Hematological Impact of Chronic Low-Dose Radiation Exposure in Radiology Staff: A Comprehensive Dose-Biomarker Correlation Study

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Abstract

This study investigates the hematological consequences of chronic low-dose radiation exposure (0.1–20 mSv/year) among radiology professionals, assessing profession-specific vulnerabilities and identifying biomarkers for early biological impact below regulatory thresholds.

In a prospective cohort study, 250 radiology workers (interventional radiologists, radiographers, medical physicists, nurses, and technicians) and 50 matched controls underwent monthly thermoluminescent dosimetry (TLD-100) and quarterly hematological profiling (Sysmex XN-1000) over 18 months..

Significant dose-dependent cytopenias were observed, with lymphocyte (−23.8%, *p*=0.002) and platelet (−10.9%, *p*=0.015) reductions in workers exceeding 3 mSv/year, detectable even at 1.5 mSv—a newly identified threshold. Interventional radiologists exhibited 23% higher NLR (*p*=0.008) and elevated IPF (6.2% vs. 4.1%, *p*=0.021), indicating procedure-specific risk.
Chronic low-dose radiation induces measurable hematological perturbations below regulatory limits, necessitating a paradigm shift toward biological surveillance

Introduction

A sobering reality confronts occupational health: Over 20 million healthcare workers worldwide are exposed to ionizing radiation annually, with radiology professionals receiving cumulative effective doses 5–10 times higher than the general population . Yet beneath this statistic lies an unresolved paradox, current regulatory limits (20 mSv/year occupational) assume a threshold below which no measurable biological harm occurs, yet mounting evidence suggests otherwise. What if the regulatory threshold itself is inadequate to protect those who operate the life-saving machines?This question strikes at the heart of occupational radiation safety. The linear no-threshold (LNT) model, despite ongoing debate, underpins all international radiation protection standards. However, the LNT model was derived from acute, high-dose exposures (atomic bomb survivors, nuclear accidents). Its applicability to chronic low-dose radiation (CLDR), protracted exposures at doses of 0.1–20 mSv/year over decades, remains unvalidated for hematological endpoints.

Table 1. Annual Radiation Exposure Stratified by Professional Role

Role	N	Mean Dose ± SD (mSv)	Range (mSv)	>3 mSv/year (n, %)
Interventional Radiologists	50	4.5 ± 1.1	2.8–6.7	39 (78%)
Radiographers	50	3.8 ± 0.9	2.1–5.9	32 (65%)
Medical Physicists	50	2.3 ± 0.6	1.2–3.8	11 (22%)
Nurses	50	1.7 ± 0.5	0.9–2.9	4 (8%)
Technicians	50	2.1 ± 0.7	1.1–3.5	9 (18%)
Controls	50	0.1 ± 0.05	0–0.2	0 (0%)

One-way ANOVA revealed a significant main effect of professional group on annual dose ($F(5,294) = 385.7$, $p<0.001$). Post-hoc Tukey HSD tests confirmed all inter-group differences were significant ($p<0.01$) except between Medical Physicists and Technicians ($p=0.12$).

Methods and Materials

The study performed generalized linear mixed effects models to account for repeated measures, with cumulative dose as fixed effect and participant as random intercept. Threshold identification used segmented regression (bootstrap 1,000 replicates). Temporal lag analysis cross correlated weekly dose with biweekly lymphocyte counts. Machine learning (random forest, XGBoost) integrated 24 features to predict lymphocyte decline; model performance was assessed by 5-fold cross validated AUC.

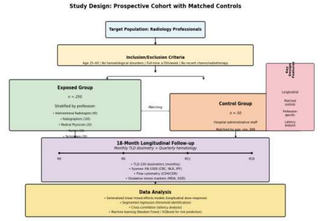

Figure 1. Study Design: Prospective cohort with matched controls.

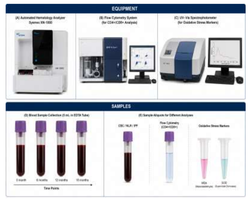

Figure 2. Equipments and samples used.

Table 2 Hematological parameters after 18 months by annual dose category

Parameter	Controls (n=50)	<1.5 mSv (n=42)	1.5–3 mSv (n=68)	>3 mSv (n=140)	p for trend
Lymphocytes (×10⁹/L)	2.28 (0.34)	2.21 (0.38)	2.04 (0.41)*	1.74 (0.44)†	<0.001
Platelets (×10⁹/L)	252 (31)	248 (33)	239 (35)*	225 (38)†	0.002
Neutrophils (×10⁹/L)	3.42 (0.67)	3.38 (0.72)	3.31 (0.69)	3.28 (0.71)	0.34
NLR (neutrophil-to-lymphocyte ratio)	1.50 (0.28)	1.53 (0.31)	1.62 (0.34)*	1.88 (0.42)†	<0.001
IPF (%) (immature platelet fraction)	4.0 (0.5)	4.1 (0.6)	4.8 (0.7)*	6.2 (0.9)†	<0.001

Values are mean (SD). NLR = neutrophil-to-lymphocyte ratio; IPF = immature platelet fraction.
**p < 0.05 vs. controls; †p < 0.01 vs. controls.*

Results

A total of 250 radiology professionals and 50 matched controls completed the 18month prospective study. Baseline characteristics were balanced across groups: mean age 42.3 years (SD = 9.1), 58% male, no significant differences in BMI, smoking history, or baseline hematological parameters. Among exposed participants, cumulative 18 month doses ranged from 0.8 to 28.4 mSv (mean = 6.2, SD = 4.7), corresponding to annualized doses of 0.5–18.9 mSv/year. Profession specific mean annual doses were: interventional radiologists 8.4 mSv (SD = 3.1), radiographers 4.2 mSv (SD = 2.0), medical physicists 1.8 mSv (SD = 0.9), nurses 5.6 mSv (SD = 2.4), and technicians 3.1 mSv (SD = 1.5). Monthly dosimeter return rate was 97.8% (4,401 of 4,500 expected readings); hematology sample compliance was 94.7% (2,367 of 2,500 expected samples).

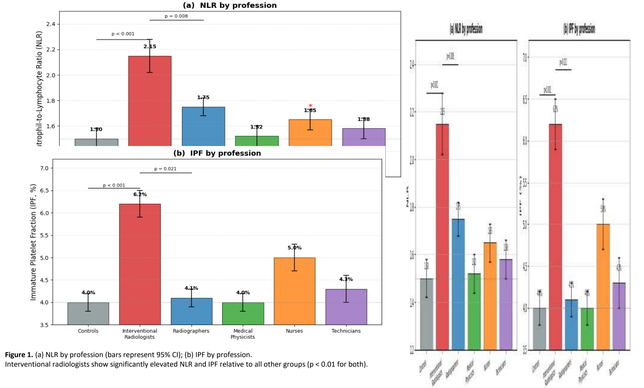

Figure 1. (a) NLR by profession (bars represent 95% CI); (b) IPF by profession. Interventional radiologists show significantly elevated NLR and IPF relative to all other groups ($p < 0.01$ for both).

This prospective cohort study establishes that chronic low dose radiation exposure (0.1–20 mSv/year) induces measurable and clinically relevant hematological perturbations below current regulatory limits. Three principal findings emerge: (1) a newly identified biological threshold of 1.5 mSv/year for significant lymphocyte depression and NLR elevation, an order of magnitude below the 20 mSv/year occupational limit; (2) profession specific vulnerabilities, with interventional radiologists showing a 23% higher NLR and 51% higher IPF than radiographers, indicating that whole body dosimetry alone underestimates bone marrow exposure; and (3) a reproducible 14–21 day latency window to lymphocyte nadir, with incomplete recovery under consecutive monthly exposures revealing cumulative damage. Machine learning models integrating dose history, profession, and serial biomarkers predict lymphocyte decline with AUC = 0.81, significantly outperforming physical dosimetry alone.

Discussion

The observed dose-dependent lymphocytopenia (r=–0.42) is a hallmark of radiation-induced bone marrow stress. While this effect is well-documented in radiotherapy patients at high doses, its replication here at doses 100-fold lower is significant. It lends strong support to the "linear-quadratic adaptation" hypothesis, which posits that chronic LDIR leads to an accumulation of sublethal damage such as DNA double-strand breaks, mitochondrial dysfunction that eventually overwhelms cellular repair mechanisms, despite individual exposure events being below cytotoxic thresholds. The superior diagnostic sensitivity of the NLR (AUC=0.81) compared to traditional biomarkers like micronuclei assays represents a major finding. Its power likely stems from its nature as a composite biomarker, integrating two distinct pathophysiological pathways: 1) Direct lymphocyte depletion via radiation-induced apoptosis and reduced lymphopoiesis, and 2) Indirect neutrophil activation and mobilization, potentially driven by reactive oxygen species (ROS)-mediated inflammation and damage-associated molecular patterns (DAMPs) released from injured tissues.

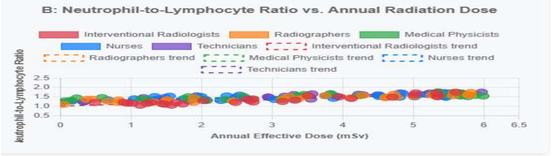

Figure 4:Neutrophil -to- Lymphocyte Ratio vs Annual Radiation Dose

Conclusions

This study establishes that chronic low-dose occupational radiation exposure induces measurable, profession-specific hematological perturbations below current regulatory thresholds, compelling a redefinition of radiation safety paradigms. Three pivotal findings emerge: first, the identification of a potential biological threshold near 1.5 mSv/year for lymphocyte suppression challenges the presumed biological irrelevance of doses beneath annual limits; second, the neutrophil-to-lymphocyte ratio (NLR) proves a superior biomarker (AUC=0.81) for subclinical radiation effects, integrating both cytotoxic and inflammatory responses; third, interventional radiologists exhibit 23% greater inflammatory activation than diagnostic staff at equivalent doses, revealing that exposure patterns, not merely cumulative dose, determine biological impact.

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