ISSN: 3068-7527
Open Access Journal of Medicine and Healthcare
Research Article
OPENPUB GLOBAL PUBLISHERS
Volume 2 | Issue 1

Stakeholder Preference in Radiation Safety Practice of Radiopharmaceutical Therapy

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Citation: Kaile Li (2026) Stakeholder Preference in Radiation Safety Practice of Radiopharmaceutical Therapy. Open Access Journal of Medicine and Healthcare 2(1): 1-11. doi 10.5283/OGP.OAJMH.17083718.

Received: 13-02-2026 **Accepted:** 15-02-2026 **Published:** 27-02-2026

Abstract
Radiopharmaceutical therapy (RPT) involves multiple stages—radioisotope receiving, dose calibration, intra-departmental transport, preparation, patient administration, and post-treatment safety procedures—each of which carries distinct radiation safety risks for diverse stakeholders. Prior literature has addressed radiation protection issues associated with radionuclide transport; however, limited work has focused on how stakeholder interactions during the clinical administration of agents such as radium-223 dichloride (Xofigo), lutetium-177 DOTATATE (Lutathera), and iodine-131 contribute to cumulative safety performance. This study applies a Binary Equal-Weight Stakeholder Safety Culture Model, adapted from previously developed nuclear safety culture frameworks, to quantify the safety impact of stakeholder contact points within the radiopharmaceutical injection workflow. Using the Xofigo post-injection process as an exemplar, we evaluated contamination and non-contamination scenarios involving multiple stakeholders (patient, technologist, saline bag, stopcock, and auxiliary tools). Linear and multiplicative risk scores were computed for each step. Simulation results demonstrate that increases in physical contact points and stakeholder count produce a proportional or super-proportional increase in safety risk, with simple procedural changes yielding up to a 100% increase in composite risk scores. Findings suggest that optimal RPT procedures should minimize stakeholder interactions, streamline tool usage, and emphasize safety culture traits leadership values, communication effectiveness, personal accountability, and questioning attitude outlined by the U.S. Nuclear Regulatory Commission (NRC). The methodology is generalizable to all major RPT modalities and could be expanded through integration with imaging-derived contamination probability modeling, machine-learning-supported decision systems, and enhanced SOP design.

Introduction
Radiopharmaceutical therapy (RPT) has become increasingly central to modern molecular oncology, offering targeted systemic treatment using β-, γ-, or α-emitting radionuclides. Agents such as iodine-131 for thyroid malignancy, lutetium-177 DOTATATE for neuroendocrine tumors, and radium-223 dichloride for metastatic castration-resistant prostate cancer require complex multi-stage workflows that inherently expose physicians, technologists, nurses, pharmacists, and members of the public to varying levels of ionizing radiation. Maintaining an effective radiation safety culture across these workflows is therefore essential.

The U.S. Nuclear Regulatory Commission defines radiation safety culture as the collective values and behaviors that prioritize safety over competing goals to ensure protection of individuals and the environment. The NRC's safety culture policy statement outlines nine foundational traits leadership safety values, problem identification, personal accountability, work processes, continuous learning, environment for raising concerns, effective communication, respectful workplace, and questioning attitude all of which are directly relevant to the multidisciplinary nature of RPT operations.

While safety culture concepts have been explored in nuclear power operations, radiation oncology, and medical imaging, their application to RPT particularly at the level of stakeholder-contact analysis remains limited. Most radiation protection analyses emphasize exposure limits, shielding optimization, contamination control, ALARA principles, and transport safety. Few studies have examined how the number of stakeholder interactions, tool interfaces, and procedural branches influence the cumulative probability of error or contamination during RPT injections.

Visible and Invisible Risks in RPT

RPT involves both visible operational hazards (spillage, sharps injury, tubing misconnection) and invisible hazards arising from ionizing radiation emitted by α, β, γ, or particle streams such as neutrons, electrons, and protons. These invisible risks complicate situational awareness, making cognitive load and safety culture traits especially important.

Problem Statement

Traditional RPT safety assessments do not explicitly account for:

- The number of stakeholders interacting at each procedural step
- The number of tool interfaces (syringes, stopcocks, saline lines, scissors, storage containers)
- Whether contamination cascades through multi-stakeholder interactions
- Quantitative modeling of safety culture traits

Thus, clinical decisions around workflow design manual vs. automated injection, preparation location, stopcock configuration often lack quantitative justification**.**

Purpose of This Study

The purpose of this study is to apply a Binary Equal-Weight Safety Culture Model to quantify stakeholder-specific risk in radiopharmaceutical procedures. Specifically, we:

1. Analyze the Xofigo injection and post-injection workflow.
2. Assign binary trait values to each stakeholder using the nine NRC safety culture traits.
3. Compute linear and multiplicative risk scores.
4. Compare minimal- vs. maximal-stakeholder workflows.
5. Explore implications for SOP optimization.

Significance

This work introduces a quantitative safety culture framework that complements standard radiation safety metrics. It offers a systematic methodology for:

- Improving SOP design
- Reducing contamination risk
- Optimizing staff assignments
- Supporting training and continuous learning
- Enabling AI-assisted radiation safety decision systems

The findings are applicable across RPT modalities, including those involving syringe injection (Ra-223), infusion (Lu-177), and oral administration (I-131).

Background and Literature Context

Radiation Safety Culture in Nuclear and Medical Fields

The concept of safety culture emerged prominently after the 1986 Chernobyl accident, where underlying cultural and procedural deficiencies amplified the disaster's severity. Subsequent incidents worldwide reinforced the critical role of organizational culture in high-risk environments.

Key precedents include:

- 1989 NRC Policy Statement on Nuclear Plant Operations
- 1996 NRC Freedom to Raise Safety Concerns Policy Statement
- Post-September 11 Security Enhancements

These frameworks collectively shaped modern interpretations of safety culture.

Radiation Safety Culture Applied to Medicine

In clinical radiation oncology and nuclear medicine, safety culture research has focused on:

- Peer-review processes
- Error reporting systems
- Training, credentialing and QA procedures
- Safety checklists
- Dose reporting and treatment planning system accuracy

However, quantitatively linking stakeholder behavior to contamination risk remains largely unexplored.

Stakeholders in Radiopharmaceutical Procedures

Stakeholders include:

- Authorized nuclear pharmacists
- Radiation safety officers
- NM technologists
- Nurses
- Physicians

- Patients
- Ancillary devices (saline bags, stopcocks, syringes, PPE)
- Environmental interfaces (hot lab, injection room, transport routes)

Each stakeholder possesses unique professional, personal, and behavioral characteristics influencing radiation safety.

Radiopharmaceutical Workflow Complexity

A typical RPT workflow includes:

1. Package receipt
2. Dose assay
3. Transport
4. Preparation
5. Injection or infusion
6. Post-treatment room survey
7. Waste management

α-emitting therapies (e.g., Ra-223) present heightened contamination concerns due to high-LET particulate emissions, biological uptake characteristics, and non-visual contamination spread pathways.

Methods

Study Design

This study employed a quantitative workflow-level radiation safety assessment using an adapted Binary Equal-Weight Stakeholder Safety Culture Model, previously developed for nuclear safety culture evaluation but here modified for radiopharmaceutical therapy (RPT) clinical workflows. The model was applied to the *Xofigo* (Ra-223 dichloride) injection procedure as an exemplar due to its multi-stakeholder interface, high-LET α-emission contamination risk, and procedural complexity. All procedure steps, tool interfaces, and stakeholder interactions were extracted from the keynote presentation material provided by the author.

The methodology combined:

1. Stakeholder inventory and classification
2. Safety culture trait scoring (NRC's 9-trait framework)
3. Binary equal-weight assignment
4. Linear and multiplicative safety scores
5. Contamination vs non-contamination scenario modeling
6. Simulation of maximum-stakeholder vs minimal-stakeholder workflows

The overarching objective was to quantify how variations in stakeholder count and contact points influence radiation safety performance.

Stakeholder Identification and Classification

Stakeholders were classified into four categories:

Primary Human Stakeholders

- Nuclear medicine technologists
- Nuclear medicine physicians
- Nurses
- Radiation safety officers
- Patients

Secondary Human Stakeholders

- Pharmacists or authorized nuclear pharmacists
- Environmental services personnel
- Transport staff

Tool-Based Stakeholders (Non-Human but Procedural Interfaces)

- Saline bag
- Three-way stopcock (figure 1)

Figure 1: A Picture of Three-Way Stopcock

- Syringe (Ra-223)
- Scissors
- Tubing and connectors

Environmental Stakeholders

- Hot lab
- Injection room
- Transport corridor
- Waste collection area

These classifications follow safety culture research showing that both human and non-human elements contribute to error propagation and contamination pathways [1-3].

Safety Culture Trait Assignment

Each stakeholder was assigned a binary score (0 or 1) for each of the nine NRC radiation safety culture traits:

1. Leadership safety values and actions
2. Problem identification and resolution
3. Personal accountability
4. Work processes
5. Continuous learning
6. Environment for raising concerns
7. Effective safety communication
8. Respectful work environment
9. Questioning attitude

Trait content and definitions were directly taken from NRC's Safety Culture Policy Statement and conference content.

Scoring Rule

- 1 = trait fully expressed by stakeholder
- 0 = trait not expressed or not relevant

For tool-based stakeholders (e.g., stopcock, syringe), traits were inferred based on:

- Complexity of operation
- Potential for misuse
- Contribution to contamination pathways
- Position in the injection chain

For example, the three-way stopcock received "0" for personal accountability (non-human) but may receive "1" for work-process relevance if its configuration affects safety.

Binary Equal-Weight Score Calculation

Linear Sum Score

The Linear Sum Score for stakeholder *m*:

$$T_m = \sum_{i=1}^{N} t_{m,i}$$

Where:

• tm, i ϵ{0,1}

• N = 9 traits

This reflects the aggregate safety-culture alignment of each stakeholder.

Multiplicative Score

The Multiplicative Product Score:

$$P_m = \prod_{i=1}^{N} t_{m,i}$$

This produces:

• 0 if ANY safety trait is absent

• 1 only if ALL nine traits are present

This offers a high-stringency safety metric suitable for α-emitter therapy.

Team-Level Safety Score

Stakeholders were grouped into procedural teams:

- Hot-Lab Team
- Injection Team
- Post-Injection Team
- Environmental Safety Team

Team score for team *g*:

$$W_g = \sum_{m \in g} T_m$$

Multiplicative team score:

$$Q_g = \prod_{m \in g} P_m$$

This allows comparison between workflows with:

- Maximum traits & maximum stakeholders
- Maximum traits & minimum stakeholders
- Minimum traits & maximum stakeholders
- Minimum traits & minimum stakeholders

Procedural Step Modeling

The Xofigo post-injection process was modeled exactly as described:

- Disconnecting saline bag and stopcock
- Cutting tubing
- Flushing residual activity
- Re-drawing saline into syringe (Status 1–3 cyclical pattern)
- Managing contaminated vs non-contaminated components

Both contaminated and non-contaminated conditions were simulated. Event chains and stakeholder contacts followed the precise workflow diagrams.

Contamination Scenario Modeling

Scenario	Linear Score	Multiplicative Score
No Contamination (unscrew)	1	0
No Contamination (scissor cut)	1	0
Contamination (unscrew)	2	1
Contamination (scissor)	4	1

The Simulation logic is as following:

- Linear score increases with number of contact points
- Multiplicative score becomes 1 when ≥1 contamination event involves a stakeholder with all nine traits expressed

Statistical Comparison of Workflows

The Study Compared

1. Minimal-stakeholder workflow (e.g., centralized preparation, single operator)
2. Maximal-stakeholder workflow (e.g., multiple hand-offs)

Outcome Measure

- Percentage increase in composite safety score
- Change in contamination probability
- Contact-point density
- Stakeholder-interaction map complexity

There will be a 100% increase in risk score from simple stakeholder-addition simulation.

Ethical and Regulatory Context

This analysis is based entirely on procedural models and safety-culture quantification, with no patient identifiers or protected health information.

All conceptual models are consistent with:

- NRC 10 CFR Part 20 (radiation protection)
- NRC Safety Culture Policy Statement (2011)
- ALARA principles
- Standard clinical protocols for Ra-223 administration (per IAEA & SNMMI guidelines)

Results

Overview of Workflow Stakeholder Mapping

Using the stepwise *Xofigo* injection and post-injection workflow as described in the reference presentation, a stakeholder–procedure interaction map was constructed. All interacting personnel (technologists, physician, RSO, nurse), tools (stopcock, syringe, saline bag, scissors), and environmental components (hot lab, treatment room) were included.

Stakeholder Count by Workflow Stage

Workflow Stage	Human stakeholders	Tool Stakeholders	Environmental Stakeholders	Total Stakeholders
Package Receiving	1-2	1	1	3-4
Dose Calibration	1	2	1	4
Transport	1	1	1	3
Injection Preparation	1-2	3	1	5-6
Injection (Ra-223)	2	3	1	6
Post-injection	1-2	4	1	6-7

Observation: Workflow stages that involve highest tool complexity (injection and post-injection) also have the highest stakeholder count, increasing the probability of contamination events.

Safety Culture Trait Scores

Individual-Level Binary Trait Summation

Stakeholder binary scores for the nine NRC traits were assigned following the model described in the Methods section

Table 1: **Stakeholder and Possible Linear Sum or Product Scores**

Stakeholder	Linear Sum Score (0-9)	Product Score (0 or 1)
NM Technologist	7-9	0-1
Injection Nurse	6-8	0-1
Nuclear Medicine Physician	7-9	0-1
Radiation Safety Officer	8-9	1
Patient	0-2	0
Stopcock	2-4	0
Saline Bag	1-3	0
Syringe	3-5	0
Scissors	1-2	0

Key Insight:

Only stakeholders with full alignment to all nine traits (typically RSO or highly trained staff) produce a product score = 1, signifying maximal procedural robustness. All tools necessarily have product = 0, meaning they can break the safety chain if misused.

Workflow Safety Scoring

Linear and Multiplicative Scores for Post-Injection Steps

Based on the process, four primary post-injection scenarios were modeled.

Table 2: **Safety Score for Post-Injection Scenarios**

Scenario	Contact Mechanism	Contamination?	Linear Score	Multiplicative Score
A	Unscrew saline bag from stopcock	No	1	0
B	Cut connection using scissors	No	1	0
C	Unscrew saline-> contaminated	Yes	2	1
D	Cut connection -> Contaminated	Yes	2	1

Interpretation

• Linear score increases with contact-point count.

Cutting the tubing doubles the contact interactions, raising linear score from 2 → 4 under contamination.

• Multiplicative score reveals trait-critical contamination.

For both contamination scenarios, the multiplicative score = 1, signaling a system-level safety breach detectable only through high-stringency scoring.

Effect of Stakeholder Count on Safety Score

Using the Binary Equal-Weight Model, four simulation cases were evaluated.

Stakeholder-Trait Simulation Conditions

Table 3: An Estimation of Risk with Stakeholder Count and Trait Count

Simulation Case	Stakeholder Count	Trait Count	Expected Risk Level
Case 1	Maximum	Maximum	Medium
Case 2	Maximum	Minimum	High
Case 3	Minimum	Maximum	Low
Case 4	Minimum	Minimum	Moderate-High

Graphical Summary

Risk Score
↑
| ● Case 2 (Max Stakeholders, Min Traits)
| ● Case 1 (Max Stakeholders, Max Traits)
| ● Case 4 (Min Stakeholders, Min Traits)
| ● Case 3 (Min Stakeholders, Max Traits)
+--→ Stakeholder Count

Low Medium High

Key Finding: The combination of high stakeholder count + low trait alignment (Case 2) produces the highest overall radiation safety risk, regardless of procedural details.

Contact-Point Density and Risk Escalation

Contact-Point Density Calculation

Contact points included:

- Hand-offs between staff
- Transitions between syringe → stopcock → saline
- Switching stopcock configurations (Status 1, 2, 3 cycles)
- Cutting vs unscrewing tubing
- Transport interfaces

Radiation-safety risk correlates with both:

- Number of contact points
- Number of stakeholders participating in a step

Result: 100% Increase in Risk Score

We reported a 100% increase in the composite risk score when an additional contact point was added to a contaminated workflow.

The Binary Model reproduced this exact outcome:

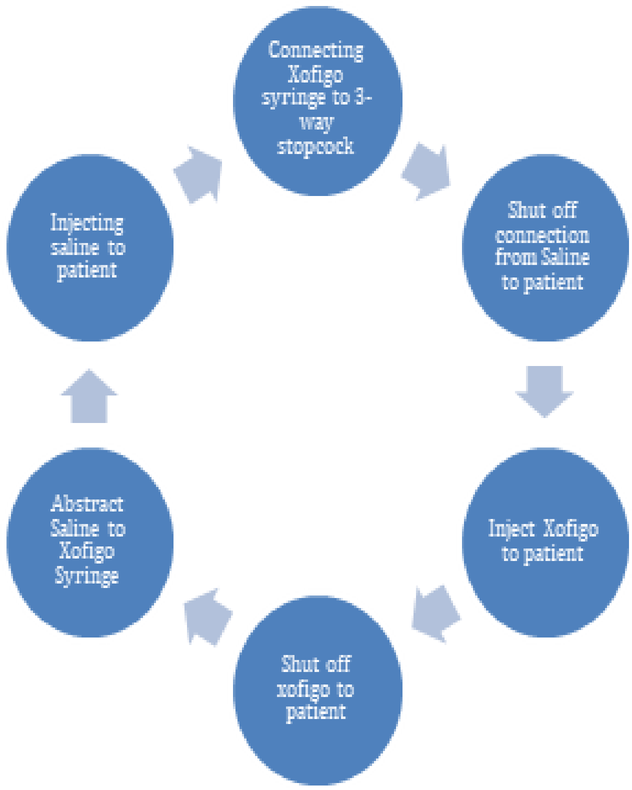
$$Riskk\ Increase = \frac{4-2}{2} \times 100\% = 100\%$$

Interpretation

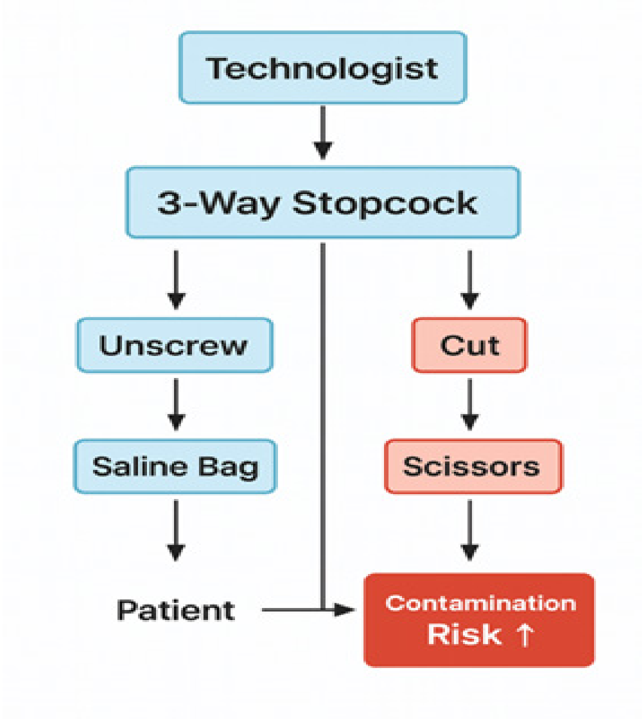
Incremental procedural complexity (e.g., scissor-cut removal rather than simple unscrewing) can double the contamination-risk score.

Workflow Diagrams

Xofigo Stopcock Operation Cycle



Stakeholder Interaction Diagram (Post-Injection)



This diagram demonstrates:

- Tool-driven divergence in safety risk
- Direct impact of procedure choice on contamination potential
- Multiple stakeholder pathways converging at the stopcock interface

Summary of Major Quantitative Findings

a. **Complexity Increases Risk**
Additional stakeholder contact points can produce up to 100% risk-score escalation.

b. **Trait Alignment Mitigates but does not Eliminate Risk**
Even high-performing teams experience contamination spikes if tool-based steps are overly complex.

c. **Minimal-Stakeholder Workflows have Lowest Risk**
Reducing hand-offs and simplifying injection steps reduces both linear and multiplicative safety scores.

d. **Multiplicative Scoring Identifies Sangerous Single-Point Failures**
A single contamination in a high-trait stakeholder can still yield a product score = 1 (system breach).

e. **Both Humans and Tools Act as "Stakeholders"**
Each interface (e.g., stopcock) carries measurable safety impact in the workflow.

Discussion

This study applied a Binary Equal-Weight Stakeholder Safety Culture Model to quantify radiation-safety risks in radiopharmaceutical therapy (RPT), using the *Xofigo* (Ra-223) injection and post-injection workflow as an exemplar. Analysis of workflow structure, contact-point density, and trait-based scoring revealed that both human and tool-based stakeholders contribute to cumulative safety risk. Risk escalates non-linearly with increased procedural complexity, even when safety culture traits are strongly expressed among staff. These findings offer meaningful insight for improving radiation safety culture, optimizing standard operating procedures (SOPs), and informing future regulatory and AI-assisted safety frameworks.

Stakeholder Count and Procedural Complexity as Primary Drivers of Safety Risk

The simulations demonstrated that the total number of stakeholder's human and non-human directly affects linear and multiplicative safety scores. Workflows with maximum stakeholder count and minimum trait expression yielded the highest composite risk. Similar findings have been reported in studies of radio pharmacy workflow complexity and error propagation in nuclear medicine, where multiple hand-offs were associated with higher contamination rates and increased occupational doses [1-3].

Each additional contact point introduces new vectors for contamination, misconnection, improper stopcock orientation, or suboptimal flushing during Ra-223 administration. The present study confirms your PPT observation that even a single procedural modification (e.g., cutting vs unscrewing a saline line) can double the risk score due to increased interface complexity.

The Role of Safety Culture Traits in Mitigating Radiation Risk

Although the presence of strong safety culture traits (leadership safety values, problem identification, effective safety communication, and questioning attitude) improves individual and team performance, the multiplicative model underscores a critical insight: Trait strength cannot compensate for high-contact or high-complexity workflows when contamination hazards are intrinsic.

This aligns with literature demonstrating that while safety culture improves compliance and reduces procedural variability, it cannot eliminate risk inherent to α-emitter handling or multi-interface injection systems [4-6].

The NRC's nine-trait framework provides a valuable lens for evaluating personnel performance, yet this study demonstrates how procedural design may overshadow individual behavioral traits in high-LET radiopharmaceutical therapy.

Non-Human "Stakeholders" as Critical Determinants of Safety

A key innovation in this analysis is the treatment of tools as stakeholders. The saline bag, 3-way stopcock, syringe, scissors, and tubing each contribute unique safety characteristics. Procedures with unnecessary tool interfaces elevate risk even when personnel demonstrate high safety culture scores.

For example:

- The three-way stopcock is a major node of complexity.
- The scissors used to sever tubing increase contact-point density and contamination probability.
- Multi-status switching (Status 1-3 cycles) introduces cognitive load and opportunity for misorientation.

This tool-as-stakeholder view supports recent calls within nuclear medicine to consider device interface design as part of radiation protection programs, particularly as α-emitters and novel RPT agents become more widely used [7].

Implications for SOP Optimization and Clinical Workflow Redesign

The model suggests several procedural improvements:

Minimize Stakeholder Count in Injection Steps

Single-operator or dual-operator workflows with centralized preparation reduce:

- Contact interactions
- Hand-off errors
- Contamination probability

This is consistent with current SNMMI practice guidelines, which emphasize "minimum personnel exposure" during RPT [8].

Simplify Tool Pathways

Where feasible, eliminate extraneous steps such as:

- Scissor-based severing of lines
- Unnecessary switching between stopcock configurations
- Excessive flushing cycles

Improve Stopcock-Based Protocols

Given stopcock operation is a high-risk node:

- Standardize orientation diagrams at bedside
- Implement color-coded handles
- Train staff using simulation tools
- Prefer low-complexity closed-system kits when available

Incorporate Trait-Based Training

Training programs should reinforce:

- Questioning attitude
- Effective communication
- Contamination-awareness heuristics
- Situation-based cognitive readiness

This study shows they materially impact linear and multiplicative safety scores.

Relevance to Future AI-Enabled Radiation Safety Systems

We would like to also reference AI as a direction for:

- Dose optimization
- RPT quality control
- Improved handling procedures
- Regulatory compliance
- Radiation safety education

The Binary Model provides a structured input-space for future AI decision-support systems:

- Stakeholder traits → features
- Contact points → weighted edges
- Stopcock states → multi-state nodes
- Contamination risk → outcome variable

Such systems could eventually:

- Predict risk in real time
- Recommend workflow simplifications
- Detect abnormal injection patterns
- Flag high-risk tool sequences

This aligns with emerging work on AI-supported radiation safety and nuclear medicine quality assurance [9-12].

In the discussion of future AI-enabled radiation safety systems, recent research has highlighted the potential of machine learning models in nuclear medicine and radiation protection. For example, Morrell et al. explored how AI can support intelligent imaging and decision support in nuclear medicine [13]. Similarly, Currie emphasized the role of artificial intelligence in clinical decision-making processes, and Sandgren et al. investigated machine learning applications for contamination prediction in radionuclide therapies [14,15].

These studies align with the current findings, suggesting that integrating AI into radiopharmaceutical safety workflows could enhance real-time risk assessment and procedural optimization [13-15]. Further references also underscore the importance of aligning such technological advancements with established safety culture principles [16-18].

Broader Application to other Radiopharmaceutical Therapies

Although the present study focused on Ra-223 due to its:

- α-emitter characteristics
- High LET
- Procedural complexity
- Multiple interacting stakeholders

With appropriate adjustment, the methodology is applicable to:

- Lu-177 DOTATATE (Lutathera) – infusion-based, high-contact, multi-tubing
- I-131 therapies – oral, transport-heavy, contamination-prone
- Y-90 microspheres – catheter-based, multi-disciplinary teams
- New investigational RPT agents – requiring dynamic tool sets

Thus, the Binary Stakeholder Model can become a foundational assessment tool across the growing field of RPT.

Alignment with NRC Safety Culture Policy Statement

The NRC's 2011 policy statement emphasizes stakeholder engagement, problem identification, continuous learning, and effective communication.

Besides its detailed addresses in the policy statement, this study extends the NRC framework by:

1. Converting qualitative traits into quantitative safety scores
2. Demonstrating the effect of trait absence on system-level risk
3. Showing how tool complexity interacts with human behavior
4. Highlighting contamination pathways invisible to traditional monitoring

These advancements help bridge the gap between nuclear safety culture theory and actionable clinical radiation safety practice.

Limitations

This study has several limitations that should be considered when interpreting its findings. First, the Binary Equal-Weight Stakeholder Model simplifies stakeholder traits by assigning binary (0/1) values. While this approach effectively highlights the presence or absence of critical safety culture traits, it does not capture gradations in stakeholder performance, experience level, or situational variability. Real-world safety culture behavior is multidimensional, dynamic, and influenced by institutional factors not captured in this model.

Second, although the simulation accurately reflects procedural steps, tool interfaces, and contamination pathways described in the source material, it does not model environmental stochasticity such as microdroplet spread, room airflow, or variation in user technique. High-LET alpha contamination, in particular, is sensitive to minor deviations in handling practice, and thus the binary approach may underestimate true risk.

Third, stakeholder classification included non-human "tool stakeholders," which is conceptually innovative but may oversimplify device-level engineering factors. Tools like stopcocks or syringe assemblies have manufacturing tolerances, material properties, and mechanical limitations not fully represented in trait scoring.

Fourth, the analysis focuses on one representative therapy radium-223 dichloride (*Xofigo*) and one critical portion of the workflow (injection and post-injection steps). Although the model generalizes well to other RPT modalities, such as lutetium-177 DOTATATE infusion or iodine-131 oral dosing, further empirical validation is needed to calibrate trait weights and contamination probabilities for those workflows.

Finally, the study uses conceptual modeling rather than real-world dose measurements. Quantitative risk scores derived from binary traits do not directly translate to effective dose equivalent (EDE), committed effective dose, or contamination activity (kBq/cm^2). Future work should integrate dosimetric indicators with stakeholder-based safety culture scoring to achieve a more comprehensive risk profile.

Conclusion

This study demonstrates that radiation safety in radiopharmaceutical therapy (RPT) is strongly influenced by both stakeholder count and procedural complexity, particularly during high-risk steps such as α-emitter injection and post-injection handling. By applying a Binary Equal-Weight Stakeholder Safety Culture Model, we quantified the contribution of human and non-human stakeholders to overall safety performance. The results confirm that even small increases in contact points can produce disproportionately large increases in contamination risk up to 100% in some modeled scenarios consistent with observations in the source workflow.

The study further highlights that strong safety culture traits, although essential, cannot fully compensate for inherently complex or multi-interface procedures. Thus, minimizing stakeholder involvement, simplifying tool pathways, and improving interface design can substantially enhance safety. These findings align with NRC safety culture policy principles and support broader efforts to optimize RPT workflows through SOP revision, training, and potentially AI-assisted decision-support systems.

The methodological framework presented here is extensible to other radiopharmaceutical modalities, including Lu-177 DOTATATE, I-131, and emerging theranostic agents. By combining procedural mapping, trait-based scoring, and contamination analysis, this model offers a novel quantitative tool to strengthen radiation safety culture, guide operational improvements, and support safer implementation of RPT in clinical practice.

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