available at: https://www.sinesp.org.br/images/42_-_PORTARIA_3214_1978_MTE_APROVA_AS_NORMAS_REGULAMENTADORAS_NR.pdf.

BRASIL. 1989. Comissão Nacional de Energia Nuclear (CNEN): Criação da NN 3.05: Requisitos de Radioproteção e Segurança para Serviços de Medicina Nuclear - Portaria CNEN/DExI 01, de 19 de Jan, 1989. Available at: https://memoria.cnen.gov.br/manut/ImprimeLeg.asp?Tipo=PRT%20%20&Ano=1989&Numero=1.

BRASIL. 2013. Comissão Nacional de Energia Nuclear (CNEN) - NN 3.05: Requisitos de Segurança e Proteção Radiológica para Serviços de Medicina Nuclear. Available at: https://www.gov.br/cnen/pt-br/acesso-rapido/normas/grupo-3/ansn-3-05-requisitos-de-seguranca-e-protecao-radiologica-para-servicos-de-medicina-nuclear.pdf.

BRASIL. 2018. Comissão Nacional de Energia Nuclear (CNEN) - NN 3.02: Serviços de Radioproteção. Available at: https://www.gov.br/cnen/pt-br/acesso-rapido/normas/grupo-3/ansn-3-02-servicos-de-radioprotecao.pdf.

BRASIL. 2021. Criação da Autoridade Nacional de Segurança Nuclear (ANSN) – Lei n° 14.222, de 15 Out, 2021. Available at: https://www.planalto.gov.br/ccivil_03/_ato2019-2022/2021/lei/l14222.htm.

BRASIL. 2022a. Norma Regulamentadora 32 – Segurança e Saúde no Trabalho em Serviços de Saúde. Portaria n° 485, de 11 Nov, 2005 (atualizada em 20 dez. 2022). Available at: https://www.gov.br/trabalho-e-emprego/pt-br/acesso-a-informacao/participacao-social/conselhos-e-orgaos-colegiados/comissao-tripartite-partitaria-permanente/arquivos/normas-regulamentadoras/nr-32-atualizada-2022.pdf.

BRASIL. 2022b. Norma Regulamentadora 7 – Programa de Controle Médico de Saúde Ocupacional (PCMSO). Portaria n° 3.124, de 8 Jun, 1978 (atualizada em 10 mar. 2022). Available at: https://www.gov.br/trabalho-e-emprego/pt-br/acesso-a-informacao/participacao-social/conselhos-e-orgaos-colegiados/comissao-tripartite-partitaria-permanente/normas-regulamentadora/normas-regulamentadoras-vigentes/nr-07-atualizada-2022-1.pdf.

BRASIL. 2025a. Comissão Nacional de Energia Nuclear (CNEN) - NN 3.01: Requisitos Básicos de Radioproteção e Segurança Radiológica de Fontes de Radiação. Available at: https://www.gov.br/cnen/pt-br/acesso-rapido/normas/grupo-3/copy2_of_NormaCNENNN3.01.pdf.

BRASIL. 2025b. Comissão Nacional de Energia Nuclear (CNEN) - NN 7.01: Requisitos para Certificação da Qualificação de Supervisores de Proteção Radiológica. Available at: https://www.gov.br/cnen/pt-br/acesso-rapido/normas/grupo-7/NormaCNENNN7.01nova.pdf.

BRYANT PE, RICHES AC & TERRY SYA. 2010. Mechanisms of the formation of radiation-induced chromosomal aberrations. Mutat Res Toxicol Environ Mutagen 701: 23-26. https://doi.org/10.1016/j.mrgentox.2010.03.016.

DJOKOVIC J, JANKOVIC S, MILOVANOVIC A & BULAT P. 2023. Chromosomal Aberrations, Micronuclei, Blood Parameters and Received Doses in Workers Exposed to Ionizing Radiation. Med Lav 114: e2023036. DOI: 10.23749/mdl.v114i4.14280.

ESCALONA MB, RYAN TL & BALAJEE AS. 2022. Current developments in biodosimetry tools for radiological/nuclear mass casualty incidents. Environ Adv 9: 100265. https://doi.org/10.1016/j.envadv.2022.100265.

FENECH M. 2020. Cytokinesis-Block Micronucleus Cytome Assay Evolution into a More Comprehensive Method to Measure Chromosomal Instability. Genes (Basel) 11: 1203. https://doi.org/10.3390/genes11101203.

FERNANDES TDS, AMARAL A, CAVALCANTI MB, BRAGA LRP & MELO RAM. 2006. Unstable chromosomal aberrations and micronuclei analyses in the biomonitoring of workers occupationally exposed to ionising radiation. Int J Low Radiat 3: 299-300.

FERREIRA-LUCENA LR, XAVIER AISF, NETTO AM, MAGNATA SSLP, SIQUEIRA LIMA G & AMARAL A. 2024. Extending culture time to improve Mitotic Index for cytogenetic dosimetry. Int J Radiat Biol 100: 1029-1040. DOI: 10.1080/09553002.2024.2356545.

GNANASEKARAN TS. 2021. Cytogenetic biological dosimetry assays: recent developments and updates. Radiat Oncol J 39: 159-166. DOI: 10.3857/roj.2021.00339.

GONÇALVES OD. 2009. O programa nuclear brasileiro e a física médica no Brasil. Rev Bras Física Médica 3: 151-156.

HERATE C & SABATIER L. 2020. Retrospective biodosimetry techniques: Focus on cytogenetics assays for individuals exposed to ionizing radiation. Mutat Res Mutat Res 783: 108287. https://doi.org/10.1016/j.mrrev.2019.108287.

HOURDAKIS CJ, BOZIARI A & MANETOU A. 2010. Performance evaluation of diagnostic radiology dosimeters in clinical and calibration X-ray beams. Health Phys 98: 704-716. DOI: 10.1097/HP.0b013e3181d18d45.

IAEA - INTERNATIONAL ATOMIC ENERGY AGENCY. 2011. Cytogenetic Dosimetry: Applications in Preparedness for and Response to Radiation Emergencies, Vienna, p. 247. Available at: http://www-pub.iaea.org/MTCD/Publications/PDF/EPR-Biodosimetry%202011_web.pdf.

ICRP - INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION. 1959. Recommendations of the International Commission on Radiological Protection. ICRP Publication 1, New York: Pergamon Press. Available at: https://journals.sagepub.com/doi/pdf/10.1016/S0074-27402880016-X.

ICRP - INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION. 1991. 1990 Recommendations of the International Commission on Radiological Protection. ICRP Publication 60. Ann ICRP 21. Available at: https://journals.sagepub.com/doi/pdf/10.1177/ANIB_21_1-3.

ICRU - INTERNATIONAL COMMISSION ON RADIATION UNITS AND MEASUREMENTS. 1993. Quantities and units in radiation protection dosimetry. ICRU Report 51, Bethesda, MD: ICRU. Available at: https://www.aapm.org/pubs/protected_files/ICRU/ICRU_Report_51_Quantities_and_Units_in_Radiation_Protection_Dosimetry_AAPM.pdf.

ILO - INTERNATIONAL LABOUR OFFICE. 1998. Technical and ethical guidelines for workers' health surveillance, Geneva: ILO. Available at: https://www.ilo.org/sites/default/files/wcmsp5/groups/public/%40dgreports/%40dcomm/%40publ/documents/publication/wcms_publ_9221108287_en.pdf.

JAKSIC A, NIKOLOV J & PALMA A. 2023. Special issue: applications of radiation in science and technology. Eur

Phys J Spec Top 232: 1459-1463. https://doi.org/10.1140/epjs/s11734-023-00907-4.

JAMAL N, LEE NBN, RAHIM RA, YUSOF N, TALIB Y, HASSAN H & RAHMAN HA. 2009. A review on current status on cytogenetic biodosimetry methods for radiation dose assessment. J Nucl Relat Technol 6. Available at: https://www.semanticscholar.org/paper/A-REVIEW-ON-CURRENT-STATUS-ON-CYTOGENETIC-METHODS-Jamal-Lee/cacd175de05baf37809b81684bec2e369bbb5f3c.

KIM YJ, LEE JW, CHO YH, CHOI YJ, LEE Y & CHUNG HW. 2022. Chromosome Damage in Relation to Recent Radiation Exposure and Radiation Quality in Nuclear Power Plant Workers. Toxics 10: 94. doi: 10.3390/toxics10020094.

KOTRE CJ. 2022. ALARP: when does reasonably practicable become rather pricey? Br J Radiol 95: 1138. https://doi.org/10.1259/bjr.20220612.

LEE W, JANG E, KIM K & BANG Y. 2022. Underestimation of Radiation Doses by Compliance of Wearing Dosimeters among Fluoroscopically-Guided Interventional Medical Workers in Korea. Int J Environ Res Public Health 19(14): 8393. doi: 10.3390/ijerph19148393.

LEMOS-PINTO MMP & AMARAL AJ. 2011. Análise citogenética na investigação de incidentes radiológicos. Editora Eskalab Ltda., São Paulo, SP. Newslab 18(105): 76-86.

LEMOS PINTO MMP, SANTOS NFG & AMARAL A. 2010. Current status of biodosimetry based on standard cytogenetic methods. Radiat Environ Biophys 49: 567-581. https://doi.org/10.1007/s00411-010-0311-3.

M'KACHER R, COLICCHIO B, JUNKER S, EL MAALOUF E, HEIDINGSFELDER L, PLESCH A, DIETERLEN A, JEANDIDIER E, CARDE P & VOISIN P. 2023. High Resolution and Automatable Cytogenetic Biodosimetry Using In Situ Telomere and Centromere Hybridization for the Accurate Detection of DNA Damage: An Overview. Int J Mol Sci 24: 5699. https://doi.org/10.3390/ijms24065699.

MILLER DL, VAÑÓ E, BARTAL G, BALTER S, DIXON R, PADOVANI R, SCHUELER B, CARDELLA JF & DE BAÈRE T. 2010. Occupational Radiation Protection in Interventional Radiology: A Joint Guideline of the Cardiovascular and Interventional Radiology Society of Europe and the Society of Interventional Radiology. J Vasc Interv Radiol 21: 607-615. https://doi.org/10.1007/s00270-025-04195-4.

MONTORO, ALMONACID M, VILLAESCUSA JI & VERDU G. 2009. Unexplained overexposures on physical dosimetry reported by biological dosimetry. Proc 31st Annu Int Conf IEEE Eng Med Biol Soc Eng Futur Biomed EMBC, p. 881-884. DOI: 10.1109/IEMBS.2009.5334711.

MUNOZ BNS, DE SOUZA CD, PIRES SR, BARBOSA AHP & MEDEIROS RB. 2022. Evaluation of a Direct Ion Storage dosimeter efficiency to measure dose during interventional cardiology procedures. Brazilian J Radiat Sci 10: 1-15. DOI: 10.15392/bjrs.v10i3.2072.

NOGUEIRA FAM, SZWARCWALD CL & DAMACENA GN. 2020. Exposição a agrotóxicos e agravos à saúde em trabalhadores agrícolas: o que revela a literatura? Rev Bras Saúde Ocup 45: e36. https://doi.org/10.1590/2317-6369000041118.

OBRADOR E, SALVADOR R, VILLAESCUSA JI, SORIANO JM, ESTRELA JM & MONTORO A. 2020. Radioprotection and Radiomitigation: From the Bench to Clinical Practice. Biomedicines 8: 461. https://doi.org/10.3390/biomedicines8110461.

OKUNO E. 2013. Efeitos biológicos das radiações ionizantes: acidente radiológico de Goiânia. Estud Av 27: 185-200. https://doi.org/10.1590/S0103-40142013000100014.

PINTO M & AMARAL A. 2014. Biological dose assessment after low-dose overexposures in nuclear medicine. Radiat Prot Dosimetry 162: 254-259. https://doi.org/10.1093/rpd/nct285.

PIOTROWSKI I, DAWID A, KULCENTY K & SUCHORSKA WM. 2021. Use of Biological Dosimetry for Monitoring Medical Workers Occupationally Exposed to Ionizing Radiation. Radiation 1: 95-115. https://doi.org/10.3390/radiation1020009.

RAMALHO AT, CURADO MP & NATARAJAN AT. 1995. Lifespan of human lymphocytes estimated during a six year cytogenetic follow-up of individuals accidentally exposed in the 1987 radiological accident in Brazil. Mutat Res Mol Mech Mutagen 331: 47-54. https://doi.org/10.1016/0027-5107(95)00049-O.

SAKAMOTO-HOJO ET. 2018. Lessons from the accident with 137Cesium in Goiania, Brazil: Contributions to biological dosimetry in case of human exposure to ionizing radiation. Mutat Res Toxicol Environ Mutagen 836: 72-77. https://doi.org/10.1016/j.mrgentox.2018.05.019.

SILVA EH, MARIN CJ, VANHAVERE F & BULS N. 2019. A study of the underestimation of eye lens dose with current eye dosemeters for interventional clinicians wearing lead glasses. J Radiol Prot 40: 215. DOI: 10.1088/1361-6498/ab55ca.

SOUZA DCB, COLLARES ATS, CONTINI CLF, DA SILVEIRA E & VOLTOLINI JR. 2022. Proteção radiológica nas exposições médicas: aspectos legais e históricos. Res Soc Dev 11: e54511326736. DOI: http://dx.doi.org/10.33448/rsd-v11i3.26736.

SUMPTION N, AINSBURY L, GOODHEAD D, HIRAMA T, AKASHI M, MONOBE M, ANDO K & ANDERSON R. 2011. High Frequency of Simple and Complex Chromosome Aberrations Detected in the Tokai-mura Survivor four and Five Years after the 1999 Criticality Accident. J Radiat Res 52: 300-308. doi: 10.1269/jrr.10125.

SUTO Y. 2016. Review of Cytogenetic analysis of restoration workers for Fukushima Daiichi nuclear power station accident. Radiat Prot Dosimetry 171: 61-63. https://doi.org/10.1093/rpd/ncw187.

VALENTE D ET AL. 2017. Utilização de biomarcadores de genotoxicidade e expressão gênica na avaliação de trabalhadores de postos de combustíveis expostos a vapores de gasolina. Rev Bras Saúde Ocup 42(1): 1-21. DOI: 10.1590/2317-6369000124415.

VENNERI L, ROSSI F, BOTTO N, ANDREASSI MG, SALCONE N, EMAD A, LAZZERI M, GORI C, VANO E & PICANO E. 2009. Cancer risk from professional exposure in staff working in cardiac catheterization laboratory: Insights from the National Research Council's Biological Effects of Ionizing Radiation VII Report. Am Heart J 157: 118-124. https://doi.org/10.1016/j.ahj.2008.08.009.

VINNIKOV V & BELYAKOV O. 2022. Clinical Applications of Biological Dosimetry in Patients Exposed to Low Dose Radiation Due to Radiological, Imaging or Nuclear Medicine Procedures. Semin Nucl Med 52: 114-139. https://doi.org/10.1053/j.semnuclmed.2021.11.008.

VINNIKOV VA. 2024. Effect of changing the radiation dose range on the in vitro cytogenetic dose response to gamma-rays. Int J Radiat Biol 100: 875-889. https://doi.org/10.1080/09553002.2024.2338511.

WILKINS R ET AL. 2025. Activities of ISO Working Group 18: Biological and Physical Retrospective Dosimetry. Disaster Med Public Health Prep 19: e251. doi: 10.1017/dmp.2025.10095.

WILKINS RC, CARR Z & LLOYD DC. 2016. An update of the who biodosenet: Developments since its inception. Radiat Prot Dosimetry 172: 47-57. doi: 10.1093/rpd/ncw154.

YANG Z, VRIELINCK H, JACOBSOHN LG, SMET PF & POELMAN D. 2024. Passive Dosimeters for Radiation Dosimetry: Materials, Mechanisms, and Applications. Adv Funct Mater 34: 2406186. https://doi.org/10.1002/adfm.202406186.

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Data availability

All data analyzed in this study are available in the references cited herein.