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RADIATION PROTECTION CHALLENGES IN HYBRID IMAGING FACILITIES IN RESOURCE-LIMITED SETTINGS

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ABSTRACT

Hybrid imaging has become an essential component of contemporary oncologic, neurologic, and infection-related imaging, yet it's safe implementation remains uneven in resource-limited settings. The challenge is no longer only the acquisition of PET/CT, SPECT/CT or PET/MR systems, but the capacity to sustain shielding design, workload estimation, dosimetry, quality assurance, regulatory oversight, waste control and specialist staffing over the operational life of the service. International standards already provide a coherent radiation protection framework through optimization, diagnostic reference levels, workplace monitoring, quality assurance, and regulatory control. However, implementation in lower-resource environments is frequently constrained by retrofitted facilities, limited access to clinically qualified medical physicists, weak internal dosimetry infrastructure, incomplete extremity and eye-lens monitoring, delayed calibration and maintenance support, and uneven inspection capacity. These constraints interact rather than operate independently. Infrastructure limitations increase dependence on administrative controls; workforce shortages weaken optimization and incident review; regulatory gaps reduce external verification; and procurement constraints delay shielding upgrades, automation, servicing and calibration. The result is a narrower margin for sustained optimization and demonstrable compliance. This review examines these challenges from a systems perspective, with emphasis on infrastructure and shielding, workforce capacity, radiopharmaceutical handling, CT optimization, monitoring and dosimetry systems, regulatory oversight, waste management, safety culture, economic constraints and equity-related implications. It argues that radiation protection performance in hybrid imaging is determined less by scanner availability alone than by the coherence of the surrounding protection system. Priority needs include stronger workforce development, more explicit integration of hybrid imaging into national radiation protection programmes, improved monitoring and QA infrastructure, and life cycle planning for shielding, servicing, calibration and waste control.

Keywords: Hybrid imaging; PET/CT; SPECT/CT; PET/MR; Radiation protection; Resource-limited settings; Medical physics; Diagnostic reference levels

1 INTRODUCTION

Hybrid imaging has moved from a specialized adjunct to a mainstream component of modern medical imaging. The International Atomic Energy Agency (IAEA) describes hybrid imaging as encompassing PET/CT, PET/MR and SPECT/CT, and notes that these systems have transformed lesion localization, staging, treatment response assessment and molecular characterization across a broad range of clinical indications. At the same time, the global expansion of hybrid imaging has exposed marked heterogeneity in access, infrastructure, education and implementation capacity, especially in lower-resource settings. [7]

The radiation protection significance of this expansion is substantial. Hybrid imaging combines radiopharmaceutical-related exposure pathways with CT-related patient dose considerations and, in PET-based systems, adds the distinctive occupational burden associated with handling unsealed positron-emitting radionuclides and working near injected patients. The IAEA Basic Safety Standards and associated medical-use guidance already require optimization, quality assurance, workplace monitoring, staff competence and regulatory control across this full chain of practice, while ICRP Publication 135 recommends that the radionuclide and CT components of hybrid imaging be considered separately for diagnostic reference level purposes. [1–4]

In resource-limited settings, however, implementation of this framework is shaped by systemic constraints. The WHO Regional Office for Africa has identified diagnostic imaging as one of the least developed components of many health systems in the region, citing deficits in infrastructure, standards, quality management, and trained personnel. The 2025 World Health Assembly resolution on strengthening medical imaging capacity similarly emphasized the need for sustainable investment in infrastructure, maintenance, calibration and workforce development rather than equipment procurement alone. [5,6]

Recent African evidence illustrates the scale of the problem. Hybrid imaging infrastructure remains concentrated in a small number of countries and major urban centres, while workforce surveys show large gaps between available and required clinically qualified medical physics support in diagnostic radiology and nuclear medicine services. These findings indicate that radiation protection in hybrid imaging should be analyzed not only as a technology issue, but as a problem of coupled infrastructure, workforce, regulatory, and dosimetric capacity. [8,9]

This review therefore examines radiation protection challenges in hybrid imaging facilities in resource-limited settings, with emphasis on shielding design assumptions, workload estimation, radiopharmaceutical handling, internal and external dosimetry, CT optimization, monitoring systems, regulatory oversight, waste management, safety culture, economic constraints and equity-related implications. The objective is not to restate general radiation protection principles, but to analyze how operational and systemic limitations modify their implementation in practice. [1,2,7]

2 METHODS

This manuscript is a focused narrative review with policy and operational emphasis. Priority was given to IAEA Safety Standards and technical publications, ICRP recommendations, WHO policy documents, ISO internal-monitoring guidance and selected peer-reviewed studies addressing hybrid imaging implementation, medical physics workforce capacity and nuclear medicine service distribution in lower-resource settings. Sources were selected for their direct relevance to PET/CT, SPECT/CT and PET/MR, and for their ability to link radiation protection requirements with service delivery realities. [1–18]

The analysis was organized around five interdependent domains: infrastructure and shielding; workforce and competence; dosimetry and monitoring systems; regulatory oversight and quality management; and economic and procurement conditions. These domains were then interpreted in relation to dose optimization, compliance verification, incident prevention, and long-term sustainability. The review is analytical rather than exhaustive and focuses on recurrent structural patterns rather than attempting a country-by-country catalogue of all national arrangements. [1,2,5–9]

3 INTERNATIONAL REGULATORY AND OPERATIONAL FRAMEWORK

The international basis for radiation protection in hybrid imaging is already well established. GSR Part 3 sets out the general requirements for occupational and public protection, education and training, monitoring, optimization and regulatory control. In medical exposure, it requires governments and regulatory bodies to establish diagnostic reference

levels through consultation with health authorities and professional bodies and requires registrants and licensees to use those reference levels as part of optimization. ICRP Publication 103 provides a broader protection framework, while ICRP Publication 135 gives more specific advice on DRLs and emphasizes that the CT component of hybrid imaging should be assessed using CT-specific quantities such as CTDIvol and DLP. [1,3,4]

IAEA SSG-46 translates these requirements into the clinical environment. It addresses area designation, radiopharmaceutical handling, staff monitoring, internal and external dosimetry, quality assurance, investigation of unintended and accidental exposures, radioactive waste management and management-system responsibilities. Its significance for hybrid imaging lies in the fact that it treats PET/CT and SPECT/CT as integrated practices that require combined control of radionuclide-related and CT-related exposure pathways, rather than as stand-alone nuclear medicine or CT services. [2]

The existence of international standards does not ensure uniform implementation. WHO policy works on medical imaging capacity, and IAEA technical reviews both show that lower-resource settings often face simultaneous constraints in infrastructure, maintenance, service support, calibration, education and regulatory capacity. Hybrid imaging therefore presents a particular systems challenge: the standards are clear, but the operational conditions needed to sustain compliance and optimization are unevenly distributed. [5–7]

4 RADIATION PROTECTION CHALLENGES IN HYBRID IMAGING FACILITIES IN RESOURCE-LIMITED SETTINGS

4.1 Infrastructure and Shielding Constraints

Infrastructure-related radiation protection problems arise less from the scanner alone than from the mismatch between modality complexity and the physical and technical maturity of the host institution. In many lower-resource settings, PET/CT, SPECT/CT or PET/MR are introduced into hospitals that were not originally designed for combined radionuclide and CT workflows. WHO and WHO AFRO documents link imaging underdevelopment directly to deficits in infrastructure, standards, maintenance, quality systems and trained workforce capacity, while IAEA planning guidance for PET services identifies capital cost, operational cost and staffing as major barriers in developing settings. [5,6,20]

The shielding problem is therefore architectural as much as dosimetric. IAEA guidance on PET/CT emphasizes that all surrounding areas, including spaces above and below uptake and scanning rooms, must be assessed because dose at any occupied point may reflect contributions from multiple source locations rather than a single fixed source. Small uptake rooms may require substantially more shielding than scan rooms, and this is difficult to achieve in retrofitted conventional radiology suites where wall thickness, floor loading, circulation patterns and vertical adjacency were designed for x ray practice rather than 511 keV photons from injected patients. [12,13,20]

These constraints directly affect the designation of controlled and supervised areas. SSG-46 requires injection rooms, hot laboratories, radiopharmacy spaces, waiting rooms dedicated to injected patients and hybrid imaging rooms themselves to be designated as controlled areas, while the control-panel area is generally treated as a supervised area. In retrofitted facilities with shared corridors, reporting rooms and mixed occupancies, these zoning requirements are harder to achieve through structural barriers alone, leading to greater reliance on administrative controls such as restricted access, occupancy limits and altered staff circulation. [2]

Shielding calculations are also vulnerable where workload estimation is weak. AAPM Task Group 108 stresses that, after administration, the patient becomes the dominant radiation source, so shielding design must consider the entire period that the patient remains in the department rather than scanner occupancy alone. In resource-limited settings, simplified point-source assumptions, vendor-prepared layouts or highly conservative barriers may substitute for more detailed modelling because access to advanced software, Monte Carlo support and independent medical physics review is limited. Where throughput rises beyond original planning assumptions, or CT use drifts from attenuation correction toward routine diagnostic protocols, the resulting mismatch can narrow the safety margin for workers and members of the public. [12–14]

The occupational implication is that shielding weakness rarely remains a purely structural issue. It redistributes exposure risk into workflow, particularly during dispensing, injection, uptake supervision, and patient positioning. Under ICRP Publication 103 and GSR Part 3, the occupational effective dose limit remains 20 mSv per year averaged over five years, with no more than 50 mSv in any single year, while the public dose limit remains 1 mSv per year in planned exposure situations. In lower-resource facilities, compliance with these limits may still be achieved, but it becomes more dependent on administrative restriction and staff behavior than on robust engineered protection. [1,3,12,13]

4.2 Workforce Capacity and Expertise

Workforce limitations are a primary determinant of whether hybrid imaging protection requirements can be translated into routine practice. GSR Part 3 requires the regulatory body to ensure requirements for education, training, qualification and competence, while SSG-46 requires that radiological medical practitioners, medical physicists, technologists, radiopharmacists and radiation protection officers be competent for their assigned functions. In hybrid imaging, this requirement is especially demanding because the practice combines diagnostic radiology and nuclear medicine expertise. [1,2]

The availability of clinically qualified medical physicists remains a major constraint in resource-limited settings. A large African survey based on the IAEA staffing model found major shortfalls in imaging and nuclear medicine medical physics services, with only a small number of countries offering legislative recognition of medical physics as a health profession and with several facilities operating without adequate CQMP support. These deficits are consequential because IAEA guidance assigns medical physicists' central responsibility for shielding review, acceptance testing, optimization, dosimetry support, QA design, and verification of monitoring systems. [8,10]

Radiation protection officer coverage is a related weakness. SSG-46 requires the RPO to be competent in occupational and public protection relevant to the specific practice, and notes that the necessary education and training depend on the complexity of the facility. In hybrid imaging, RPO responsibilities span controlled-area designation, staff monitoring, contamination control, waste handling and incident response across both radionuclide and x ray pathways. Where the function is nominal, part-time, or combined with unrelated duties, radiation protection becomes more reactive than preventive. [2]

Training gaps in internal dosimetry and hybrid-modality-specific safety further weaken optimization. The IAEA clinical training guide for medical physicists specializing in nuclear medicine treats internal dosimetry, radiopharmaceutical handling, facility design, PET/CT commissioning and contamination control as structured competencies rather than optional topics. In practice, however, training pathways in many lower-resource environments remain stronger for stand-alone radiology or stand-alone nuclear medicine than for combined hybrid practice. Staff turnover then compounds the problem by interrupting continuity in local protocols, QA routines, investigation levels, and incident learning. [10,11]

4.3 Internal Dosimetry and Radiopharmaceutical Handling

Internal dosimetry in hybrid imaging follows a different protection logic from shielding-based external exposure control. ICRP Publication 130 and ICRP Publication 78 frame internal dose assessment as a model-based process that links intake, biokinetics, dosimetry and measurement data, while ISO 16637 specifies minimum requirements for programmes that monitor staff exposed to medical radionuclides as unsealed sources. In practical nuclear medicine, this means that protection depends on contamination control and monitoring intake as much as on ambient dose-rate reduction. [17–19]

The radiopharmacy stage is the most structurally vulnerable point in lower-resource facilities. SSG-46 recommends dispensing equipment that conforms to relevant standards, use of shielded syringes and vials, local shielding, designated unsealed-source work areas, and extremity dosimetry whenever hand exposure may be significant. Where automated dose dispensers and injector systems are unavailable, optimization shifts back to manual technique, operator skill and local shielding accessories. This increases sensitivity to variation in practice, especially during high-throughput PET workflows. [2,12]

Contamination control is often weaker than external monitoring. SSG-46 requires routine monitoring for both radiation and surface contamination in laboratories and other areas where unsealed sources are handled. However, surface contamination monitoring is only an indicator of intake potential and does not by itself provide a defensible estimate of internal dose. In facilities without routine thyroid counting, whole-body counting or validated urine analysis, low-level recurrent intakes may remain poorly characterized, and spill response may be limited to decontamination and external checks rather than intake assessment. [2,17–19]

Waste handling interacts directly with this problem. Poor segregation of syringes, tubing, residual vials, absorbent materials and contaminated protective equipment can sustain opportunities for skin contamination or accidental incorporation beyond the radiopharmacy boundary. The resulting weakness is not always dramatic, but it leaves internal exposure control less developed than external protection and makes the regulatory record of unsealed-source practice less robust. [2,17]

4.4 CT Component Optimization Challenges

In hybrid imaging facilities, the CT component is often the least systematically optimized part of the workflow in resource-limited settings, not because its radiological significance is minor, but because optimization infrastructure is usually weaker on the CT side than on the radiopharmaceutical side. ICRP Publication 135 recommends that DRLs for hybrid procedures be set and presented separately for each modality, with CT represented by CTDIvol for each sequence and cumulative DLP for the examination. This requirement is central because it makes clear that the CT contribution should not be treated as an invisible adjunct to nuclear medicine. [4]

The operational problem is that protocol optimization is frequently constrained by limited staffing, weak audit infrastructure and absence of advanced dose-management software. The IAEA guidance on dose management systems notes that such platforms facilitate quality management, patient-dose review and optimization by collecting, monitoring and evaluating dose-related data, but also acknowledge challenges in their implementation and QA. Without these systems, facilities rely on manual extraction of CTDIvol and DLP from scanner consoles or DICOM headers, which weakens routine oversight in busy departments. [14]

This software gap directly affects the use of size-specific dose estimate. AAPM Reports 204 and 220 established SSDE and the use of water-equivalent diameter as more patient-relevant approaches than CTDIvol alone, but these methods remain underused where scanners do not export the required data consistently or no software exists to calculate size metrics at scale. Under such conditions, facilities often default to CTDIvol, DLP or scanner-generated effective dose values, even though these are less suitable for patient-specific optimization. [15,16]

Pediatric adaptation is particularly vulnerable. ICRP Publication 135 recommends weight bands and age-appropriate grouping for pediatric DRLs, but in many lower-resource settings local pediatric DRLs remain absent and hybrid imaging protocols are adapted from adult defaults rather than derived from systematic local dose surveys. Overreliance on effective dose further obscures organ-specific burdens, especially where CT in PET/CT shifts between attenuation correction and fully diagnostic use. Quality-control frequency also tends to drift from preventive to reactive where phantoms, trained personnel and protected QA time are limited. [4,14–16,21]

4.5 Monitoring and Dosimetry System Limitations

A monitoring system for hybrid imaging should verify compliance with dose limits, detect abnormal exposures early, support optimization, and generate records suitable for trend analysis. Under GSR Part 3, individual monitoring is required for workers who normally work in controlled areas, or who may receive significant occupational dose, whenever such monitoring is appropriate, adequate, and feasible. In hybrid imaging, this requirement is more demanding than in conventional radiology because both external exposure and internal contamination are relevant, and because lens and extremity dose may be more informative than whole-body Hp(10) alone. [1,2]

Many services still depend primarily on passive personal dosimetry for routine whole-body monitoring. That architecture is acceptable for legal dose recording, but it is weaker as an operational control system in hybrid imaging, where exposure peaks are tied to specific tasks such as dispensing, injection, patient escort, and positioning. If TLD processing and reporting are delayed, abnormal exposures are often recognized only retrospectively, after the same task sequence or equipment problem has recurred. [1,2]

The weakest part of many programmes is incomplete monitoring of the quantities that matter most in nuclear medicine work. SSG-46 recommends Hp(0.07) extremity dosimetry whenever hand exposure may be significant and recognizes Hp(3) as the preferred quantity for lens monitoring. Yet in many lower-resource facilities, ring dosimetry and dedicated lens monitoring are absent or inconsistent. This means that compliance may appear adequate for whole-body badges while the quantities most likely approach investigation thresholds remain poorly characterized. [2]

Environmental and workplace monitoring gaps add a second layer of weakness. Periodic surveys, contamination checks, and, where appropriate, continuous area monitoring are part of the evidence base for workplace classification, shielding verification, and dose assessment when individual monitoring is incomplete. Where these surveys are sparse, poorly calibrated or performed only after incidents, compliance verification becomes overly dependent on passive badge records and less capable of supporting trend analysis or meaningful local investigation levels. [1,2]

4.6 Regulatory and Oversight Challenges

The core regulatory challenge is not lack of international standards but uneven translation of those standards into enforceable national practice. GSR Part 3 requires governments and regulatory bodies to establish DRLs, ensure optimization, authorize medical practices and require quality assurance and event reporting. Hybrid imaging does not sit outside this framework; the difficulty lies in whether national oversight systems have the specificity and capacity needed to apply it to PET/CT, SPECT/CT and PET/MR workflows. [1,4]

Limited inspection capacity is a persistent weakness. IAEA inspection guidance expects regulators to verify area classification, monitoring, personal dosimetry, optimization arrangements, acceptance testing, waste controls and incident reporting, but also acknowledges that inspection frequency may be constrained by regulatory resources. In hybrid imaging, the burden is greater because the inspector is reviewing a combined practice spanning CT optimization, unsealed-source control, contamination management, shielding verification and radioactive waste handling. Where inspections are infrequent, licensing conditions may remain formally in force while practical verification becomes document-centered rather than performance-centered. [1,2]

Absence or immaturity of national DRLs is especially important because it weakens one of the principal mechanisms through which ALARA is operationalized in patient imaging. ICRP Publication 135 recommends hybrid-modality-specific DRLs, but implementation remains uneven across low- and middle-income settings. Where national or robust local DRLs are absent, facilities often compare performance only informally or against imported values, which reduces the regulatory force of optimization and makes corrective action more difficult to trigger. [4]

Cross-border variability compounds the problem. International standards provide a common framework, but they do not eliminate national differences in inspection frequency, licensing detail, staffing requirements or acceptable QA alternatives. Similar facilities may therefore operate under markedly different regulatory expectations across neighbouring jurisdictions. The practical consequence is not only uneven enforcement, but uneven optimization and uneven defensibility of local protection measures. [1,2,6]

4.7 Waste Management and Environmental Protection

Waste management in hybrid imaging is sometimes treated as a downstream housekeeping issue, but under the IAEA framework it is part of the core radiation protection system. GSR Part 3 requires radioactive waste and discharges to the environment to be managed in accordance with the authorization and requires monitoring sufficient to verify compliance with discharge conditions. SSG-46 further requires shielded temporary storage for solid and liquid radioactive waste and designated arrangements for authorized discharge of liquid effluent. [1,2]

The principal limitation in many resource-constrained services is the absence of dedicated, shielded interim storage designed around radionuclide half-life, waste form and workflow volume. Decay-in-storage is often the preferred strategy for diagnostic hybrid imaging waste because most radionuclides are short-lived, but it is only effective where segregation, labeling, storage security, inventory control and representative measurements before release are reliable. In practice, weak record keeping or inadequate decay rooms can turn an apparently simple strategy into a compliance problem. [2]

PET radionuclides partly ease and partly complicate this picture. The short half-life of fluorine-18 reduces long-term storage burden, but it also imposes strict timing on production, dispensing, use and residual waste tracking. This increases the need for accurate segregation and documentation of failed batches, residual syringes, tubing, quality-control materials and contaminated consumables. Retrofitted departments may also lack direct and identifiable drainage routes for liquid waste, making authorized discharge and effluent characterization harder to sustain. [2,12,20]

The environmental risk in these circumstances is usually not catastrophic release but chronic weak control. Poor segregation, inadequate decay-storage capacity, unclear drain pathways and limited effluent monitoring can produce avoidable contamination of non-controlled areas or poorly characterized discharges. The long-term regulatory issue is therefore whether the facility can demonstrate that waste control remains engineered and documented, rather than improvised at the point of disposal. [1,2]

4.8 Quality Assurance and Safety Culture

In resource-limited hybrid imaging facilities, the main QA weakness is usually not the absence of individual checks, but the incomplete maturation of an integrated programme that spans radiopharmacy, PET or SPECT instrumentation, the CT component, staff dosimetry and records review. GSR Part 3 requires a comprehensive programme of quality assurance for medical exposures with active participation of medical physicists and other relevant professionals, while SSG-46 requires regular and independent audits whose frequency matches the complexity and risk of procedures performed. [1,2]

Hybrid imaging is particularly vulnerable to immature QA systems because one service may include cross-modality protocols, dose calibrators, scanner constancy testing, CT image quality, shielding verification, contamination control and waste pathways. A department may perform scanner constancy checks or basic CT QC yet still lack an end-to-end programme that can detect protocol drift or monitor whether optimization remains effective over time. The IAEA CT QA programme and dose-management guidance both show that sustained optimization depends on a structured cycle of baseline testing, periodic review, tolerances, action levels, and follow-up. [14,21]

Incident reporting and near-miss documentation are important indicators of programme maturity. GSR Part 3 requires investigation, recording, corrective action, and regulatory reporting for significant unintended or accidental medical exposures. SSG-46 further notes that voluntary and anonymous safety reporting and learning systems can improve safety culture. In lower-resource services, however, reporting often remains paper-based, blame-sensitive or poorly integrated with hospital governance, so near misses may be under-documented even where formal reportable events are investigated. [1,2]

Safety culture is therefore not a separate soft issue from QA. Under GSR Part 3 it is part of the management system and requires commitment from leadership, open communication, a questioning attitude and allocation of resources. For hybrid imaging, this has direct dosimetric relevance: sustained optimization depends on whether the service has protected time for QA, managerial support for corrective action and a culture that treats abnormal doses, workflow deviations and equipment drift as reportable safety information. [1,2]

4.9 Economic and Procurement Constraints

Economic constraints influence radiation protection most strongly at the procurement stage because design choices made there determine how much protection margin is built into the service before clinical operation begins. The 2025 World Health Assembly resolution on medical imaging capacity calls for needs assessment, feasibility studies, sustainable investment in infrastructure, maintenance and quality management, and application of life-cycle health-technology-management practices. This has direct radiation protection significance because shielding, calibration, servicing, monitoring and staffing all depend on decisions made before or during procurement. [6]

This is especially relevant for shielding upgrades. IAEA planning guidance identifies capital cost, operating cost and organizational readiness as major barriers to PET implementation and notes that renovation is satisfactory only if sufficient space exists to meet functional and radiation-protection requirements. In underfunded projects, the likely result is not necessarily gross non-compliance, but a narrower engineering margin in which departments rely more heavily on occupancy controls, workflow restrictions or later retrofits to compensate for compromises made during installation. [12,20]

Cost barriers also affect automation, service support and calibration. Automated dispensing systems can reduce manual handling burden and improve consistency, but they compete financially with scanner acquisition, shielding, HVAC modifications and staff recruitment. Delayed equipment servicing does not automatically make a department unsafe, but it lengthens the interval between fault detection and correction, increasing the chance that optimization will drift or that artefacts and dosimetric deviations will persist. Calibration infrastructure gaps have a similar effect by reducing traceability and slowing verification of dose calibrators, survey meters and CT dosimetry instruments. [6,10,14,21]

The long-term implication of these procurement constraints is cumulative rather than catastrophic. Underinvestment in shielding upgrades, deferred automation, slow servicing and weak calibration support each narrows the safety margin a little. Over time, this can leave a department more dependent on staff experience, workaround practices and administrative controls to maintain acceptable occupational and patient protection. [6,14,20,21]

4.10 Equity and Access Considerations

Equity in hybrid imaging is shaped primarily by where facilities are located and who is realistically able to reach them. African data show that PET/CT and SPECT/CT capacity is concentrated in a small number of countries and major urban centres rather than geographically distributed service networks. The current continental picture indicates that most PET/CT cameras and a large majority of SPECT or SPECT/CT systems are concentrated in a handful of northern and southern African countries, while access in many other settings remains absent or limited to one metropolitan facility. [7,9]

The radiological consequence of this concentration is not only unequal service availability. Dose audits, occupational monitoring records, protocol reviews and QA datasets are generated where services exist, which means that national exposure experience is disproportionately derived from urban tertiary institutions with relatively higher technical capacity. Population-level exposure monitoring is therefore likely to reflect the practices of a small number of referral centres rather than a geographically representative service base. [5,6,9]

Pediatric and other protocol-sensitive groups are also underrepresented in local dosimetry evidence. ICRP Publication 135 requires subgroup-aware DRL development, but in many resource-limited settings local pediatric hybrid-imaging datasets remain sparse, making protocol adaptation more dependent on imported guidance than local surveys. The result is an evidentiary asymmetry: radiation protection data are strongest where infrastructure is concentrated and weakest where access is limited or absent. [4,9]

4.11 Synthesis and Systemic Interaction

The preceding analysis indicates that radiation protection vulnerabilities in hybrid imaging are best understood as system interactions rather than isolated deficiencies. Infrastructure constraints affect shielding, zoning, patient flow and waste handling. Workforce shortages weaken protocol optimization, internal dosimetry, QA execution and incident review. Regulatory limitations reduce the frequency and depth of external verification. Dosimetric system weaknesses limit timely detection of abnormal exposures and reduce the reliability of trend analysis. Economic constraints then shape all of these domains by determining whether facilities can fund shielding upgrades, automation, calibration, servicing and specialist staffing. [1,2,5–10,12,14,20,21]

What makes these weaknesses especially important in hybrid imaging is their tendency to compound. A facility retrofitted into a constrained urban hospital may begin with narrow shielding margins. If that same facility also lacks adequate medical physics support, protocol review and verification become weaker. If regulatory inspection is infrequent and personal dosimetry feedback is delayed, emerging problems are less likely to be detected early. If maintenance and calibration support are then slow because of procurement constraints, the institution becomes progressively more dependent on staff vigilance and local workarounds rather than on engineered and audited control. None of these factors alone necessarily implies dose-limit exceedance, but together they narrow the margin for sustained optimization. [1,2,6,8,10,12,14]

A system-level interpretation is therefore essential. The decisive issue is not whether a department possesses a scanner, a license or a physicist in nominal terms, but whether shielding design, staff competence, monitoring systems, QA cycles, inspection, maintenance and waste control are all strong enough at the same time to support continuous optimization. Where one or more components remain weak, the others are forced to compensate, usually through tighter workflow discipline, reduced flexibility and greater dependence on tacit local experience. [1,2,6,7]. These relationships are illustrated in Figure 1, while the principal challenge domains, operational consequences and corresponding mitigation pathways are summarized in Table 1.

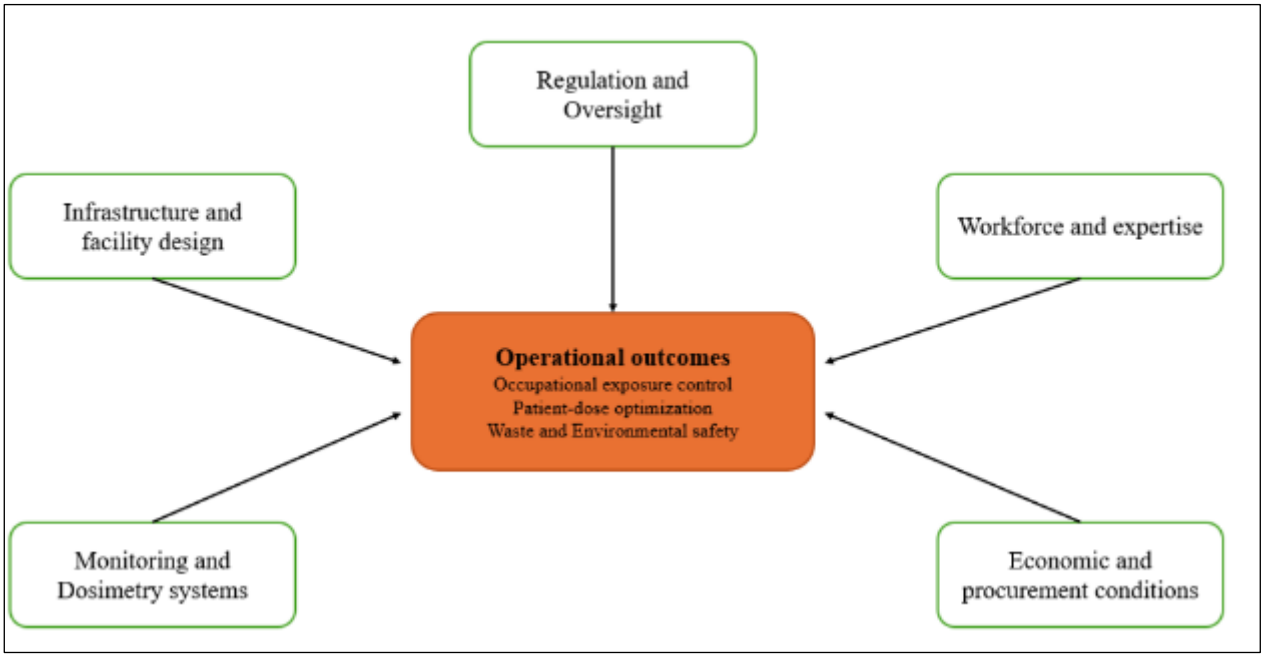

Figure 1: Conceptual framework of interdependent radiation protection challenges in hybrid imaging facilities in resource-limited settings.

Table 1: Systems-level categorization of key challenges, operational consequences and plausible mitigation pathways.

Domain	Representative challenge	Primary consequence	Mitigation pathway
Infrastructure	Retrofitted spaces, constrained shielding, limited waste rooms	Weak zoning and narrow engineering margins	Early design review, barrier verification, phased infrastructure upgrades
Workforce	Shortage of CQMPs, uneven RPO coverage, limited hybrid-specific training	Incomplete optimization, QA and incident learning	Structured training, retention measures, regional support models
Monitoring	Passive-only dosimetry, delayed readout, limited extremity and lens monitoring	Slow detection of abnormal exposures and weak trend analysis	Mixed passive/active monitoring, expanded extremity programmes, formal investigation levels
Regulatory oversight	Infrequent inspections, weak DRL frameworks, uneven licence enforcement	Variable external verification and inconsistent ALARA implementation	Risk-based inspection, hybrid-imaging-specific guidance, national DRL development
Economic and procurement	Delayed servicing, limited automation, weak calibration support	Progressive dependence on workarounds rather than engineered control	Life-cycle procurement, service contracts, calibration infrastructure investment
Equity and access	Urban concentration of scanners and weak rural coverage	Narrow operational evidence base and subgroup underrepresentation	Distributed data capture, referral-linked monitoring, subgroup-specific protocol audit

5 RESEARCH GAPS AND PRIORITIES

The first research gap is the limited availability of operational radiation protection data from hybrid imaging services in lower-resource environments. Much of the published literature still focuses on scanner performance, diagnostic utility or institution-specific optimization studies, whereas fewer studies describe staff-dose trends, compliance failures, near-miss patterns, waste-management performance or the effects of delayed servicing and calibration on dose governance. This leaves a weak empirical base for comparing protection-system maturity across settings. [7–9]

A second gap concerns workforce-linked outcomes. African surveys clearly show major shortages in clinically qualified medical physicist services for imaging and nuclear medicine, yet few studies link these workforce deficits quantitatively to missed QA tests, delayed corrective actions, weak DRL implementation or incomplete monitoring programmes. More longitudinal work is needed to connect staffing profiles to measurable radiation protection indicators at facility level. [8,10,11]

A third gap is the underdevelopment of subgroup-specific dosimetry evidence. International guidance is explicit on pediatric adaptation and modality-specific DRLs, but local evidence for pediatric PET/CT, protocol-specific organ dose estimation and patient-size-based optimization remains sparse in many lower-resource systems. Future studies would be strengthened by mixed-methods designs combining dosimetry, audit records, service logs, staffing data and regulatory history. [4,14–16]

6 PRACTICAL PRIORITIES FOR STRENGTHENING RADIATION PROTECTION

The first priority is to embed hybrid imaging more explicitly within national radiation protection programmes. This includes DRL development for both the radionuclide and CT components, risk-based inspection criteria specific to hybrid imaging, and clearer regulatory expectations for internal dosimetry, waste control and multimodality QA. International standards already support these measures; the practical need is stronger national translation and implementation. [1,2,4]

The second priority is workforce strengthening. The available African evidence indicates that service expansion is outpacing clinically qualified medical physics support. Sustainable hybrid imaging therefore requires not only initial training but recognition of the profession, structured clinical training pathways, continuing professional development,

retention mechanisms and stronger hybrid-modality-specific competence development for physicists, technologists and radiation protection personnel. [8–11]

The third priority is stronger monitoring architecture. Passive whole-body dosimetry alone is insufficient for a practice in which extremity dose, internal contamination risk and workflow-specific exposure peaks are important. Facilities need more timely personal dosimetry feedback, more consistent ring and lens monitoring where justified, improved area and contamination monitoring, and better linkage between monitoring data and local investigation levels. [1,2,17–19]

The fourth priority is life-cycle procurement and maintenance planning. WHO and the IAEA both emphasize that imaging safety depends on more than equipment acquisition. Shielding upgrades, calibration support, service contracts, QA tools and, where feasible, automation for dispensing and injection should be treated as integral parts of the protection system rather than optional additions after commissioning. [6,12,14,20,21]

7 CONCLUSION

Radiation protection in hybrid imaging facilities in resource-limited settings is best understood as a systems problem. The main vulnerability does not arise from a single deficit, but from the interaction of constrained infrastructure, limited specialist staffing, incomplete dosimetry systems, uneven regulatory oversight and procurement or maintenance weakness. International standards already provide the necessary protection framework, but the operational capacity required to implement that framework consistently remains uneven.

The evidence reviewed here shows that hybrid imaging capacity is growing, including in Africa, but that service distribution, workforce support and monitoring maturity remain highly unequal. In such settings, departments may remain clinically functional while operating with reduced margins for optimization, verification, and sustained QA. The decisive issue is therefore not scanner presence alone, but whether shielding, staffing, monitoring, QA, waste management and oversight are strong enough at the same time to support durable compliance and optimization. Hybrid imaging in resource-limited settings should thus be analysed not only as an access problem or a technology problem, but also as a radiation protection governance problem.

STATEMENTS ON COMPLIANCE WITH ETHICAL STANDARDS

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Disclosure of conflict of interest

The authors declare no conflicts of interest regarding this manuscript.

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