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RESEARCH ARTICLE

A HYBRID APPROACH TO IDENTIFYING FACTORS ASSOCIATED WITH RADIATION SAFETY KNOWLEDGE AMONG HEALTHCARE PROFESSIONALS

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ABSTRACT

OBJECTIVE:

Radiation safety knowledge is fundamental to protecting both healthcare workers and patients. Yet, persistent knowledge gaps continue to compromise safe clinical practice. This study aimed to evaluate radiation safety knowledge among healthcare professionals in central Vietnam and to identify key factors associated with higher competency.

METHODOLOGY:

In this cross-sectional study, healthcare professionals from a national general hospital in central Vietnam were surveyed using a standardized instrument developed in accordance with national radiation safety guidelines endorsed by the Vietnamese Ministry of Health, the Ministry of Labour, Invalids and Social Affairs, and the Ministry of Science and Technology. A hybrid analytical framework integrating Bayesian Model Averaging (BMA), Lasso, and Ridge regression was applied to identify independent predictors. Model robustness was further validated through standard regression and bootstrapping analyses.

RESULTS:
The overall radiation safety knowledge was suboptimal, with an average score of 35%. Knowledge of preventive measures was higher (69.3%), while awareness of radiation risks and radiographic room safety was notably limited. Key predictors of higher radiation safety knowledge included direct involvement with X-rays (β=16.85, $P<0.001$), higher educational attainment (β=15.72, $P<0.001$), older age (β=13.99, $P<0.001$), participation in radiation-related training courses (β=9.08, $P<0.001$), and access to multiple information resources (β=6.27, $P<0.05$). The hybrid statistical approach provided robust insights, with results consistent across different models. Both standard regression and bootstrapping analyses confirmed the stability of these findings.

CONCLUSIONS:
This study highlights a significant gap in radiation safety knowledge among healthcare professionals in central Vietnam. Significant knowledge gaps underscore the need for targeted training, curriculum integration, and enhanced access to radiation safety resources at healthcare settings. The study also recommends the usage of hybrid statistical approaches in robust inference generation.

KEYWORDS
Radiation safety knowledge, Healthcare professionals, Bayesian model averaging (BMA), Lasso Regression, Ridge regression

INTRODUCTION

Radiation technology is indispensable in modern healthcare, enabling precise diagnostics and effective treatments across multiple disciplines [1]. While its benefits are well-documented, improper or excessive exposure poses serious risks to both patients and healthcare professionals. Prolonged occupational radiation exposure has been associated with increased risks of cancer, genetic mutations, and other adverse health effects, as demonstrated by epidemiological studies [2, 3]. The International Commission on Radiological Protection (ICRP) and the World Health Organization (WHO) emphasize the critical importance of strict adherence to radiation safety protocols to mitigate unnecessary exposure and protect occupational health [2, 4]. Ensuring healthcare professionals – particularly those in radiology and related specialties – possess adequate radiation safety knowledge is fundamental to implementing protective measures effectively.

Despite established guidelines, recent evidence highlights suboptimal awareness, attitudes, and practices regarding radiation protection among healthcare workers, with mixed findings across studies [5]. Most research has centred on assessing general knowledge of radiation safety standards [5], while relatively few studies have examined knowledge of facility safety requirements or the specific health risks associated with prolonged exposure. Determinants of radiation safety knowledge remain inconsistent across contexts. Han et al. in South Korea identified gender, age, marital status, education, and work experience as significant factors [6], whereas Farajollah et al. in Iran emphasized age, education level, and participation in refresher courses [7]. Studies in Turkey [8] and Iran [9] also reported differing determinants, such as professional level and educational background, with limited consensus. Notably, research in low- and middle-income countries (LMICs) remains sparse, despite the rapid expansion of medical imaging infrastructure in regions such as Vietnam [10]. Addressing these knowledge gaps is essential for improving occupational health practices and ensuring safe radiation use in resource-limited settings.

Vietnam has invested significantly in healthcare infrastructure over the past decade, leading to the establishment of new radiology departments equipped with advanced imaging technology [11]. National regulatory bodies have introduced comprehensive policies and training programs to promote radiation safety [11-13]. Yet, the extent to which healthcare professionals in Vietnam are adequately prepared to manage radiation exposure remains unclear. Evaluating current knowledge levels and identifying key determinants are crucial steps toward strengthening occupational safety and optimizing policy implementation [14].

To address these gaps, the present study assesses radiation safety knowledge and its associated factors among healthcare professionals in central Vietnam. Given the limitations of standard regression in handling model uncertainty, multicollinearity, and high-dimensional data, especially with small sample sizes [15], we adopt a hybrid analytical approach, integrating Bayesian Model Averaging (BMA), Least Absolute Shrinkage and Selection Operator (Lasso), and Ridge regression to identify key predictors. This complementary strategy ensures robust inference, with cross-validation optimizing regularization parameters and performance metrics guiding model selection. Upon model selection, a standard regression framework is applied for model inference on associated factors. By combining these methods, this study provides critical insights for policymakers, educators, healthcare administrators, and practitioners to improve radiation safety practices.

Although the data for this study were collected several years ago, the findings remain relevant to current healthcare practice and policy because radiation safety knowledge, training gaps, and adherence to radiation protection principles continue to be ongoing concerns in healthcare systems, particularly in resource-constrained and rapidly developing clinical settings. Furthermore, baseline evidence from earlier periods remains important for understanding persistent workforce educational needs, informing institutional training strategies, and evaluating progress in radiation safety awareness over time.

METHODS

STUDY DESIGN AND SETTING

A cross-sectional study was conducted from late 2018 to 2019 across three hospitals in central Vietnam: Quang Nam Provincial General Hospital, Quang Nam National General Hospital, and Quang Nam Mountainous Northern Provincial General Hospital. A structured questionnaire was used for data collection.

DATA SAMPLE AND SAMPLING

Healthcare professionals working in radiation-related departments – including diagnostic imaging, interventional radiology, cardiovascular intervention, trauma surgery, neurosurgery, and general surgery – were eligible. These included medical doctors, associate medical doctors, technicians, and nurses. Sample size estimation was based on a power of 0.80, a significance level of 0.05, and a medium effect size (Cohen's $f^2 = 0.20$) for a regression model with nine predictors, yielding a minimum requirement of 88 participants. To account for anticipated non-response, the minimum sample was inflated using a two-component adjustment: a 20% allowance for incomplete or unusable questionnaires (e.g., missing data, refusal to complete all items), which is consistent with rates recommended in similar survey-based studies among healthcare professionals or in clinical settings [16], and an additional 30% allowance for non-participation and recruitment difficulties due to the demanding schedules of clinical staff across three hospital sites during routine working hours [17]. This combined adjustment yielded a target sample of 137. Ultimately, 153 healthcare workers completed the survey.

MEASUREMENTS

The questionnaire was developed and validated following national radiation safety guidelines issued by the Ministry of Health, the Ministry of Labour, Invalids and Social Affairs, and the Ministry of Science and Technology [11-13, 18]. It comprised two sections. The first collected data on data on gender, age group (20–29, 30–39, ≥40 years), education level (vocational, university, postgraduate), professional role (medical doctor, technician, nurse), years of experience, daily working hours, and sources of radiation safety knowledge (formal training, hospital-based training, media, and peer discussions). These variables were analyzed as predictors of radiation safety knowledge.

The second section consisted of 19 items covering three knowledge domains: (i) radiographic room safety (7 items) [4, 5], (ii) radiation exposure risks (6 items) [2, 4, 5], and (iii) radiological protection measures (6 items) [2, 5, 19]. Each correct response was scored as 1 point, with a maximum score of 19. The total score, expressed as a percentage, was the primary dependent variable.

The questionnaire underwent pilot testing with ~10 participants to assess feasibility. Internal reliability was high (Cronbach's α = 0.88), and no major issues regarding comprehension or feasibility were identified.

DATA COLLECTION

Data collection was conducted following ethical approval from Hanoi Medical University and the three participating hospitals. Prior to recruitment, the principal investigator liaised with department heads to present study objectives and obtain institutional support. Eligible participants, identified from hospital records, were invited to private interview sessions. A structured, face-to-face interview was conducted after obtaining written informed consent. Participants could seek clarification on any item, and responses were reviewed for completeness.

STATISTICAL APPROACHES AND ANALYSIS

Descriptive statistics summarized demographic characteristics and radiation safety knowledge scores (Table 1, Table 2, Figure 1). The dependent variable, knowledge score (%), normally distributed was summarized (Table 2).

To enhance model selection and address multicollinearity in high-dimensional data, we employed a hybrid approach integrating Bayesian Model Averaging (BMA; Table 3), Least Absolute Shrinkage and Selection Operator (Lasso), and Ridge regression (Table 4). This complementary strategy ensures robust inference, with cross-validation optimizing regularization parameters. Further methodological details are provided in the supplement. Final model inference was conducted using standard regression and bootstrapping, ensuring result stability (Figure 2). Multiple testing adjustments were performed using the Benjamini-Hochberg procedure, with an adjusted false discovery rate (FDR) threshold of <0.05 [20].

All statistical analyses were conducted using Stata version 18.5 [21] and R version 4.4.1 [22].

SENSITIVITY ANALYSIS

To ensure robust findings, a hybrid approach was employed for model selection, incorporating BMA, Lasso, and Ridge regression to identify factors associated with the outcome. The results were consistent across models (Tables 3 and 4). For model inference, both standard regression and bootstrapping analyses yielded stable regression coefficients and *p*-values (Figure 2).

ETHICAL APPROVAL

The research approval was granted by the Institute for Preventive Medicine and Public Health and Hanoi Medical University (No. 5425/QD-DHYHN dated 09/10/2018). Participants provided informed consent to participate in the survey and agreed for data usage in the research.

RESULTS

In table 1 of the 153 participants, they were predominantly male (86.3%), mostly aged 30–39 years (43.8%). Most had vocational or school-level education (34.0%) and worked as technicians (45.8%), primarily in diagnostic imaging (57.6%) and handling X-ray procedures (57.5%). A majority (71.9%) worked 6–8 hours daily, 58.8% had ≥5 years' experience, 47.1% received Ministry training, and 77.1% obtained information from colleagues.

TABLE 1. GENERAL CHARACTERISTICS OF THE STUDY PARTICIPANTS

Variables (N=153)	n (%)
Gender	
Men	132 (86.3)
Women	21 (13.7)
Age (years)	
20-29	51 (33.3)
30-39	67 (43.8)
≥40	35 (22.9)
Education level	
University graduate	18 (11.8)
University	41 (26.8)
College	42 (27.5)
Vocational/school education	52 (34.0)
Professional level	
Doctor	38 (24.8)
Technician	70 (45.8)
Nurse/assistant doctor	45 (29.4)
Radiation departments	
Diagnosis imaging	88 (57.6)
Cardiovascular/cardiovascular intervention	30 (19.6)
Other radiation departments	35 (28.8)
Working with X-rays (Direct vs. indirect)	
Direct	88 (57.5)
Indirect	65 (42.5)
Average duration of working with X-ray radiation per day	
< 6 hours	33 (21.6)
6-8 hours	110 (71.9)
> 8 hours	10 (6.5)
Working years in X-ray setting	
< 5 years	63 (41.2)
≥ 5 years	90 (58.8)
Attending training courses by the Ministry of Science and Technology	
Yes	72 (47.1)
No	81 (52.9)
Access to information resources	
Colleagues	118 (77.1)
Media	71 (46.4)
Schools	75 (49.0)
Hospital-based training	40 (26.1)
Number of information resources	
1-2 resources	73 (47.7)
≥ 3 resources	80 (52.3)

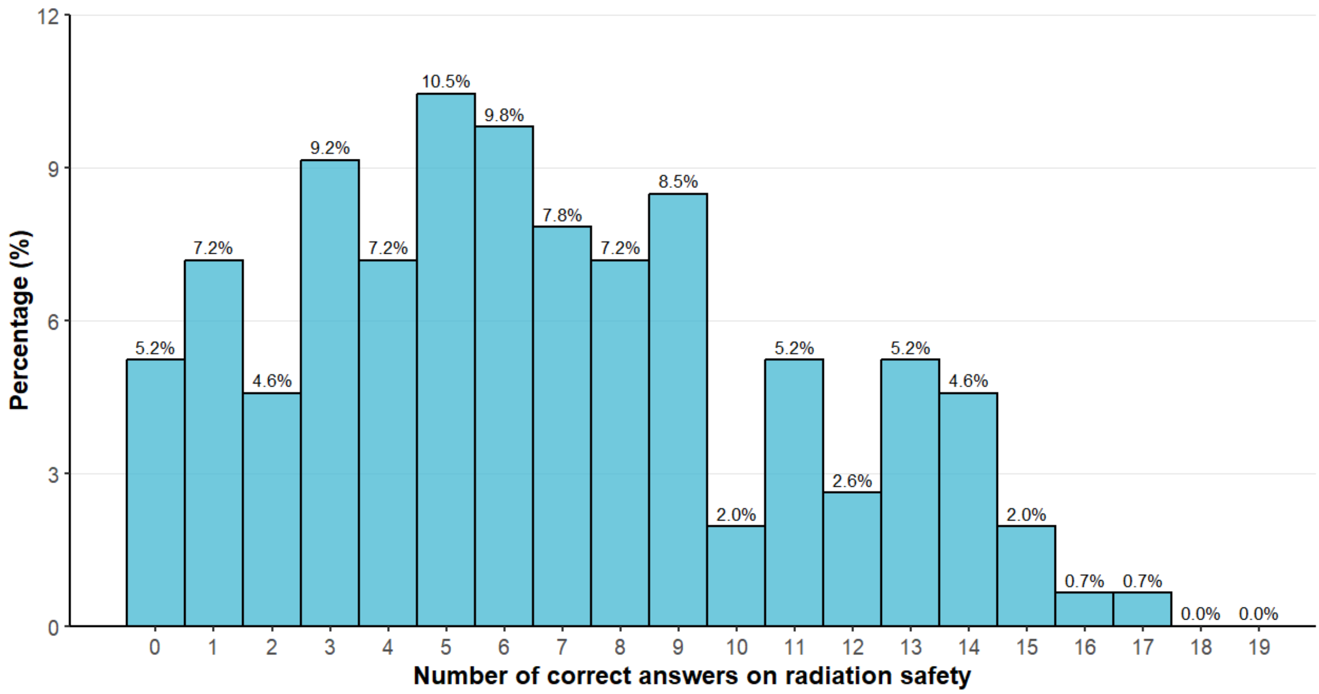
Table 2 summarizes participants' knowledge of radiation safety. Correct responses regarding radiographic room safety ranged from around 19% for radiation source facility requirements to 47% for standard room dimensions. Knowledge of radiation exposure risks was generally limited, with 22.2% identifying the properties of X-rays, 21.6% recognizing early symptoms of radiation-related diseases, and 13.1% knowing the consequences of radiological contamination. In contrast, knowledge of radiological protection measures was generally higher, with 69.3% aware of preventive measures and over half correctly answering questions on annual dose limits for health workers (50.3%) and frequency of individual dose assessments (56.9%). The overall level of radiation safety knowledge was ~35 (SD = 22.05).

TABLE 2. GENERAL KNOWLEDGE ABOUT RADIATION SAFETY AMONG THE STUDY PARTICIPANTS (N=153)

No.	Knowledge questions	Answer correctly n (%)
	Safety requirements of a radiographic room	
1	Radiographic room design and construction	62 (40.5)
2	Layout of radio-diagnostic facilities: room walls, warning signs, warning lights, safety regulation notice	41 (26.8)
3	Standard room dimensions	72 (47.1)
4	Requirements for standard radiation source facilities	29 (18.9)
5	Requirements for radiological equipment such as DSA and C-Arms	47 (30.7)
6	Minimum safe distance between the radiation source and the operator	32 (20.9)
	Risks of radiation exposure	
7	Properties of X-rays	34 (22.2)
8	Cell damage related to X-rays	45 (29.4)
9	Factors affecting the radiation dose	48 (31.5)
10	Active ingredients help reduce oxidation and neutralize free radicals caused by X-rays	41 (26.8)
11	Types of diseases caused by X-rays	54 (35.3)
12	Early symptoms of radiation-related diseases	33 (21.6)
13	Consequences of radiological contamination (cancer, gene mutation, infertility)	20 (13.1)
	Radiological protection measures	
14	Preventive measures for individuals from radiation exposure: reducing exposure duration, using protection equipment, keeping a safe distance, lead lining on door	106 (69.3)
15	Dose limit of radiation/ year for the health worker	77 (50.3)
16	Dose limit of radiation/ year for the patient	62 (40.8)
17	Frequency of individual dose assessment for radiation workers in one year	87 (56.9)
18	Frequency of screening for radiation workers in one year	99 (64.7)
19	Frequency of checking radiological equipment	72 (47.1)
	Radiation safety knowledge level (mean (SD))	34.95 (22.05)

Figure 1 visualizes the distribution of the total number of correct answers to X-ray-related questions. The data demonstrates a bimodal distribution, with a primary peak (10.5%) at 5 correct answers and a secondary peak (5.2%) at 13 correct answers. The majority of respondents answered fewer than 10 questions correctly, and no participant achieved a perfect score (19 correct answers), indicating a general lack of comprehensive knowledge across all items assessed.

FIGURE 1. DISTRIBUTION OF RESPONDENT PERCENTAGE BY THE TOTAL NUMBER OF CORRECT ANSWERS



Alt text: Bar chart depicting the distribution of correct answers on radiation safety knowledge among healthcare professionals. The horizontal axis represents the number of correct answers, while the vertical axis shows the corresponding percentage of participants.

The BMA analysis results (Table 3) indicate that among the seven possible models generated, the three most probable models are presented. Model 1 demonstrated the best overall fit, as reflected by the highest posterior model probability (PMP = 56%), the lowest Bayesian information criterion (BIC = -182.37), and the lowest root mean squared error (RMSE = 13.52) and R2 value comparable or higher than the other models (0.74 vs. 0.75 and 0.73). This model retained five key predictors: direct involvement with X-rays, educational level, age group, participation in radiation-related training courses, and access to multiple radiation-related information resources. Each of these factors showed a posterior inclusion probability (PIP) of 100%, indicating their consistency across all best models. In contrast, variables such as years of exposure, professional level, working and exposure hours per day, and gender did not meet the threshold for inclusion in Model 1.

TABLE 3. BAYESIAN MODEL AVERAGING ANALYSIS FOR IDENTIFYING FACTORS ASSOCIATED WITH RADIATION SAFETY KNOWLEDGE

Variables	PIP[A]	Post. Mean (Beta)[A]	Post. SD (SE)[A]	Model 1	Model 2	Model 3
Working with X-rays (Direct vs. indirect)	1.00	17.13	2.58	1.00	1.00	1.00
Educational level (University vs. lower)	1.00	16.50	2.10	1.00	1.00	1.00
Age group (≥40, 30-39, vs. 20-29 years old))	1.00	6.53	1.49	1.00	1.00	1.00
Training courses (yes vs. no)	1.00	8.67	2.63	1.00	1.00	1.00
Number of information resources (≥3 vs. <3 resources)	1.00	5.89	3.42	1.00	1.00	0.00

Working and exposing years (≥5 vs. <5 years)	0.84	0.55	1.57	0.00	1.00	0.00
Professional level (Others vs medical doctor degree)	0.06	-0.14	0.90	0.00	0.00	0.00
Working and exposed hours per day (>=6 vs. <6 hours)	0.06	0.09	0.69	0.00	0.00	0.00
Gender (male vs. female)	0.05	-0.06	0.68	0.00	0.00	0.00
Model fit						
Posterior model probability (PMP)				0.56	0.12	0.11
R^2				0.74	0.75	0.73
BIC				-182.37	-179.24	-179.14
RMSE				13.52	21.08	13.63

Post.: Posterior; PIP: Posterior inclusion probabilities; BIC: Bayesian information criterion; RMSE: Root mean-squared error

[A]Average values of 7 models selected by the BMA

Table 4 presents the results of Lasso and Ridge regression analyses for selecting factors associated with radiation safety knowledge. Both models achieved good fit (R^2 = 0.74; RMSE ≈ 11.1), with coefficients estimated using optimal lambda values (λ = 0.78 for Lasso; λ = 0.23 for Ridge) and 95% confidence intervals (CIs) obtained through bootstrapping with 1,000 resamples. Five key predictors consistently showed significant positive associations in both models: direct involvement with X-rays, higher educational attainment, older age, attendance at radiation-related training courses, and access to three or more information resources. Direct involvement with X-rays had the strongest association (Lasso β = 15.78, 95% CI: 10.28 to 21.28; Ridge β = 14.72, 95% CI: 10.72 to 18.73), followed by higher education and older age. In contrast, variables such as working and exposure years, professional level, working hours per day, and gender did not show significant associations, with their confidence intervals including zero. Lasso and Ridge regression reveals the results in consistency with the BMA.

TABLE 4. LASSO AND RIDGE REGRESSION ANALYSIS FOR IDENTIFYING FACTORS ASSOCIATED WITH RADIATION SAFETY KNOWLEDGE

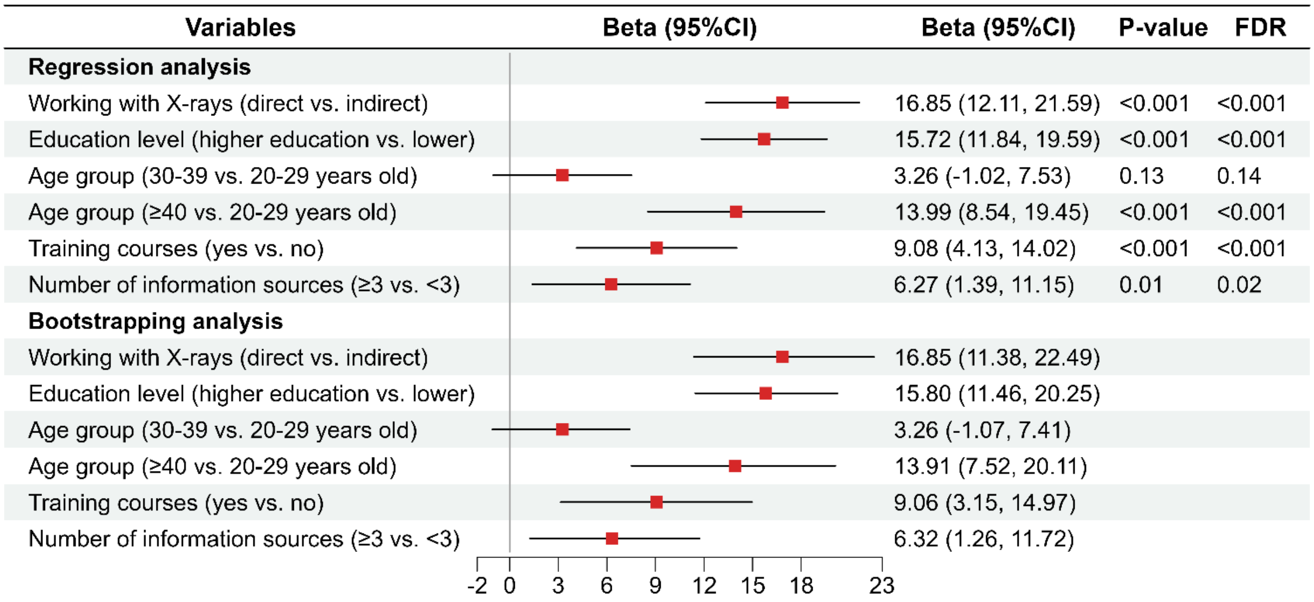
Variables	Lasso model	Ridge model
	Beta[A1] (95%CI)[A2]	Beta[B1] (95%CI)[B2]
Working with X-rays (Direct vs. indirect)	15.78 (10.28, 21.28)	14.72 (10.72, 18.73)
Educational level (University vs. college or lower degree)	15.06 (9.24, 20.88)	13.44 (8.57, 18.32)
Age group (≥40, 30-39, vs. 20-29 years old))	5.26 (1.97, 8.54)	4.94 (2.44, 7.43)
Training course attendance (yes vs. no)	8.03 (2.40, 13.66)	8.61 (4.47, 12.74)
Number of information resources (≥3 vs. <3 resources)	6.41 (1.01, 11.82)	7.14 (3.08, 11.19)
Working and exposing years (≥5 vs. <5 years)	2.00 (-2.19, 6.19)	3.62 (-0.10, 7.34)
Professional level (Others vs medical doctor degree)	-1.16 (-5.80, 3.48)	-3.94 (-8.72, 0.84)
Working and exposed hours per day (>=6 vs. <6 hours)	0.00 (-1.96, 1.96)	0.35 (-3.39, 4.10)
Gender (male vs. female)	0.00 (-1.33, 1.33)	-1.22 (-4.90, 2.47)
Model fit		
R^2	0.74	0.74
RMSE	11.13	11.11

A1 and B1: Regression coefficients estimated using the optimal lambdas (λ = 0.78 for Lasso and λ = 0.23 for Ridge regression) obtained through 10-fold cross-validation.

A2 and B2: 95% confidence intervals (CIs) for the regression coefficients estimated using bootstrapping techniques with 1,000 resamples, based on the optimal lambdas from Lasso and Ridge regression.

Figure 2 presents the results of the linear regression and bootstrapping analysis evaluating the association between various independent variables and radiation safety knowledge. The analysis indicates that direct involvement with X-rays, higher educational attainment, age ≥40 years, participation in training courses, and access to three or more information sources are significantly and positively associated with higher knowledge scores. Specifically, health professionals working directly with X-rays scored 16.85% higher in radiation safety knowledge compared to those with indirect exposure. Similarly, having a university-level education, being in the age group ≥40 years, attending training courses, and accessing three or more information sources were associated with significantly higher scores of 15.72%, 13.99%, 9.08%, and 6.17%, respectively. The bootstrapping analysis corroborated the findings of the standard regression model.

FIGURE 2. STANDARD REGRESSION AND BOOTSTRAPPING ANALYSIS OF FACTORS ASSOCIATED WITH RADIATION SAFETY KNOWLEDGE



Alt text: Forest plot displaying regression coefficients (Beta) with 95% confidence intervals for various factors associated with radiation safety knowledge, based on regression and bootstrapping analyses

DISCUSSION

MAIN FINDINGS OF THIS STUDY

This study assessed radiation safety knowledge among healthcare professionals in central Vietnam and identified key associated factors using a hybrid analytical approach that combined BMA, Lasso, and Ridge regression. The findings highlight significant predictors: direct involvement with X-rays, higher education, older age, participation in radiation-related training, and access to multiple information resources. These results underscore the need for targeted training and improved information dissemination to enhance radiation safety competency.

WHAT IS ALREADY KNOWN ON THIS TOPIC

Previous studies have consistently reported suboptimal awareness, attitudes, and practices concerning radiation safety among healthcare workers [5]. However, findings on key determinants remain inconsistent across different settings, with most research focusing narrowly on general knowledge of radiation safety standards rather than facility-specific safety requirements or health risks associated with prolonged exposure. Furthermore, standard regression approaches commonly employed in these studies may introduce biases due to model selection limitations. Research in LMICs remains particularly scarce, leaving significant knowledge gaps regarding context-specific predictors of radiation safety competency.

WHAT THIS STUDY ADDS

The overall level of radiation safety knowledge among healthcare professionals was not adequate, with an average score of approximately 35% correct responses. Knowledge of radiological protection measures was relatively higher, with 69.3% of participants aware of preventive measures. However, knowledge of the risks of radiation exposure and safety requirements for radiographic rooms was notably limited. Only 22.2% of participants correctly identified the properties of X-rays, and a mere 13.1% were aware of the consequences of radiological contamination. The bimodal distribution of correct answers, with peaks at 5 and 13 correct responses out of 19, further highlights the uneven distribution of knowledge, with the majority of participants scoring below 50%. These findings are consistent with previous studies in LMICs [5, 14, 23, 24]. revealing persistent gaps that may compromise the safety of both healthcare workers and patients. Targeted educational interventions and continuous professional development programs are needed to address this knowledge deficit and promote safer practices.

The hybrid analytical approach employed in this study, integrating BMA, Lasso, and Ridge regression, provided robust insights into the factors associated with radiation safety knowledge. BMA, with its ability to account for model uncertainty, identified five key predictors with high posterior inclusion probabilities (PIP = 100%): direct involvement with X-rays, higher educational attainment, older age, participation in radiation-related training courses, and access to multiple information resources. These findings were corroborated by Lasso and Ridge regression, which consistently highlighted the same factors as significant predictors of radiation safety knowledge. The consistency across these models underscores the reliability of the identified predictors. The hybrid approach validated the robustness of the selected predictors and demonstrated the utility of combining multiple statistical methods to address the challenges of multicollinearity [25, 26], and small sample sizes [15], which are common in healthcare research.

The standard regression and bootstrapping analyses further validated the findings from the hybrid models, supporting that direct involvement with X-rays, higher educational attainment, older age, participation in training courses, and access to multiple information resources are significantly associated with higher radiation safety knowledge scores. Healthcare professionals who worked directly with X-rays, had a university-level education, attended radiation-related training, and had access to diverse information resources demonstrated notably higher knowledge scores than their counterparts. Older age was also positively correlated with higher scores, likely reflecting the cumulative experience and greater exposure to safety protocols over time. These results underscore the importance of a combination of formal education [2, 27, 28], continuous training [2, 28], and access to varied information sources [2] in enhancing radiation safety knowledge. The stability of results across bootstrapping analyses strengthens their validity and reliability [2].

Despite the age of the dataset, the present findings continue to have practical relevance for current healthcare systems. Radiation safety remains a critical component of clinical governance and occupational health policy, particularly as the use of diagnostic imaging technologies continues to expand globally. The identified associations between professional role, training exposure, and radiation safety knowledge may still inform contemporary workforce education strategies, especially in regional and resource-limited hospital settings where access to continuous professional development may vary. In this context, the study provides useful baseline evidence for evaluating ongoing improvements in radiation safety training and policy implementation.

LIMITATIONS OF THIS STUDY

Despite its robust methodology, this study has several limitations. First, there is the temporal gap between data collection and publication. Radiation safety policies and hospital practices in Vietnam may have evolved during this period. However, baseline assessments of this nature remain valuable as reference points for evaluating the effectiveness of subsequent policy and training interventions. Future studies should assess whether the knowledge gaps identified here have been addressed under current regulatory frameworks. Second, the cross-sectional design restricts causal inference between predictors and radiation safety knowledge. Third, reliance on self-reported data introduces potential response bias. Future studies should incorporate objective knowledge assessments and observational validation. Nevertheless, these limitations do not diminish the study's practical significance. The findings emphasize the need for targeted interventions—mandatory radiation safety training, continuous professional development, and improved access to educational resources. They also highlight the importance of embedding radiation safety education within formal medical and technical curricula.

In conclusion, this study reveals a substantial gap in radiation safety knowledge among healthcare professionals in central Vietnam. The integration of Bayesian Model Averaging, Lasso, and Ridge regression robustly identified key predictors of higher competency: direct X-ray involvement, higher education, older age, participation in radiation training, and access to multiple information sources. These findings illustrate the value of hybrid statistical frameworks for deriving reliable inferences. The results underscore an urgent need for focused educational interventions, strengthened training programs, and the systematic integration of radiation safety into medical curricula to safeguard both healthcare workers and patients from preventable radiation exposure.

CONFLICT OF INTEREST

The authors have no conflicts of interest associated with the material presented in this paper.

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References

1. He, Y., et al., Advancements in radiobiology techniques and applications for personalized radiation therapy in nuclear medicine. Journal of Radioanalytical and Nuclear Chemistry, 2024. 333(12): p. 6121-6132.
2. WHO. Enhancing radiation safety culture in health care: guidance for health care providers. 2024 10/02/2025]; Available from: https://www.who.int/publications/i/item/9789240091115.
3. Jenkins, N.W., et al., Intraoperative risks of radiation exposure for the surgeon and patient. Ann Transl Med, 2021. 9(1): p. 84.
4. The International Commission on Radiological Protection, The 2007 Recommendations of the International Commission on Radiological Protection. ICRP Publication 103. 2007.
5. Behzadmehr, R., et al., Radiation protection among health care workers: knowledge, attitude, practice, and clinical recommendations: a systematic review. Reviews on Environmental Health, 2021. 36(2): p. 223-234.
6. Han, E.O., Relationship between knowledge, attitude, behavior, and self-Efficacy on the radiation safety management of radiation ưorkers in medical institutions. Journal of Radiation Protection and Research, 2007. 32(2): p. 89-96.
7. Farajollahi, A.R., et al., Radiographers' professional knowledge regarding parameters and safety issues in plain radiography: a questionnaire survey. Br J Radiol, 2014. 87(1040): p. 20140090.
8. Yurt, A., B. Cavuşoğlu, and T. Günay, Evaluation of awareness on radiation protection and knowledge about radiological examinations in healthcare professionals who use ionized radiation at work. Mol Imaging Radionucl Ther, 2014. 23(2): p. 48-53.
9. Fatahi-Asl, J., M. Tahmasebi, and V. Karami, The protection knowledge and performance of Radiographers in some hospitals of Ahvaz County. Jentashapir J Health Res, 2013. 4(5): p. 405-412.
10. Nam, P.K. and A. Heshmati, Recent Trends in Vietnam’s Rapid Economic Development 1990 - 2023. 2024: Springer Singapore. 247.
11. Quan, N.K. and A.W. Taylor-Robinson, Vietnam's Evolving Healthcare System: Notable Successes and Significant Challenges. Cureus, 2023. 15(6): p. e40414.
12. Ministry of Science and Technology, Circular No. 19/2012/TT-BKHCN: Regulations on controlling and assuring radiation safety in occupation radiation and public radiation. 2012, MOST: Vietnam.
13. Ministry of Science and Technology, Circular No. 34/2014/TT-BKHCN: Regulations on training on radiation safety for radiation technicians and professionals in charge of radiation safety and radtion safety training services. 2014, MOST: Vietnam.
14. Zekioğlu, A. and Ş. Parlar, Investigation of awareness level concerning radiation safety among healthcare professionals who work in a radiation environment. Journal of Radiation Research and Applied Sciences, 2021. 14(1): p. 1-8.
15. Feldkircher, M. and S. Zeugner. Bayesian model averaging with BMS for BMS version 0.3.5. 2022 10/02/2025]; Available from: chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/http://bms.zeugner.eu/tutorials/bms.pdf.
16. Althubaiti, A., Sample size determination: A practical guide for health researchers. Journal of General and Family Medicine, 2023. 24(2): p. 72-78.

17. Lwanga, S.K., S. Lemeshow, and WHO, Sample size determination in health studies: a practical manual. 1991, World Health Organization: World Health Organization.
18. Ministry of Health, Decision No. 3299/QĐ-BYT: Technical guidelines on radiation diagnostics and treatment. 2011, MOH: Vietnam.
19. International Atomic Engergy Agency, Radiation Protection and Safety of Radiation Sources: International Basic Safety Standards: General Safety Requirements Part 3. 2014, IAEA: Vienna.
20. Benjamini, Y. and Y. Hochberg, Controlling the False Discovery Rate: A Practical and Powerful Approach to Multiple Testing. Journal of the Royal Statistical Society. Series B (Methodological), 1995. 57(1): p. 289-300.
21. Stata, Stata Statistical Software: Release 18.5. 2024, In StataCorp LLC.
22. R Core Team, R: A language and environment for statistical computing. 2024, R Foundation for Statistical Computing.
23. Alavi, S.S., et al., Medical radiation workers' knowledge, attitude, and practice to protect themselves against ionizing radiation in Tehran Province, Iran. Journal of Education and Health Promotion, 2017. 6(1): p. 58.
24. Sirimongkolkasem, T. and R. Drikvandi, On Regularisation Methods for Analysis of High Dimensional Data. Annals of Data Science, 2019. 6(4): p. 737-763.
25. Zou, H., The Adaptive Lasso and Its Oracle Properties. Journal of the American Statistical Association, 2006. 101(476): p. 1418-1429.
26. Pennsylvania State University. Lesson 6: Regression shrinkage methods. 2023 10/02/2025]; Available from: https://online.stat.psu.edu/stat508/lessons/Lesson06.
27. Alhazmi, F.H., et al., Prospective Health Professionals' Knowledge, Awareness, Attitude, and Practice Concerning MRI Safety. The Open Public Health Journal, 2023. 16.
28. Ploussi, A., E.P. Efstathopoulos, and E. Brountzos, The Importance of Radiation Protection Education and Training for Medical Professionals of All Specialties. Cardiovasc Intervent Radiol, 2021. 44(6): p. 829-834.

MODELLING APPROACHES TO MODEL SELECTIONS

To enhance model selection and address the inherent challenges of small sample sizes and multicollinearity in high-dimensional data, we employed a hybrid modelling approach integrating BMA (Table 3), Lasso regression, and Ridge regression (Table 4).

BMA was chosen to mitigate model uncertainty, which is a well-recognized issue in frequentist approaches, particularly when multiple potential predictors are involved and sample sizes are limited [1]. BMA estimates all possible combinations of predictors and constructs a weighted average over these models based on their posterior probabilities. This allows for more robust inference by accounting for model uncertainty. Specifically, if *K* variables are considered, BMA evaluates 2^K combinations and assigns weights to each model according to their posterior model probability (PMP) derived from Bayes' theorem.[1]

$$p(M_\gamma|y,X) = \frac{p(y|M_\gamma,X)p(M_\gamma)}{p(y|X)} = \frac{p(y|M_\gamma,X)p(M_\gamma)}{\sum_{s=1}^{2^K} p(y|M_s,X)p(M_s)} \tag{1}$$

Where $p(y|X)$ denotes the incorporated likelihood, which is constant over all models and is simply a multiplicative effect. The posterior model probability (PMP) $p(M\gamma|y, X)$ is proportional to the marginal likelihood of the model $p(y|M\gamma, X)$, the probability of the data y given the model $M\gamma$, times a prior model probability $p(M\gamma)$. The process of renormalization leads to the PMPs, and thus the model weighted posterior distribution for any statistic θ (for example β):

$$p(\theta|y,X) = \sum_{\gamma=1}^{2^K} p(\theta|M_\gamma,y,X)p(M_\gamma|X,y) \tag{2}$$

The model prior to $p(M\gamma)$ can be defined by the researcher such that it should reflect prior beliefs. A popular choice is to set a uniform prior probability for each model $p(M\gamma) \propto 1$ to represent the lack of prior knowledge [1].

In addition, Lasso regression and Ridge regression were used to ensure robust variable selection and coefficient stability. Lasso regression applies an L_1-penalty, which forces some coefficients to exactly zero, effectively performing variable selection while simultaneously shrinking other coefficients.[2] This method is especially suitable for sparse models where only a subset of predictors is relevant. In contrast, Ridge regression applies an L_1-penalty, shrinking all coefficients toward zero without setting any to exactly zero, thereby stabilizing the model and reducing the impact of multicollinearity [3, 4]. The objective functions for Lasso and Ridge, respectively, minimizes the residual sum of squares subject to a constraint on the sum of the absolute values of the coefficients are presented below:

$$\sum_{i=1}^{n}\left|y_i - \sum_{j=1}^{p}\beta_j\, x_{i\,j}\right|^2 + \lambda\sum_{j=1}^{p}|\beta_j| \tag{3}$$

$$\sum_{i=1}^{n}\left(y_i - \sum_{j=1}^{p}\beta_j\, x_{i\,j}\right)^2 + \lambda\sqrt{\sum_{j=1}^{p}\beta_j^2} \tag{4}$$

Here, n, p and λ represent the number of observations, the number of variables and the tuning parameter controlling the degree of shrinkage, respectively, with λ selected using cross-validation to minimize prediction error. x_{ij} denotes the value of variable j for individual i, and β_j represents the regression coefficient for variable j.

The rationale for combining these methods was to capitalize on the strengths of each: BMA for comprehensive model selection with uncertainty quantification,[1] Lasso for identifying key predictors, and Ridge for improving coefficient stability and prediction accuracy.[3] Performance metrics, including root mean squared error (RMSE), adjusted R^2, and Bayesian Information Criterion (BIC), were used to evaluate and compare models for model selection. The optimal regularization parameter λ for Lasso and Ridge was chosen using cross-validation to minimize prediction error.[3] Upon completing model selection, we performed standard linear regression analyses to estimate parameters and derive statistical inferences, ensuring robust and interpretable results (Figure 2).

References

1. Feldkircher, M. and S. Zeugner. *Bayesian model averaging with BMS for BMS version 0.3.5*. 2022 10/02/2025]; Available from: chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/http://bms.zeugner.eu/tutorials/bms.pdf.
2. Sirimongkolkasem, T. and R. Drikvandi, *On Regularisation Methods for Analysis of High Dimensional Data.* Annals of Data Science, 2019. **6**(4): p. 737-763.
3. Zou, H., *The Adaptive Lasso and Its Oracle Properties.* Journal of the American Statistical Association, 2006. **101**(476): p. 1418-1429.
4. Pennsylvania State University. *Lesson 6: Regression shrinkage methods*. 2023 10/02/2025]; Available from: https://online.stat.psu.edu/stat508/lessons/Lesson06.