ORIGINAL ARTICLE
DOI: 10.15343/0104-7809.202650e19452025I
ISSN: 1980-3990

Cytogenetic alterations associated with occupational exposure to ionizing radiation in radiology technicians: a systematic review

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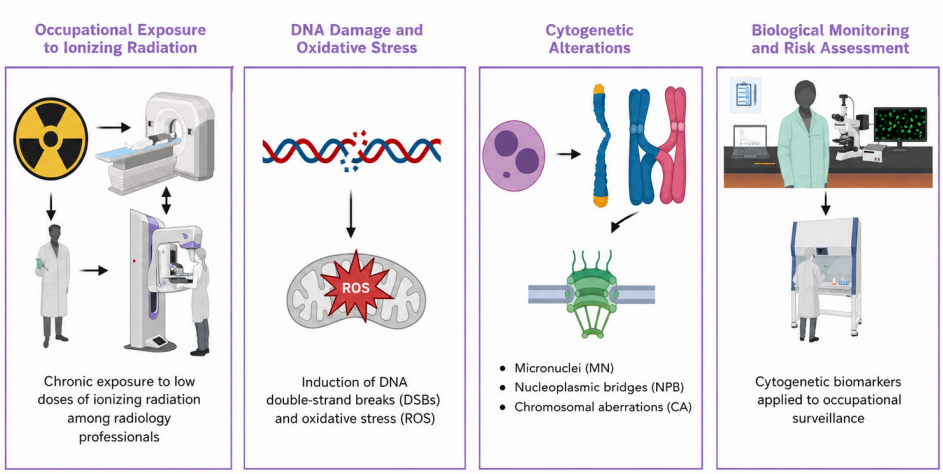
Highlights

- *Chronic exposure to low doses of ionizing radiation is associated with measurable genomic instability in radiology professionals.*
- *Individual and occupational factors – including age, sex, smoking, length of service, and work sector – may influence the magnitude of cytogenetic damage.*
- *Periodic cytogenetic monitoring may complement individual dosimetry in occupational surveillance and in the prevention of late radiation effects.*
- *Micronuclei, nucleoplasmic bridges, nuclear buds, dicentrics, and structural chromosomal aberrations were the most frequently assessed biomarkers.*
- *Digital radiological systems were associated with lower genotoxic damage intensity compared to analog and computed radiography systems.*

Graphical Abstract



Abstract

Occupational exposure to ionizing radiation represents a relevant physical hazard for radiology technicians and radiological service workers, potentially inducing measurable cytogenetic damage even in low-dose scenarios. The objective of this study was to synthesize recent evidence on cytogenetic alterations associated with occupational exposure to ionizing radiation in radiology professionals, identifying the most frequently altered biomarkers and their relationship with dosimetry, work sector, and individual characteristics. This is a systematic review conducted in accordance with PRISMA 2020 guidelines. Observational studies with primary human data, a non-exposed control group, and quantitative assessment of cytogenetic biomarkers were included. Five studies published between 2021 and 2025, involving more than 2,600 participants, met the eligibility criteria. The included studies reported higher frequencies of cytogenetic damage in exposed workers compared to controls, particularly for micronuclei, nucleoplasmic bridges, nuclear buds, dicentrics, and structural chromosomal aberrations. The magnitude of the findings varied according to the biomarker used, the type of radiological technology, the occupational sector, and confounding factors such as age, sex, and smoking. The correlation between individual dosimetry and biological damage was heterogeneous. It is concluded that occupationally exposed radiology professionals constitute a relevant group for cytogenetic surveillance, and that biodosimetry may complement physical dosimetry in occupational monitoring programs.

Keywords: Radiation Exposure. Cytogenetics. Biomarkers. Genomic Instability.

Associate Editor: Edison Barbieri
Mundo Saúde. 2026,50:e19452025
O Mundo da Saúde, São Paulo, SP, Brasil.
https://revistamundodasaude.emnuvens.com.br

Received: 20 december 2025.
Accepted: 13 may 2026.
Published: 01 june 2026.

INTRODUCTION

Occupational exposure to ionizing radiation constitutes one of the main physical hazards faced by radiology technicians and radiological service workers[1,2,3]. Despite technological advances, the expansion of digital systems, and improvements in radiation protection standards, professionals working in radiodiagnosis, computed tomography, radiotherapy, hemodynamics, and nuclear medicine may remain subject to chronic, intermittent, and cumulative exposures capable of producing molecular, cellular, and chromosomal damage[4,5].

Peripheral blood lymphocytes are widely used in cytogenetic biodosimetry due to their high radiosensitivity, ease of collection, and capacity to reflect chromosomal damage induced by ionizing radiation. Although Bergonié and Tribondeau's Law establishes that less differentiated cells with high mitotic activity and greater proliferative potential tend to be more radiosensitive, lymphocytes represent a notable exception: even as differentiated cells predominantly in the G0 phase, they exhibit high susceptibility to radiation-induced chromosomal breaks. Furthermore, their persistence in peripheral blood enables the identification of cytogenetic alterations resulting from recent or cumulative exposures, thereby justifying the use of micronuclei, nucleoplasmic bridges, dicentrics, and chromosomal aberrations as biomarkers of genomic instability in occupationally exposed populations[5,6,7].

Occupational exposure to ionizing radiation is monitored through individual dosimetry, with whole-body effective dose being one of the main quantities used to estimate overall radiological risk. According to the International Commission on Radiological Protection, the occupational effective dose limit is 20 mSv per year on average over five consecutive years, not exceeding 50 mSv in any single year[8]. In Brazil, ANSN Standard 3.01 establishes radiation protection and radiological safety requirements, including registration and investigation levels for individual monitoring of occupationally exposed individuals; among these, an effective dose of 6 mSv in one year or 1 mSv in one month constitutes an investigation level[9].

Conventional laboratory tests, such as the complete blood count, may assist clinical surveillance of exposed workers – particularly in cases of high exposures or suspected hematological effects. However, they exhibit low sensitivity for the early detection of genetic damage resulting from chronic low-dose exposure. National evidence, such as the assessment of hospital workers exposed to X-rays, did not demonstrate a consistent association between occupational dose and hematological alterations in leukocytes and platelets[10]. Therefore, cytogenetic biomarkers may complement physical dosimetry by identifying genomic instability prior to the emergence of overt clinical alterations.

The biological effects of ionizing radiation may be classified as deterministic or stochastic. Deterministic effects have a dose threshold and severity proportional to the dose received, manifesting primarily after high exposures – such as erythema, tissue injury, and acute radiation syndrome. In contrast, stochastic effects have no defined threshold and are characterized by a probabilistic increase in risk as a function of accumulated dose, particularly with respect to carcinogenesis and possible hereditary effects. In the occupational context, where chronic low-dose exposure predominates, the primary concern relates to stochastic effects, justifying the continuous adoption of radiation protection measures and biomonitoring[8,9].

The micronucleus assay has been employed as a tool for monitoring the health of radiation-exposed workers. Nevertheless, the frequency of micronuclei may be influenced by factors such as sex, age, lifestyle habits, metabolic conditions, smoking, and exposure to clastogenic and aneugenic agents[11,12,13,14,15]. For this reason, micronuclei are not a specific biomarker of ionizing radiation at low doses. In contrast, dicentric chromosomes and centric rings exhibit greater specificity for radiation exposure and are considered the gold standard for dose estimation following accidental exposure, while nucleoplasmic bridges have been discussed as promising markers for chronic low-dose exposure scenarios[6,7,16].

Current radiological practice adopts radiation protection measures based on the principles of justification, optimization, and dose limitation – including the ALARA principle, reduction of exposure time, increased distance from the source, and use of collective and individual shielding. However, these measures do not entirely eliminate stochastic risk. Limiting factors for their proper implementation include low risk perception, irregular use of lead garments due to discomfort and weight, work overload, insufficient technical supervision, outdated equipment, and possible underestimation of individual biological response by conventional physical dosimetry[9,17].

In this context, cytogenetic assessment should not replace individual dosimetry, but may function as a complementary tool for occupational surveillance, investigation of chronic exposure, and review of workplace practices. Recent stud-

Mundo Saúde. 2026,50:e19452025
DOI: 10.15343/0104-7809.202650e19452025I

ies demonstrate differences between occupational settings: Farkas et al. observed mean effective doses of 1.26 mSv in nuclear medicine, 0.08 mSv in radiotherapy, 0.07 mSv in diagnostic X-ray, and 0.02 mSv in computed tomography, with higher frequencies of total aberrations and aberrant cells in the nuclear medicine group compared to the computed tomography group[5].

This systematic review therefore aims to synthesize evidence from observational studies that assess, through cytogenetic biomarkers in peripheral blood lymphocytes, the alterations associated with occupational exposure to ionizing radiation in radiology technicians and radiological service workers. It further seeks to identify the most prevalent types of chromosomal damage – such as micronuclei, nucleoplasmic bridges, nuclear buds, dicentrics, and chromosomal aberrations – and to compare these findings with non-exposed control groups.

MATERIALS AND METHODS

This systematic review was conducted in accordance with PRISMA 2020 guidelines, which directed the stages of question formulation, literature search, eligibility assessment, study selection, data extraction, and result synthesis. Meta-analysis was not performed due to study heterogeneity with respect to biomarkers assessed, units of measurement, study designs, occupational profiles, and methods of exposure measurement. Accordingly, a narrative synthesis of results was adopted. Artificial intelligence tools were used solely for linguistic support and textual clarity improvement, with no involvement in study selection, data extraction, critical appraisal, or scientific interpretation.

Research question (PICO)

The research question was constructed using the PICO framework. The population (P) was defined as radiology technicians and radiological service workers occupationally exposed to ionizing radiation; the intervention (I) corresponded to chronic or intermittent occupational exposure to ionizing radiation; the comparison (C) comprised non-exposed individuals or those with minimal exposure; and the outcome (O) consisted of cytogenetic alterations assessed by micronuclei, nucleoplasmic bridges, nuclear buds, dicentrics, chromosomal aberrations, and other genotoxic markers. The central research question was therefore: what cytogenetic alterations are observed in occupationally exposed radiology professionals compared to non-exposed individuals?

Search strategy

The literature search was conducted in PubMed/MEDLINE, Scopus, ScienceDirect, and Google Scholar between November 10 and 28, 2025. Studies published between January 2021 and November 2025, in Portuguese and English, exclusively comprising original scientific articles with primary human data, were considered. The search strategy was structured in accordance with PRISMA 2020 and PRISMA-S transparency recommendations, prioritizing reproducibility and explicit description of terms, Boolean operators, and databases consulted[18,19].

In PubMed/MEDLINE, the following strategy was used: ("Radiation, Ionizing"[MeSH Terms] OR "ionizing radiation" OR "radiation exposure") AND ("Occupational Exposure"[MeSH Terms] OR occupational OR "radiology workers" OR "radiology technicians" OR "medical radiation professionals") AND ("Chromosome Aberrations"[MeSH Terms] OR cytogenetic OR micronucleus OR micronuclei OR "nucleoplasmic bridges" OR dicentric OR "comet assay"). Equivalent strategies were adapted for Scopus and ScienceDirect. Google Scholar was used as a supplementary source, with the first 100 results ranked by relevance analyzed.

The temporal delimitation from 2021 to 2025 was adopted to prioritize studies conducted in a technological and regulatory context closer to current radiological practice – characterized by the expansion of digital systems, greater availability of individual dosimetry, and updated radiation protection recommendations. It is acknowledged, however, that this restriction may exclude classical studies on cytogenetic biomonitoring. For this reason, studies predating the defined period were used as theoretical grounding in the introduction and discussion sections but were not included in the main systematic synthesis.

Inclusion criteria

Observational, cross-sectional, case-control, or cohort studies investigating cytogenetic alterations in radiology technicians or radiological service workers occupationally exposed to ionizing radiation, with comparison against a non-exposed or minimally exposed control group, were included. Only studies with primary data conducted in humans that reported quantitative cytogenetic outcomes were considered eligible.

Exclusion criteria

In vitro or animal experimental articles, narrative reviews, systematic reviews, case reports, case series, studies without a control group, publications without full-text availability, studies in which the population was simultaneously exposed to other genotoxic agents without separate reporting of results, and studies that did not present quantitative cytogenetic biomarkers were excluded.

Study selection

Selection was performed in three stages: title screening, abstract screening, and full-text review. Each stage was conducted independently by two researchers applying the pre-defined eligibility criteria. Disagreements were resolved by consensus and, when necessary, by a third researcher. The process of identification, screening, eligibility assessment, and inclusion of studies is presented in the corresponding PRISMA flowchart.

Data extraction

Data extraction was performed using a standardized spreadsheet containing: authors, year of publication, country/setting, study design, sample size for exposed and control groups, sector or radiological technology, duration of occupational exposure, effective dose or monitoring method, cytogenetic biomarkers assessed, quantitative outcome values, measures of association, p-values, 95% confidence intervals when available, confounding factors analyzed, and main conclusions.

Methodological quality assessment

The methodological quality of the included studies was independently assessed by two researchers, considering clarity in the definition of the exposed and control populations, adequacy of occupational exposure measurement, description of cytogenetic biomarkers, control of confounding factors, adequacy of statistical analysis, and completeness of result presentation. The main sources of bias considered were inadequate control group selection, absence of adjustment for age, sex, smoking, and length of service, heterogeneity of cytogenetic techniques, and lack of standardization in occupational dose measurement.

Result synthesis

Due to methodological heterogeneity among studies – particularly regarding cytogenetic techniques used, exposure durations, occupational sectors, radiological technologies, and exposure measurement units – results were synthesized narratively. Quantitative values of the main biomarkers were extracted, including means, standard deviations, medians, frequencies, between-group differences, p-values, 95% confidence intervals, and correlation coefficients, when reported by the original studies. When these measures were unavailable, results were described as "not reported." Statistical power was not recalculated due to the absence of sufficiently homogeneous data for comparable estimates across studies.

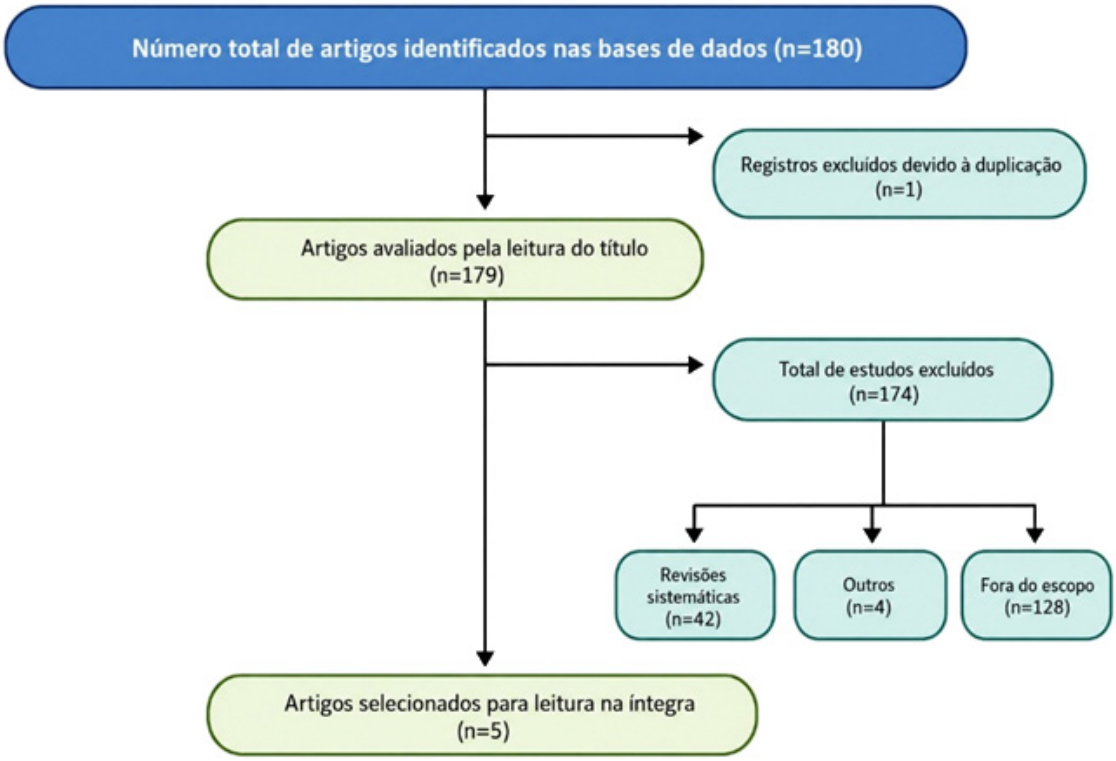


Figure 1 - Flowchart of the article selection methodology.

Table 1 - Methodological characteristics, exposure parameters, biomarkers, and main quantitative findings of studies included in the systematic review (2021–2025).

Author/Year	Country/ Design	Sample	Dose/Exposure	Biomarkers and quantitative findings	Confounders/ Limitations
Cunha Jr *et al.* (2021)[20]	Brazil; cross-sectional study	113 participants: 70 exposed and 43 controls	Occupational exposure in radiology departments with analog film (AF), computed radiography (CR), and digital radiography (DR); annual doses below the legal limit reported in the study	Micronuclei: AF 1.96 ± 0.21 vs. 1.20 ± 0.25; CR 1.89 ± 0.15 vs. 1.31 ± 0.36; DR 1.75 ± 0.11 vs. 1.59 ± 0.32. Damage was highest in analog systems and lowest in digital systems.	Comparison by radiological technology; limitations: cross-sectional design and possible influence of length of service and individual characteristics.
Çobanoğlu e Çayır (2024)[17]	Turkey; cross-sectional study	76 participants: 40 exposed and 36 controls	Personal dosimeters assessed periodically; mean working time of 11.59 years; sectors including X-ray, CT, MRI, mammography, and nuclear medicine	CBMN: significant increase in NPB, NBUD, MN, and total DNA damage in exposed workers ($p < 0.0001$ for all measures). Dosimeter readings correlated positively with NPB and NBUD.	Occupational variables — including total working hours, mean working duration, and time in projectional radiography — correlated with MN and TDD.
Farkas *et al.* (2022)[21]	Hungary; retrospective cohort with cross-sectional cytogenetic analysis	1,240 participants: 264 exposed to radiation, 188 to cytostatics, 63 to chemical laboratory agents, and 725 controls	Occupational monitoring through personal dosimetry; low occupational dose in radiotherapy and diagnostic services	Total chromosomal aberrations were higher in radiation-exposed workers; no consistent difference in dicentrics across all subgroups.	Smoking was frequent and relevant as a confounding factor; differences between occupational exposures hinder direct comparison.
Tian *et al.* (2021)[7]	China; cross-sectional study	Dicentrics: 199 exposed/78 controls; MN/NPB: 205 exposed/100 controls	Mean annual effective dose of 0.68 mSv; sectors: radiodiagnosis, radiotherapy, nuclear medicine, and interventional radiology	Dicentrics + rings: 0.29 ± 0.03 per 100 metaphases in exposed workers; NPB: 1.04 ± 0.03 per 1,000 binucleated cells; MN: 19.52 ± 0.15 per 1,000 binucleated cells. All were significantly higher in exposed workers ($p < 0.001$).	NPB was influenced by type of work and length of service; MN also by sex and age, making it less specific for radiation.
Farkas *et al.* (2025)[5]	Hungary; cross-sectional cytogenetics with retrospective cancer follow-up	1,033 participants: 301 radiation-exposed workers and 732 controls	Mean effective doses: nuclear medicine 1.26 ± 2.52 mSv; radiotherapy 0.08 ± 0.20 mSv; X-ray 0.07 ± 0.17 mSv; CT 0.02 ± 0.06 mSv	Chromatid and chromosomal aberrations were significantly higher in the exposed group. Nuclear medicine presented more total aberrations ($p = 0.025$) and aberrant cells ($p = 0.032$) than CT. No higher tumor frequency was observed in the exposed group.	Smoking elevated aberration frequency and cancer incidence; no consistent linear correlation between dosimetry and chromosomal aberrations was found.

Note: MN: micronuclei; NPB: nucleoplasmic bridges; NBUD: nuclear buds; CBMN: cytokinesis-block micronucleus assay; TDD: total DNA damage; CT: computed tomography; MRI: magnetic resonance imaging; AF: analog film; CR: computed radiography; DR: digital radiography; TLD: thermoluminescent dosimeter. Comparisons were performed qualitatively due to heterogeneity in biomarkers, units of measurement, occupational sectors, and exposure assessment methods.

RESULTS

Five observational studies were included, with sample sizes ranging from 76 to 1,240 participants per study, comprising occupationally exposed workers and respective control groups in variable proportions. In general, the studies identified higher frequencies of cytogenetic biomarkers in exposed professionals, although the magnitude of the effect varied according to the biomarker, occupational sector, radiological technology, and control of confounding factors[5,7,17,20,21].

In the study by Cunha Jr *et al.*[20], workers exposed to analog systems presented a mean micronucleus frequency of 1.96 ± 0.21, compared to 1.20 ± 0.25 in controls. In computed radiography systems, values were 1.89 ± 0.15 versus 1.31 ± 0.36; and in digital systems, 1.75 ± 0.11 versus 1.59 ± 0.32. These data indicate greater genotoxic damage in analog systems, followed by computed systems, with lower magnitude in digital systems.

Tian *et al.*[7] observed a significant increase in various cytogenetic markers in radiation professionals. The overall frequency of dicentric chromosomes and rings was 0.29 ± 0.03 per 100 metaphases in exposed professionals, while nucleoplasmic bridge and micronucleus frequencies were 1.04 ± 0.03 and 19.52 ± 0.15 per 1,000 binucleated cells, re-

spectively. All three markers were significantly higher than in controls ($p < 0.001$), reinforcing that NPB and dicentrics may be more informative than micronuclei alone in low-dose scenarios.

Çobanoğlu and Çayır[17] identified significant increases in micronuclei, nucleoplasmic bridges, nuclear buds, and total DNA damage in radiology workers compared to controls, with $p < 0.0001$ for all measures. Furthermore, dosimeter readings exhibited a positive correlation with NPB and NBUD, while occupational variables – such as total working hours, mean working duration, and time spent in projectional radiography – correlated with MN and TDD.

Farkas *et al.*5 assessed 301 radiation-exposed workers and 732 controls, observing significantly higher frequencies of chromatid and chromosomal aberrations in the exposed group. Sector-level analysis demonstrated higher mean effective doses in nuclear medicine (1.26 ± 2.52 mSv) compared to radiotherapy (0.08 ± 0.20 mSv), diagnostic X-ray (0.07 ± 0.17 mSv), and computed tomography (0.02 ± 0.06 mSv). The nuclear medicine group presented higher frequencies of total aberrations ($p = 0.025$) and aberrant cells ($p = 0.032$) compared to the computed tomography group.

Considerable heterogeneity was observed in the association between physical dosimetry and biological damage. In some studies, individual dosimeter readings correlated positively with biomarkers such as NPB and NBUD[17]. However, other investigations did not detect a linear relationship between the effective dose estimated by individual dosimetry and the magnitude of the chromosomal aberrations observed[5]. This divergence suggests that physical dosimetry, although essential for occupational control, may not fully reflect individual biological response in chronic low-dose exposure scenarios.

The statistical analyses of the included studies were predominantly based on between-group comparisons using p-values and, less frequently, on correlations or multivariable models. The absence of confidence intervals and standardized effect size estimates in some articles limited direct quantitative comparison. For this reason, results were interpreted jointly considering statistical significance, sample size, absolute biomarker magnitude, and reported confounding factors.

DISCUSSION

The results of this review demonstrate that prolonged occupational exposure to ionizing radiation is associated with measurable genomic instability in radiology technicians and radiological service workers, even when recorded doses remain within regulatory limits. These findings corroborate evidence recognizing ionizing radiation as a clastogenic agent capable of inducing chromosomal breaks, mitotic errors, structural rearrangements, and persistent DNA damage[5,7,17,20,21].

The interpretation of findings must consider that the cytogenetic biomarkers assessed do not share the same biological specificity. The micronucleus assay is widely used for its relative simplicity, reproducibility, and applicability to population biomonitoring; however, its baseline frequency may be influenced by age, sex, smoking, metabolic diseases, inflammation, and exposure to other genotoxic agents[11,12,13,14,15]. In contrast, dicentric chromosomes and rings exhibit greater specificity for ionizing radiation exposure, although they are more useful in acute or recent exposures. Nucleoplasmic bridges have been highlighted as promising markers in chronic low-dose exposure contexts, as they may reflect breakage-fusion-bridge events and exhibit a lower baseline frequency than micronuclei[6,7].

Differences between occupational settings help explain the heterogeneity of results. Nuclear medicine professionals may face higher risks of internal and external exposure due to the handling of radiopharmaceuticals and unsealed sources, while conventional radiodiagnosis and computed tomography workers tend to be exposed predominantly to external sources – generally with greater control through physical barriers, distance, and exposure time. This may account for the higher frequency of aberrations observed in nuclear medicine subgroups compared to sectors such as conventional X-ray and computed tomography[5].

The radiological technology employed also appears to influence the magnitude of cytogenetic damage. The study by Cunha Jr *et al.*[20] demonstrated higher micronucleus frequencies in professionals exposed to analog and computed radiography systems compared to digital systems. This difference is biologically plausible, given that digital systems tend to allow greater dose optimization, better operational control, and fewer repeat examinations – although such benefits depend on adequate calibration, training, and adherence to radiation protection standards.

Another critical point is the incomplete control of confounding factors. Age and sex may influence the baseline frequency of micronuclei; smoking

may increase chromosomal aberrations and oxidative damage; and length of service may reflect both cumulative exposure and technological changes over the course of a career. Studies that do not adequately adjust for these factors may over- or underestimate the association between occupational radiation and cytogenetic damage. This limitation reinforces the need to interpret findings with caution and to prioritize studies with well-matched control groups and multivariate analysis[5,7,17].

The absence of a consistent correlation between individual dosimetry and biological damage does not invalidate the use of dosimeters, but demonstrates that the recorded dose may not fully translate individual biological response. Radiosensitivity, the efficiency of DNA repair mechanisms, actual use of protective equipment, dosimeter positioning, partial body exposures, and sector-specific characteristics may modify the relationship between physical exposure and observed cytogenetic damage. Biodosimetry should therefore be understood as a complement – not a substitute – for physical dosimetry[5,6,8,9,17,22].

From an occupational surveillance perspective, the findings suggest that cytogenetic assessment may serve as a complementary tool in specific situations – such as chronic exposure, suspected dosimeter underestimation, inadequate use of protective equipment, work in higher-risk sectors, outdated equipment, or persistent alterations in biomarkers. The incorporation of such tests must, however, consider cost, laboratory standardization, frequency, clinical interpretation, and the need for clear institutional protocols[6,8,9,16,22,23].

Among the limitations of this review, the following are noteworthy: the small number of included studies, the temporal restriction to 2021–2025, the predominance of cross-sectional designs, the heterogeneity of assessed biomarkers, and the insufficient data for meta-analysis. Furthermore, some studies did not report confidence intervals, effect sizes, or complete statistical adjustment for confounding factors. Despite these limitations, the selection of recent studies allowed discussion of findings produced in a technological context closer to current radiological practice.

CONCLUSION

Based on the studies included in this systematic review, occupationally exposed radiology professionals presented higher frequencies of cytogenetic biomarkers – including micronuclei, nucleoplasmic bridges, nuclear buds, dicentrics, and chromosomal aberrations – compared to non-exposed individuals. These findings suggest genomic instability associated with chronic occupational exposure, even in low-dose scenarios and within regulatory limits.

The interpretation of these results must consider the methodological heterogeneity among studies, including differences in cytogenetic techniques, occupational sectors, radiological technologies, exposure measurement methods, and control of confounding factors. The relationship between individual dosimetry and biological damage was not consistent, reinforcing that biodosimetry may complement – but not replace – physical dosimetry. Future studies should prioritize longitudinal designs, larger samples, statistical control of confounders, reporting of confidence intervals, and standardization of the biomarkers used.

Funding

The authors thank the Fundação de Amparo à Pesquisa do Estado do Tocantins (FAPT) for its support through a research grant that made this work possible.

CRediT author statement

Conceptualization: Santos, MS; Paiva, MJM; Souza, DLC. Methodology: Brito, GR; Souza, GS; Alves, RC. Validation: Paiva, MJM; Santos, MS. Statistical Analysis: Paiva, MJM; Botelho, ML. Formal Analysis: Santos, MS; Souza, DLC. Investigation: Botelho, ML. Resources: Souza, GS; Souza, DLC. Original Draft Preparation: Brito, GR. Writing – Review & Editing: Souza, GS; Paiva, MJM. Visualization: Alves, RC; Botelho, ML. Supervision: Maykon Jhuly Martins de Paiva, Alves, RC. Project Administration: Souza, GS.

All authors have read and agreed to the published version of the manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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How to cite this article: Souza, G.S., Brito, G.R., Botelho, M.L., Souza, D.L.C., Paiva, M.J.M., Santos, M.S., Alves, R.C. (2026). Alterações citogenéticas associadas à exposição ocupacional à radiação ionizante em técnicos de radiologia: uma revisão sistemática. O Mundo Da Saúde, 50. https://doi.org/10.15343/0104-7809.202650e19452025I. Mundo Saúde. 2026,50:e19452025.