

Radiation Protection Culture in Healthcare: Evaluating Awareness, Training, and Regulatory Compliance

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Abstract

Background: The clinical adoption of ionising radiation across diagnostic radiology, interventional cardiology, nuclear medicine, and image-guided surgical suites has transformed clinical medicine. However, the accompanying surge in occupational and secondary patient radiation doses demands an institutional evolution from basic procedural adherence to an integrated Radiation Protection Culture (RPC). Radiation safety encompasses more than passive adherence to dose thresholds; it requires a collective mindset, institutional values, human behaviour, structured pedagogy, and continuous regulatory oversight.

Objectives: This review synthesises empirical evidence evaluating radiation safety awareness, educational interventions, behavioural practices, dosimetric monitoring frameworks, and administrative compliance across clinical environments.

Methods: A narrative literature analysis was conducted across academic medical and safety databases, synthesising multi-centre cross-sectional surveys, prospective dosimetric trials, pedagogical intervention studies, quality-assurance audits, and occupational epidemiological evaluations.

Results: Despite widespread qualitative endorsement of the "As Low As Reasonably Achievable" (ALARA) principle, significant knowledge gaps persist across medical specialties. Non-radiology personnel—particularly orthopaedic surgeons, interventional cardiologists, Cath-lab nurses, and anaesthesia providers—consistently display lower awareness of radiation scatter biophysics, regulatory occupational dose limits, and tissue-weighting variables than certified medical radiologic technologists. This deficit directly impacts practice: eye lens dosimeters, thyroid shields, and structural protective barriers remain underused, correlating with an elevated prevalence of occupational radiation-induced subcapsular lens changes. Passive didactic training models show minimal long-term behavioural translation, whereas structured post-licensure workshops, digital multimedia modules, and clinical simulation models produce sustained reductions in staff dose exposure. Systemic barriers—including chronic staffing shortages, high patient turnaround pressures, unmonitored physical deterioration of personal protective equipment (PPE), and fragmented reporting frameworks—impede regulatory compliance.

Conclusions: Establishing a resilient RPC requires shifting from individualized fault-finding to systems-based institutional governance. Healthcare systems must institute mandatory multi-tier post-licensure credentialing, routine radioprotective equipment surveillance, multi-dosimeter monitoring policies, and visible executive leadership to ensure that patient diagnostic benefits do not come at the expense of staff safety.

Keywords: Radiation Protection Culture, ALARA, Interventional Fluoroscopy, Occupational Radiation Exposure, Radiation Safety Training, Quality Assurance, Regulatory Compliance.

Introduction

Ionizing radiation has revolutionized modern diagnostic and therapeutic medicine. The widespread adoption of multidetector computed tomography (CT), hybrid positron emission tomography-computed tomography (PET-CT), high-dose interventional fluoroscopy, and image-guided operating theatres has improved diagnostic accuracy and enabled minimally invasive interventions ^[1,2]. However, the increased clinical use of ionising radiation increases occupational health hazards for healthcare personnel and elevates cumulative radiation risks for patient populations ^[3,4].

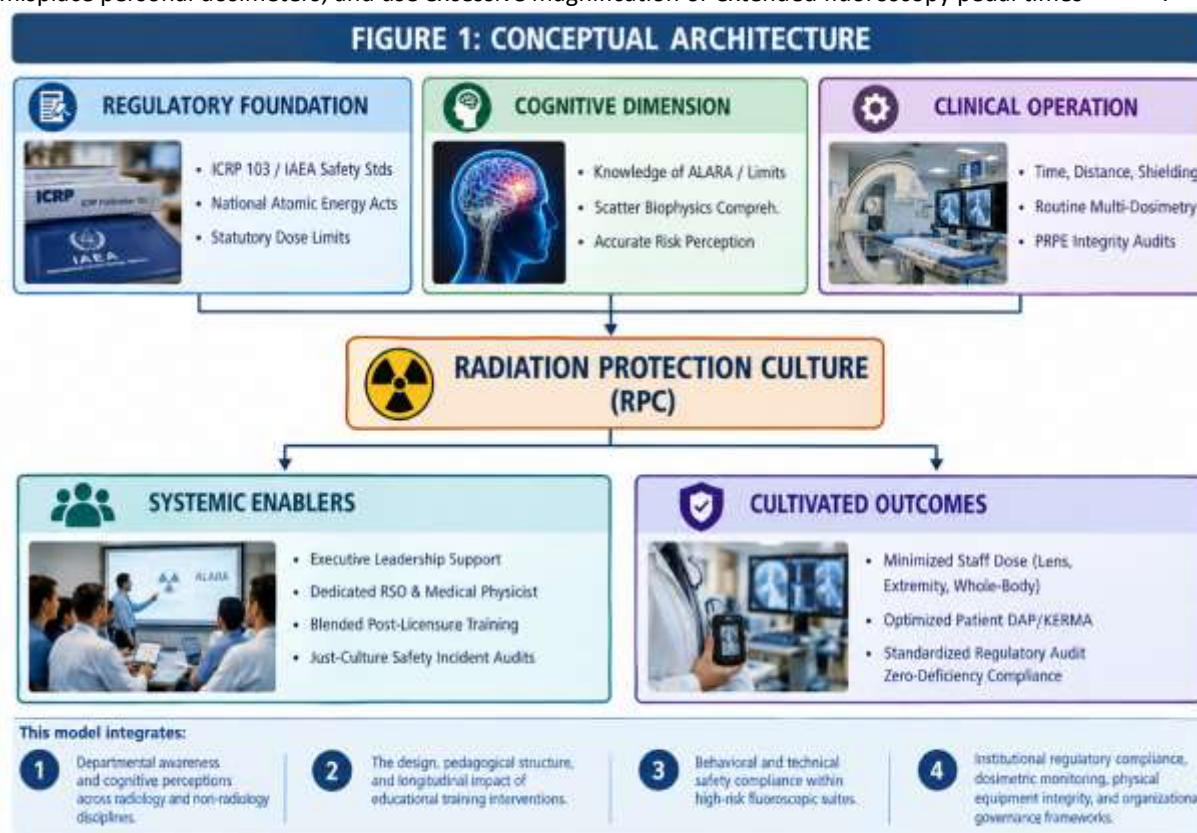
Historically, radiation protection frameworks operated under a strictly mechanistic, compliance-driven paradigm. Regulatory bodies—such as the International Commission on Radiological Protection (ICRP), the International Atomic Energy Agency (IAEA), and national statutory authorities—established dose limits, shielding requirements, and procedural mandates centred on the fundamental triad of radiation safety: time, distance, and shielding ^[5,6].

While technical safeguards, beam-shaping collimators, automated exposure controls, and lead-equivalent personal

protective equipment are widely available, structural guidelines alone cannot prevent excess exposure [7,8]. Real-world clinical adherence relies fundamentally on the human element: healthcare workers' cognitive perceptions, behavioural norms, situational awareness, and shared institutional values [9,10]. This sociotechnical dimension constitutes Radiation Protection Culture (RPC) [11,12].

Originally derived from nuclear safety analysis following major industrial incidents, the safety culture concept was translated into healthcare by international bodies, including the ICRP, the World Health Organization (WHO), and the International Radiation Protection Association (IRPA) [11,12]. Radiation protection culture is defined as the assembly of characteristics, attitudes, and operational habits in healthcare organizations and individual staff members that prioritises radiation safety as an overriding institutional imperative [11,12]. In an organization with a mature RPC, safety is not perceived as an impediment to clinical workflow or an administrative chore, but as an integral component of clinical excellence and patient-centred quality care [11,13].

Despite widespread recognition of RPC's importance, empirical field investigations reveal substantial variations across clinical settings [1,9,14]. While certified radiologic technologists (RTs) and diagnostic radiologists receive formal education in radiation biology, physics, and statutory dose limitations, non-radiology specialists who routinely deploy fluoroscopic systems—including interventional cardiologists, vascular surgeons, orthopaedic trauma teams, gastroenterologists, and perioperative nursing personnel—frequently operate without equivalent training [4,10,15]. Consequently, safety lapses persist: workers routinely bypass thyroid collars, fail to deploy protective ceiling drapes, misplace personal dosimeters, and use excessive magnification or extended fluoroscopy pedal times [10,16,17].



This narrative review synthesises current evidence regarding radiation protection culture in healthcare, addressing four main areas:

1. Departmental awareness and cognitive perceptions across radiology and non-radiology disciplines.
2. The design, pedagogical structure, and longitudinal impact of educational training interventions.
3. Behavioural and technical safety compliance within high-risk fluoroscopic suites.
4. Institutional regulatory compliance, dosimetric monitoring, physical equipment integrity, and organisational governance frameworks.

2. Foundations of Radiation Protection Culture (RPC)

2.1 The Evolution: From Engineering Controls to Behavioural Safety Culture

Radiation safety traditionally relied on engineering safeguards: structural barium-plaster wall barriers, lead-glass viewing panes, electromechanical interlocks, and automated tube potential modulation ^[5,7]. While these passive protections reduce primary beam hazards, they do not mitigate risks arising from human behaviour within exposure environments ^[9,14].

Operational data consistently demonstrate that human error, complacency, procedural shortcuts, and inadequate training account for most unintended occupational and medical radiation exposures ^[1,8,13]. Consequently, international bodies—such as the ICRP (Publication 103), the IAEA (Safety Standards Series GSR Part 3), and regional initiatives like the Asia Safe consortium—have transitioned from prescriptive compliance mandates to cultural integration ^[5,11,12].

A mature RPC requires three interlinked structural tiers ^[11,12]:

1. **The Policy/Leadership Tier:** Senior healthcare executives, chief medical officers, and hospital boards must recognize that radiation safety is a primary clinical responsibility. This commitment requires funding dedicated Radiation Safety Officers (RSOs), modernizing aging fluoroscopy suites, purchasing ergonomic, certified personal shielding, and establishing non-punitive event-reporting mechanisms ^[11,13].
2. **The Managerial/Supervisory Tier:** Department chairs, chief radiographers, and nurse supervisors must incorporate safety milestones into routine clinical operations. Responsibilities include auditing dosimeter-wearing compliance, enforcing PPE maintenance schedules, managing procedural rotation rosters to avoid cumulative occupational dose burdens, and mandating documented corrective action plans when diagnostic reference levels (DRLs) or occupational dose constraints are exceeded ^[7,18,19].



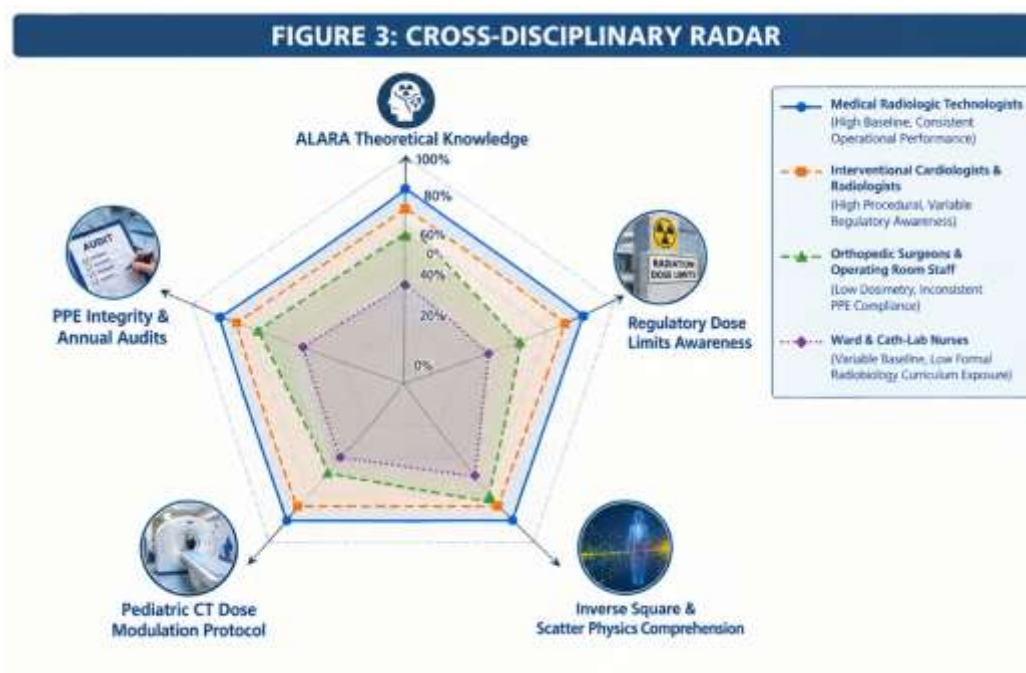
3. **The Individual Operational Tier:** Every clinician, technologist, and nurse working near ionizing radiation must take personal responsibility for ALARA practices. Clinicians must understand that self-protection directly protects patients: techniques that minimize operator scatter exposure—such as beam collimation, low-pulse rate selection, avoidance of steep gantry angulations, and physical withdrawal from the patient table during acquisition runs—simultaneously reduce radiation dose to the patient [10,16,17].

2.2 Core Biophysical Principles and Occupational Risk Profiles

Establishing an institutional safety culture requires personnel across all modalities to understand the dual biological mechanisms of ionizing radiation: deterministic effects (tissue reactions) and stochastic effects [1,9,14]:

- **Deterministic Effects (Tissue Reactions):** Characterized by a causal threshold dose below which cellular repair mechanisms typically prevent functional impairment. Once exposure exceeds this threshold, severity increases linearly or exponentially with dose [1,20]. In medical workers, primary occupational tissue reactions involve radiation-induced lens opacities (cataracts), cutaneous erythema, radiation dermatitis, telangiectasias, and localized alopecia of the lower extremities during unshielded fluoroscopy [10,20].
- **Stochastic Effects:** Radiation-induced carcinogenesis and heritable mutations operate on a linear no-threshold (LNT) dose-response model. No radiation dose is considered free of biological risk, as a single ionizing track can generate double-strand DNA breaks that evade cellular repair mechanisms, initiating oncogenesis [1,9,21]. Occupational groups in high-dose suites face potential risks of solid tumors, leukemia, and premature cardiovascular endothelial changes following decades of scatter accumulation [10,16].

Understanding these mechanisms reinforces the practical necessity of the ALARA (As Low As Reasonably Achievable) principle. ALARA does not mean avoiding radiation entirely, but using technical and behavioral measures to minimize dose while maintaining the required image quality for clinical decision-making [2,7,10].



3. Current State of Radiation Safety Awareness Across Healthcare Disciplines

Evaluating healthcare personnel awareness reveals significant variation across clinical specialties, credentialing requirements, and departmental boundaries [1,4,14].

3.1 Certified Radiologic Technologists vs. Non-Radiology Specialists

Certified Medical Radiologic Technologists (MRTs) consistently score higher than non-radiology professionals on radiation safety knowledge, biological hazard understanding, and protective equipment use [1,4,14].

- **Radiologic Technologists:** Formal licensure curricula provide technologist cohorts with foundational training in radiation physics, biological damage mechanisms, and inverse square law applications [6,14]. Technologists consistently identify the inverse square law, employ secondary collimation, wear their primary collar dosimeters, and respect structural barriers [1,7,14]. However, even among RT cohorts, knowledge gaps persist

regarding the quantitative conversion of lead equivalence, accurate numerical values for statutory organ limits (specifically the 2011 ICRP revised eye lens threshold), and modern CT parameter adjustments (e.g., volumetric CT Dose Index and Dose-Length Product) [2,14,21].

- **Orthopaedic and Operating Room Surgical Personnel:** Personnel using mobile C-arm fluoroscopy units in operating suites—including orthopaedic spine and trauma surgeons, surgical fellows, scrub technicians, and circulating nurses—frequently show lower levels of formal radiation protection knowledge [4,8]. Surgeries regularly rely on prolonged continuous fluoroscopy rather than pulsed modes, placing hands directly in the primary beam during intraoperative reduction, and displaying low adherence to lead glasses and personal dosimeters [4,8]. Many surgical personnel view radiation protection as the exclusive responsibility of visiting radiographers, leading to complacency in theatre [4,8].

3.2 Interventional Cardiologists and Interventional Radiologists

Interventional cardiologists and radiologists manage high procedural radiation exposures [10,16,17]. While interventionalists understand catheter manipulation and hemodynamic, their knowledge of radiation physics, scatter distribution geometry, and occupational risk mitigation varies considerably [10,16,17].

- Surveys by Shabani et al., Mansour et al., and Justin Paul et al. demonstrate that many operators rely heavily on equipment vendor default settings without manually optimizing pulse rates, collimating the field of view, or adjusting image intensifier/flat-panel detector distances [10,16,17].
- Gaps persist regarding how table height affects occupational scatter doses, and many operators routinely position themselves within high-intensity scatter paths without deploying ceiling-suspended or under-table lead shields [10,16,22].

3.3 Nursing Personnel in Nuclear Medicine and Fluoroscopy Environments

Registered nurses working in nuclear medicine hot labs, PET/CT suites, interventional cath labs, and surgical post-anaesthesia care units face distinct exposure profiles [9,15,16].

- **Nuclear Medicine:** As identified by Alshamrani, nurses frequently lack dedicated radiobiology education regarding internal contamination pathways, radiopharmaceutical half-lives, biological excretion dynamics, and distance-time protocols when caring for radiopharmaceutical-injected patients [15].
- **Catheterization Suites:** Cath-lab nurses often stand close to the patient during medication administration or hemodynamic decompensation, yet regularly lack tailored thyroid shields or ceiling-suspended shields [15,16]. Many facilities fail to include nursing staff in personal dosimeter rosters, leaving their occupational exposures unmonitored [15,16].

3.4 Discrepancy Between Perceptions, Attitudes, and Actual Clinical Practices

A common theme across the literature is the perception-practice paradox [1,9]:

- Staff universally recognize radiation as hazardous and report positive attitudes toward safety principles [1,9].
- However, observational audits reveal that positive self-reported attitudes do not reliably translate into clinical adherence [1,4,9].
- Healthcare professionals frequently overestimate their safety compliance in self-reported surveys while failing to wear protective eyewear, skipping personal dosimeters, or remaining close to the scatter field during real-time fluoroscopic exposures [1,4,9,16].



4. Educational and Pedagogical Strategies: From Theory to Practice

Educational interventions are essential for establishing and maintaining an institutional radiation safety culture [6,18,23]. However, the format, frequency, and delivery of training determine its long-term clinical efficacy [6,8,23].

4.1 Didactic Training vs. Interactive Multimedia and Simulation Modalities

Traditional didactic lectures and passive reading materials show limited efficacy in altering long-term clinical safety habits [6,8]:

- Comparative pedagogical trials, such as those by Charmchi et al., demonstrate that interactive multimedia modules, dynamic video instruction, and practical digital learning yield significantly higher retention and procedural compliance than static print brochures [8].
- Simulation labs utilising tissue-equivalent anthropomorphic phantoms, augmented reality (AR) scatter cloud visualisations, and real-time electronic dosimeters offer immediate visual feedback [6,10]. Observing how a 5 cm table height adjustment or a 10-degree cranial tube angulation shifts the scatter cloud provides a more lasting educational impact than reviewing abstract inverse square formulas in a classroom [10,22].

4.2 Impact of Post-Licensure Training and Continued Professional Development

Undergraduate training in allied health and medical schools provides insufficient preparation for the radiation

challenges of specialized clinical practice ^[6,23].

- Alamoudi demonstrated that dedicated, structured pre- and post-internship courses for radiologic technologist interns lead to significant improvements in radiobiology and radiation protection scores ^[6].
- For practising specialists, structured post-licensure courses are essential ^[17]. Justin Paul et al. evaluated the impact of targeted post-licensure workshops—specifically the "Ten Commandments of Radiation Safety"—among interventional cardiologists in India ^[17]. Participants exhibited sustained improvements in primary pedal management, low-pulse rate selection, regular ceiling-suspended screen use, and consistent dosimeter wearing ^[17]. Institutional policies must move away from one-time onboarding seminars, mandating instead modular, biennial recertification for any physician holding fluoroscopy privileges ^[17,23].

4.3 Longitudinal Dose Monitoring During Clinical Training

Students and residents in radiology, interventional cardiology, and surgical specialties represent vulnerable populations prone to radiation safety lapses ^[18,23]:

- Abuzaid et al. monitored occupational radiation doses in radiography students during clinical rotations, finding significant fluctuations in personal exposures tied to rotation sites, workflow volumes, and variable preceptor supervision ^[18].
- Without continuous dosimetric oversight and designated safety mentors, trainees often adopt bad habits from senior clinicians, such as discarding lead glasses or leaning over the patient table during active fluoroscopy ^[18,23].

Integrating radiation protection competencies into residency milestones and student clinical evaluations is essential to protect trainees and develop safety-conscious practitioners ^[18,23].

5. High-Risk Clinical Environments: Fluoroscopy, Operating Suites, and Cath Labs

High-dose fluoroscopic suites present substantial challenges to radiation protection culture ^[10,16,17,22]. While diagnostic radiology technologists typically operate systems from shielded control booths, interventionalists, surgeons, and circulating staff work inside the procedure room alongside the patient—the primary source of scatter radiation ^[10,16,22].

Table 1: Cross-Sectional Evidence on Radiation Safety Knowledge, Behavioural Practice, and Training Across Healthcare Personnel

Study & Year	Target Population & Sample Size	Design & Setting	Primary Knowledge / Practice Domains Evaluated	Key Empirical Findings & Cultural Deficits	Ref.
Pepele (2023)	Diagnostic Radiology & Nuclear Medicine Workers (n = 104)	Cross-sectional survey; Multiple hospital modalities	Permissible dose limits, shielding protocols, ALARA application, self-reported PPE use.	68% demonstrated accurate ALARA conceptual knowledge, but fewer than 42% accurately recalled statutory annual dose limits; regular dosimeter use was inconsistent outside central radiology.	^[1]
Vashistha et al. (2026)	Medical Radiation Workers & Students (n = 120)	Cross-sectional survey; Tertiary care academic department	TLD badge utilization, lead apron inspection, ALARA comprehension, lead-equivalence parameters.	Radiographers demonstrated higher technical knowledge (78%) compared to clinical students (49%); 34% could not identify the standard lead equivalence required for thyroid shielding.	^[7]
Khamtuikrua & Suksompong (2020)	Radiology vs. Non-Radiology Healthcare Staff (n = 422)	Cross-sectional observational study; Quaternary care academic center	Radiation biophysics, deterministic tissue risks, annual dose limits, protective shielding.	Radiologists and radiographers scored significantly higher ($p < 0.001$) than surgical and nursing personnel; 72% of non-radiology staff were unaware of their personal occupational dose limits.	^[4]

Study & Year	Target Population & Sample Size	Design & Setting	Primary Knowledge / Practice Domains Evaluated	Key Empirical Findings & Cultural Deficits	Ref.
Yashima & Chida (2023)	Medical Radiologic Technologists (n = 384)	Multicenter national survey; General hospital imaging units	Biological risks, radiation emergency preparedness, safety culture operationalization.	High fundamental physics knowledge, but variable understanding of low-dose cancer risks; institutional radiation safety culture metrics correlated with hospital bed capacity and dedicated RSO presence.	[14]
Goula et al. (2021)	Multidisciplinary Health Professionals (n = 250)	Cross-sectional questionnaire; Public tertiary hospitals	Health professionals' attitudes, psychological risk perception, behavioral protection adoption.	Marked psychological dread of radiation observed among nursing cohorts; safety compliance was driven more by perceived personal fear than systematic procedural understanding.	[9]
Justin Paul et al. (2026)	Interventional Cardiologists (n = 210)	Nationwide survey; Catheterization laboratories across India	Impact of post-licensure "Ten Commandments" course on fluoroscopy time, pulse rate, shielding.	Participants completing dedicated post-licensure workshops were significantly more likely to utilize under-table shielding (74% vs. 38%) and routinely implement low-dose fluoroscopy pulsing protocols.	[17]
Alamoudi (2025)	Radiologic Technologist Interns & Undergraduates (n = 86)	Prospective pre- and post-intervention survey; Academic university hospital	Radiation physics, radiobiology, modern international safety standards, PPE handling.	Structured educational intervention increased mean overall safety scores from 52.4% at baseline to 84.1% post-course (p < 0.0001), underscoring the inadequacy of unsupplemented curricula.	[6]
Alshamrani (2025)	Registered Nurses in Nuclear Medicine (n = 78)	Descriptive cross-sectional survey; Dedicated nuclear medicine suites	Radiopharmaceutical handling, half-life awareness, contamination control, personal dosimetry.	Severe deficits identified in nurse knowledge regarding radiopharmaceutical safe distances and biological excretion timelines; 61% had never attended a formal post-nursing radiation safety course.	[15]
Almalki et al. (2021)	Orthopedic Operating Room Personnel (n = 112)	Cross-sectional multicenter survey; Orthopedic surgical suites	Intraoperative C-arm radiation risks, eye lens protection, lead apron wearing, dosimeter habits.	Only 39.3% demonstrated acceptable overall radiation knowledge; fewer than 18% consistently wore leaded safety glasses, and 67% did not wear a personal dosimeter during fluoroscopy-guided surgery.	[8]
Mansour et al. (2024)	Multidisciplinary Cath-Lab Personnel (n = 185)	Multicenter cross-sectional study; High-volume cardiac cath units	Exposure awareness, positioning geometry, eye lens limits, PPE compliance across roles.	Primary interventionalists possessed moderate technical knowledge, but fellows, cath-lab nurses, and scrub techs exhibited low awareness; over 80% of nursing staff did not monitor eye lens doses.	[16]

Study & Year	Target Population & Sample Size	Design & Setting	Primary Knowledge / Practice Domains Evaluated	Key Empirical Findings & Cultural Deficits	Ref.
Shabani et al. (2018)	Interventional Radiologists & Cath-Lab Staff (n = 95)	Cross-sectional KAP evaluation; University interventional suites	Quantitative KAP scores, shielding maintenance, ceiling drape and table skirt utilization.	Practice scores lagged substantially behind self-reported positive attitudes; lack of ceiling-suspended shield deployment correlated with procedural urgency and poor equipment positioning ergonomics.	[10]

5.1 Scatter Field Dynamics and Operator Ergonomics

The primary source of occupational radiation exposure in fluoroscopic environments is secondary Compton scattering emitted from the patient's irradiated tissue [10,22].

- **The Inverse Square Law:** This remains the most effective principle for reducing staff exposure: doubling the distance from the scattering patient volume reduces the dose rate by a factor of four [5,10]. In clinical practice, non-primary operators—such as anesthesiologists, circulating nurses, and students—often stand closer to the patient table than clinically necessary, receiving preventable scatter doses [4,16].
- **Table Height and X-Ray Tube Geometry:** System position substantially alters the scatter field [10,22]. Positioning the X-ray tube beneath the patient table and the flat-panel detector as close to the patient's anterior surface as possible reduces the primary beam path length, limits air kerma, and directs high-intensity backscatter toward the floor rather than the operator's upper body and eyes [10,22].
- **Gantry Angulation:** Steep oblique views (e.g., Left Anterior Oblique [LAO] with cranial tilt in cardiac catheterization) direct scatter trajectories toward the primary operator's workstation, increasing lens and thyroid dose rates up to tenfold compared to standard posteroanterior projection angles [10,17,22].

5.2 Technical and Behavioural Interventions in Cardiac Catheterization

Interventional cardiologists experience some of the highest recorded cumulative radiation exposures among medical personnel [10,16,17,22]. Improving RPC in catheterization laboratories requires combining technical equipment modifications with behavioural adaptations [17,22].

1. **Pulse Rate Modulation:** Replacing traditional continuous fluoroscopy or 30-pulse-per-second (pps) rates with 7.5 pps or 15 pps reduces cumulative scatter fields by 50% to 75% without compromising coronary guidewire navigation or stent positioning [17,22].
2. **Radiation-Aware Collimation:** Tight secondary collimation to the immediate cardiac region of interest restricts primary beam area, lowering scatter generation and patient Dose-Area Product (DAP) [17,22].
3. **Optimized Magnification:** Avoiding electronic magnification unless clinically necessary limits the automated dose rate increases that modern X-ray tubes use to maintain image pixel brightness [10,22].
4. **Structural Shielding:** Routinely deploying ceiling-suspended articulated lead acrylic shields and under-table leaded curtains can reduce operator torso and head scatter exposure by up to 90% [10,22]. However, operators often fail to adjust these shields during bed translations, leaving themselves unprotected [10,16].

5.3 Deterministic Consequences: The Occupational Cataract Burden

In 2011, the ICRP revised its deterministic threshold for radiation-induced cataractogenesis downward, reducing the equivalent dose limit for the lens of the eye from 150 mSv/year to 20 mSv/year averaged over five consecutive years, with no single year exceeding 50 mSv [5,20]. This regulatory reduction followed epidemiological evidence demonstrating that lens opacification occurs at lower cumulative exposure thresholds than previously recognized [20,24].

Rose et al. evaluated radiation-induced cataracts in interventionalists occupationally exposed to ionizing radiation, identifying a significantly higher prevalence of subclinical posterior subcapsular lens opacities—a characteristic biological marker of radiation exposure—among high-volume interventionalists compared to unexposed controls [20]. Despite these risks:

- Lead glasses (typically offering 0.50–0.75 mm lead equivalence, reducing lens doses by 85–95%) remain widely underused [8,16,20].
- Clinicians cite common reasons for non-compliance, including physical discomfort, bridge slippage during lengthy cases, fogging, and lack of prescription-ground lead lenses [8,10,20].

- Healthcare systems rarely mandate dedicated eye lens dosimeters (worn on the temple or forehead adjacent to the ocular globe), preventing accurate monitoring against statutory limits ^[20,24].

6. Personal Dosimetry, PPE Integrity, and Safety Infrastructure

An organization's safety culture depends on the quality, calibration, and maintenance of its protective equipment and personal monitoring technologies ^[2,7,19,25].

Table 2: Regulatory Directives, Monitoring Guidelines, and Protective Standards

Regulatory Standard / Directive	Mandated Technical Parameters	Clinical Target Modalities	Operational Compliance Challenges
ICRP Publication 103 (2007) / IAEA GSR Part 3	Occupational dose limit: 20 mSv/yr (averaged over 5 yrs); Public: 1 mSv/yr; Rigorous application of Justification, Optimization, and Dose Limitation.	All clinical ionizing radiation departments (Radiology, Cath Labs, Radiotherapy, Nuclear Medicine).	Inconsistent local dose constraint definitions; variable clinical justification for repeat diagnostic scans; limited clinical physicist staffing in community hospitals.
ICRP Statement on Tissue Reactions (2011)	Eye lens occupational dose limit reduced from 150 mSv/yr to 20 mSv/yr (averaged over 5 yrs, max 50 mSv in any single yr).	Interventional fluoroscopy, catheterization labs, hybrid vascular ORs.	Chronic non-wearing of leaded eyewear; severe absence of specialized ocular lens dosimeters ($H_p(3)$); lack of awareness among surgical specialists.
EURADOS Working Group 12 Guidelines	Double-dosimetry algorithm implementation: one badge worn under the apron at chest/waist level, second badge outside the apron at collar/thyroid level.	High-dose interventional suites, cardiac electrophysiology, neuro-interventional radiology.	Staff non-compliance with dual-badge wearing; confusion regarding which badge is worn under vs. over the apron; delayed reading turnaround from central dosimetry labs.
IEC / ISO Radiation Protection Standards	Annual physical, radiographic, or fluoroscopic integrity screening for all Personal Radiation Protective Equipment (PRPE). Minimum 0.25–0.50 mm lead equivalence.	Operating theatres, diagnostic imaging, interventional rooms, pediatric catheterization labs.	Absence of standardized digital asset tracking (RFID/barcodes); lack of structured retirement protocols for damaged aprons; improper hanging and folding storage practices.
National Radiation Protection Authorities (e.g., AERB, US-NRC/OSHA, EU-BSS)	Statutory appointment of certified Radiation Safety Officers (RSOs); periodic area dosimetry surveys; mandatory patient DRL establishment and reporting.	Nationwide licensed healthcare institutions containing ionizing radiation apparatus.	Regulatory inspection delays; fragmented administrative support; incomplete integration of non-radiology fluoroscopy equipment into central compliance registries.

6.1 The Double-Dosimetry Protocol and EURADOS Working Group 12 Findings

Accurate estimation of effective dose (E) and operational organ equivalent doses in fluoroscopy-intensive environments presents complex dosimetric challenges ^[22,24]. Wearing a single thermoluminescent dosimeter (TLD) or optically stimulated luminescent dosimeter (OSLD) under a lead apron reliably captures whole-body torso dose, but significantly underestimates exposure to unshielded tissues, including the head, ocular lens, thyroid gland, and hands ^[22,24].



To address this challenge, international bodies—including the European Radiation Dosimetry Group (EURADOS Working Group 12)—recommend the double-dosimetry algorithm ^[24]:

- **Over-Apron Collar Dosimeter:** Measures superficial equivalent dose ($H_p(0.07)$) and reflects unattenuated scatter incident on the head, neck, and thyroid ^[22,24].
- **Under-Apron Chest/Waist Dosimeter:** Measures deep equivalent dose ($H_p(10)$), tracking attenuated exposure to primary blood-forming and internal visceral organs ^[22,24].
- **Combining Algorithm:** National regulatory frameworks use specific weighting equations to calculate whole-body effective dose.

$$\text{Effective Dose (E)} = \alpha \cdot H_p(10)_{\text{under}} + \beta \cdot H_p(0.07)_{\text{over}}$$

where α and β represent empirically validated weighting coefficients ^[22,24].

Despite these standardized algorithms, double-dosimetry faces real-world compliance challenges ^[22,24]. As reviewed by Ferrari et al., workers routinely reverse badge positions, misplace outer dosimeters, or leave monitoring devices stored on lead aprons inside the fluoroscopy room, where they register false-positive background scatter ^[24]. Overcoming these issues requires moving to real-time active electronic personal dosimeters (APDs) ^[10,24]. Active

dosimeters offer real-time digital displays, audio-visual alarms that trigger when instantaneous dose rates exceed pre-set thresholds, and wireless network syncing to central dashboards, supporting immediate behavioural corrections during complex cases ^[10,24].

6.2 Physical Integrity of Personal Protective Equipment (PPE)

A critical element of RPC is the routine maintenance of lead aprons, thyroid shields, and ovarian/gonadal protective devices ^[7,19,25].

- **Physical Degradation:** Lead rubber and modern lead-composite or non-lead synthetic protective materials undergo mechanical stress over time. Improper storage—such as folding aprons, throwing them over chairs, or hanging multiple units on unapproved racks—causes internal cracking, tensile shearing, and material slippage that remains hidden beneath outer nylon fabrics ^[19,25].
- **Integrity Screening:** In a 4-year longitudinal follow-up study, Kellens et al. evaluated the physical degradation of Personal Radiation Protective Equipment (PRPE), finding structural defects (tears, seams separation, and radiolucent micro-cracks) in up to 15–20% of active inventory ^[19].
- **Quality Assurance Audits:** Departments must establish formal quality-assurance protocols. Every piece of shielding should be assigned a distinct serial number or RFID barcode, tracked within an asset database, and undergo annual fluoroscopic or radiographic inspection ^[19,25]. Defects exceeding 15 mm² in critical organ zones or 5 mm along protective seams require prompt disposal to prevent accidental exposure ^[19,25].

7. Regulatory Compliance, Auditing, and Safety Infrastructure

Technical tools and educational curricula cannot function effectively without supportive institutional safety systems ^[11,13,26,27].

Table 3: Synthesis of Core Literature Across Identified Thematic Domains

Thematic Area	Consolidated Empirical Findings	Key Structural Deficits & Behavioral Roadblocks	Recommended Solutions & Strategic Interventions	Supporting References
Cognitive Knowledge & Awareness Gaps	Technical radiographers possess strong fundamental knowledge; non-radiology physicians, orthopedic surgeons, and nurses show persistent knowledge deficits regarding scatter physics and dose metrics.	Perception-practice paradox; personnel assume self-protection is automated; false sense of security; confusion between radiation and contamination risks.	Mandatory cross-departmental radiation safety curricula; standardized pre-licensure and credentialing requirements across surgical and nursing specialties.	[1,4,7,9,14,15]
Pedagogical Strategies & Training Efficacy	Passive didactics, printed brochures, and single onboarding seminars show minimal long-term behavioral change; interactive multimedia and hands-on simulation yield sustained improvements.	Training perceived as an administrative burden; lack of time in clinical rotations; irregular training intervals without practical reinforcement.	Simulation labs using anthropomorphic phantoms and active dosimeters; required biennial micro-learning re-certification for fluoroscopy privileges.	[6,8,17,18,23]
Fluoroscopic Suites & Operator Ergonomics	High scatter exposures to ocular lenses and lower extremities occur during complex, prolonged fluoroscopy; interventional staff remain at elevated risk for radiation-induced cataracts.	Poor deployment of ceiling and under-table shielding; low adherence to lead glasses; improper table-detector positioning; high-pulse default selections.	Routine adoption of 7.5–15 pps fluoroscopy; use of ergonomic 0.75 mm Pb glasses; mandatory procedural positioning guidelines with peer-led safety auditing.	[10,16,17,20,22]

Thematic Area	Consolidated Empirical Findings	Key Structural Deficits & Behavioral Roadblocks	Recommended Solutions & Strategic Interventions	Supporting References
Dosimetry & Shielding Maintenance	Double-dosimetry algorithms provide accurate dose approximations, but suffer from user non-compliance; 15–20% of clinical PPE inventory exhibits structural shielding defects.	Lack of ocular dosimeters; dosimeter non-wearing; improper apron folding causing internal lead fracture; absence of systematic asset tracking systems.	Transition to real-time active dosimeters (APDs); institutional RFID-tracked annual radiographic PPE inspection programs with defined retirement thresholds.	[7,19,24,25]
Regulatory Frameworks & Institutional Culture	Isolated safety mandates fail without active administrative support, designated RSO authority, and open incident reporting systems.	Bureaucratic reporting hurdles; production pressure over-riding safety pauses; blame-oriented safety cultures that discourage near-miss reporting.	Implementation of anonymous incident systems; executive visibility in safety rounds; establishment of institutional safety charters and DRL review boards.	[11,12,13,26,27,28]

7.1 Hazard Identification and Risk Assessment (HIRA) in Healthcare

Institutional safety culture requires structured Hazard Identification and Risk Assessment (HIRA) across all hospital areas utilizing ionizing radiation [13,26].

- **Operational Challenges:** Sahoo et al. conducted a comprehensive HIRA analysis in a tertiary public hospital, revealing systemic safety vulnerabilities: unmonitored access corridors, missing illuminated warning signs outside fluoroscopy rooms, inadequate storage for contaminated waste in nuclear medicine, and backlogged TLD badge readouts [13].
- **Resource Disparities:** In low- and middle-income healthcare settings, resource constraints create severe operational hurdles [26,27]. Shungube and Khoza documented acute structural challenges among radiographers in Eswatini, where high patient workloads, limited functional lead aprons, and absent institutional radiation policies routinely undermined safety standards [26].
- **Socioeconomic Impact:** Similarly, Kyei et al. highlighted the operational realities of limited-resource radiotherapy departments, where heavy clinical case burdens force staff to choose between patient throughput and comprehensive safety procedures [27]. Addressing these disparities requires targeted capital investment, clinical management support, and clear regulatory oversight [13,26,27].

7.2 Radiation Emergency Preparedness and Crisis Management

A robust radiation protection culture extends beyond routine imaging to encompass institutional readiness for radiological emergencies and mass-casualty incidents [28].

- **Preparedness Deficits:** As documented by Xu et al., medical workers across general hospitals frequently display low preparedness for radiation crisis management [28].
- **Critical Capabilities:** Emergency room personnel, triage nurses, and trauma surgeons often demonstrate poor understanding of contamination triage, radiological decontamination zones, internal radionuclide chelation pathways, and protective attire for handling contaminated casualties [28].
- **Training Needs:** Radiation safety infrastructure must integrate regular drill simulations for industrial source loss, orphan source discoveries, and nuclear accidents, ensuring that clinical teams can provide care while containing contamination [14,28].

8. Overcoming Structural Barriers: Implementing a High-Reliability Safety Culture

Transitioning a healthcare organization toward a mature, high-reliability radiation protection culture requires systemic institutional interventions [11,12].

8.1 Leadership Walk-Rounds and Executive Support

Safety culture is driven by leadership behaviour ^[11,13]. Hospital chief executive officers, medical directors, and department heads must visibly participate in safety rounds alongside Radiation Safety Officers ^[11,13].

When executive leadership prioritises radiation safety—by funding ergonomic, lightweight bismuth-composite or lead-free aprons, replacing obsolete fluoroscopy units, and attending radiation safety committee meetings—clinical staff recognise that safety is a shared institutional value rather than an individual administrative burden ^[11,12,19].

8.2 Transitioning to a Non-Punitive "Just Culture"

A persistent barrier to safety culture maturation is the fear of punitive disciplinary action following an inadvertent dose excursion, protocol deviation, or lost dosimeter ^[11,12]. Organizations must adopt a Just Culture framework ^[11]:

- Healthcare systems distinguish between human error (e.g., misreading an exposure chart under stress), at-risk behaviour (e.g., taking procedural shortcuts to shorten turnaround times), and reckless behaviour (e.g., intentionally operating without required shielding) ^[11,12].
- Establishing anonymous near-miss and incident reporting systems encourages personnel to report safety vulnerabilities, equipment malfunctions, or inadvertent patient overexposures without fear of retaliation ^[11,13].

Investigating these events allows clinical teams to resolve latent system weaknesses before they lead to severe deterministic injuries or significant occupational overexposures ^[11,12].

8.3 Standardization of Multidisciplinary Credentialing

National licensing frameworks must eliminate the historical separation between diagnostic radiology departments and outside fluoroscopy users ^[4,8,10]. Any physician seeking hospital privileges to operate mobile C-arms or interventional suites—including vascular surgeons, orthopaedists, and cardiologists—should be required to complete accredited post-licensure radiation safety training and demonstrate practical competence before gaining machine access ^[8,17].

Ongoing credential maintenance should require biennial retraining, verified dosimeter compliance, and participation in peer-reviewed clinical dose audits ^[8,17,23].

9. Future Horizons in Radiation Protection

The next decade will see modern technological innovations integrated into radiation protection culture, providing new tools to mitigate occupational exposure:

1. **Artificial Intelligence and Real-Time Dose Tracking:** Advanced machine learning algorithms integrated directly into interventional fluoroscopy suites can analyze scatter cloud mechanics in real time, factoring in patient BMI, table height, gantry angle, and beam filtration ^[2,24]. Projected onto intraprocedural displays, these systems alert operators when their position intersects high-intensity scatter lobes, enabling proactive positional adjustments ^[10,24].
2. **Robotic Interventional Suites and Tele-Navigation:** Fully motorised, robotic endovascular catheter navigation systems allow the primary interventionalist to perform procedures from an ergonomically designed, radiation-shielded control cockpit situated away from the patient table ^[10,22]. This separation eliminates scatter exposure to the operator's head, eyes, and torso, reducing cumulative occupational doses by over 95% ^[10,22].
3. **Suspended Zero-Gravity Protection Suits:** Suspended personal radiation shielding systems, supported by overhead tracks, eliminate lead apron weight from the operator's cervical and lumbar spine while providing high-density (1.0 mm lead equivalent) continuous shielding against primary scatter fields ^[10,22]. Overcoming the orthopaedic and physical strains of wearing heavy protective equipment will help remove long-standing barriers to staff compliance ^[10,19].

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