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RADIATION DOSE ESTIMATION FOR NUCLEAR MEDICINE NURSES USING THE MONTE CARLO-BASED PHITS SIMULATION CODE

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Abstract

Background. Radioiodine therapy with ^{131}I presents a considerable occupational radiation exposure risk due to prolonged patient radioactivity. ^{131}I emits β- particles (Emax 0.606 MeV) and γ- rays (0.364 MeV and 0.637 MeV) and has a physical half-life of approximately 8 days. Ensuring radiation safety for medical personnel requires a detailed understanding of the spatial and temporal dose distribution within isolated therapy rooms. Combining Monte Carlo-based PHITS simulation with real dosimetry provides practical guidance for room design, workflow optimization and alignment with ALARA principles.

Objective. This study aimed to characterize spatial and temporal variations of radiation in a ^{131}I patient room and to identify actionable strategies to reduce occupational exposure.

Materials and methods. PHITS (Particle and Heavy Ion Transport code System, version 3.34) was used to simulate radiation distribution in a constructed patient room model. An anatomically realistic MRCP-AM male phantom (ICRP Publication 145) with thyroid-based ^{131}I activity was implemented as the radiation source to model patient-specific exposure conditions. Relative errors were maintained below 5%. Additionally, nurse activity logs were analyzed to evaluate procedure durations and estimate real-world contributions to cumulative dose.

Results. Simulations revealed spatial gradients, with consistently highest dose rates recorded near the bed for all models except the bathroom phantom scenario. Across 72 hours, dose rates decreased by approximately 20% between 0-24 hours, a further 38-40% from 48-72 hours, and by roughly 50% overall. The MRCP-AM phantom produced higher near-bed dose rates, reflecting anatomical modulation of emission. Simulated values agreed with measured dosimetry, particularly at distant positions. Workflow assessment showed that although 68% of procedures lasted under 10 minutes, short-duration close-range tasks disproportionately contributed to staff exposure.

Conclusion. This study demonstrates that PHITS can reliably model ^{131}I radiation fields and supports optimizing nursing workflow to minimize close-proximity exposure, particularly within the first hours after administration.

Key words: *Iodine-131; radioiodine therapy; radiation protection; PHITS simulation;*

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Резюме

ОЦЕНКА ДОЗ ОБЛУЧЕНИЯ МЕДИЦИНСКИХ СЕСТЕР В ЯДЕРНОЙ МЕДИЦИНЕ С ИСПОЛЬЗОВАНИЕМ СИМУЛЯЦИОННОГО КОДА PHITS НА ОСНОВЕ МЕТОДА МОНТЕ-КАРЛО

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Актуальность и введение. Радиотерапия ^{131}I представляет существенный риск профессионального облучения из-за длительной радиационной активности пациента. Радионуклид ^{131}I испускает β-частицы (Emax 0,606 МэВ) и γ-излучение (0,364 и 0,637 МэВ), а его физический период полураспада составляет около 8 суток. Обеспечение радиационной безопасности медицинского персонала требует понимания пространственного и временного распределения дозы в изолированных терапевтических палатах. Комбинация моделирования Монте-Карло с реальными дозиметрическими измерениями предоставляет практические рекомендации по проектированию помещений, оптимизации рабочего процесса и соблюдению принципов ALARA.

Целью данного исследования являлась характеристика пространственных и временных вариаций радиации в палате пациента, получающего терапию ^{131}I, и определение практических стратегий снижения профессионального облучения.

Материалы и методы. Для моделирования распределения излучения использовалась программа PHITS (Particle and Heavy Ion Transport code System, версия 3.34), в которой была воссоздана геометрия палаты. Был применен как источник анатомически реалистичный мужской фантом MRCP-AM с активностью в области щитовидной железы. Относительная ошибка поддерживалась ниже 5%. Также были проанализированы дневники активности медсестёр для оценки длительности процедур и их вклада в суммарную дозу.

Результаты. Симуляции выявили выраженные пространственные градиенты: максимальные уровни дозы фиксировались возле кровати во всех моделях, кроме сценария с фантомом в ванной. За 72 часа уровни дозы снизились примерно на 20% в интервале 0-24 часов и ещё на 38-40% в период 48-72 часов, что составило около 50% общего уменьшения. Модель MRCP-AM давала более высокие значения рядом с кроватью, что отражает анатомическое влияние на распределение излучения. Результаты симуляции хорошо согласовывались с дозиметрическими измерениями, особенно в удалённых точках. Анализ рабочего процесса показал, что хотя 68% процедур длились менее 10 минут, кратковременные вмешательства вблизи пациента существенно увеличивали вклад в профессиональную дозу.

Заключение. Это исследование демонстрирует, что PHITS надёжно моделирует радиационные поля ^{131}I и подтверждает необходимость оптимизации работы персонала для минимизации близкого контакта в первые часы после введения радиофармпрепарата.

Ключевые слова: *Йодид-131; радиойодтерапия; радиационная защита; PHITS симуляция;*

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Түйіндеме

МОНТЕ-КАРЛО ӘДІСІНЕ НЕГІЗДЕЛГЕН PHITS СИМУЛЯЦИЯЛЫҚ КОДЫН ҚОЛДАНУ АРҚЫЛЫ ЯДРОЛЫҚ МЕДИЦИНА МЕДБИКЕЛЕРІНЕ АРНАЛҒАН РАДИАЦИЯЛЫҚ ДОЗАНЫ БАҒАЛАУ

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Зерттеудің өзектілігі. ^{131}I радиойодтерапиясы пациенттің ұзақ уақыт бойы радиация шығаруы салдарынан медицина қызметкерлері үшін айтарлықтай сәуле түсу қаупін тудырады. ^{131}I радионуклиді β-бөлшектерді (Emax 0.606 МэВ) және γ-сәулелерді (0.364 және 0.637 МэВ) шығарады, физикалық жартылай ыдырау кезеңі шамамен сегіз тәулікке тең. Медицина қызметкерлерінің радиациялық қауіпсіздігін қамтамасыз ету үшін оқшауланған емдеу палаталарындағы дозаның кеңістіктік және уақыттық таралуын терең түсіну қажет. Монте-Карло моделдеуі мен нақты дозиметриялық өлшемдерді біріктіру бөлмені жобалау, жұмыс процесін оңтайландыру және ALARA принциптерін сақтау үшін практикалық ұсынымдар береді.

Бұл **зерттеудің мақсаты** ^{131}I терапиясы кезінде пациент палатасындағы радиацияның кеңістіктік және уақыттық өзгерістерін сипаттау және қызметкерлердің сәулеленуін төмендетуге бағытталған стратегияларды айқындау.

Материалдар мен әдістер. PHITS бағдарламасы (Particle and Heavy Ion Transport code System, нұсқа 3.34) бөлме геометриясын құрастырып, радиацияның таралуын модельдеу үшін қолданылды. Симуляцияда қалқанша безі аймағына ^{131}I белсенділігі енгізілген анатомиялық дәл MRCP-AM ер адам фантомы ғана пайдаланылды. Салыстырмалы қателік 5%-тен төмен деңгейде ұсталды. Сонымен қатар, медбикелердің жұмыс күнделіктері талданып, процедуралардың ұзақтығы мен олардың жиынтық дозаға қосқан үлесі бағаланды.

Зерттеу нәтижелері. Модельдеу нәтижелері кеңістіктік градиенттің айқын екенін көрсетті: ең жоғары доза деңгейлері барлық модельдерде төсек маңында тіркелді (ваннадағы фантом моделінен басқа). 72 сағат ішінде доза қуаты 0-24 сағат аралығында шамамен 20%-ға, ал 48-72 сағат аралығында 38-40%-ға төмендеп, жалпы 50% шамасында азайды. MRCP-AM моделі төсек жанында жоғарырақ мәндер көрсетті, бұл анатомиялық факторлардың сәуле таралуына әсерін білдіреді. Симуляция нәтижелері, әсіресе алшақ нүктелерде, нақты дозиметриялық өлшемдермен жақсы сәйкес келді. Жұмыс үдерісін талдау 68% процедуралардың ұзақтығы 10 минуттан аспайтынын, бірақ пациентке жақын арада орындалатын қысқа тапсырмалар қызметкерлердің жиынтық сәулеленуіне едәуір үлес қосатынын көрсетті.

Зерттеу қорытындысы. Бұл зерттеу PHITS бағдарламасының ^{131}I радиациялық өрістерін сенімді модельдей алатынын және алғашқы сағаттарда пациентке жақын болуды барынша қысқарту қажеттілігін көрсетеді.

Түйінді сөздер: *Йод-131; радиойодтерапия; радиациялық қорғаныс; PHITS симуляциясы.*

Дәйексөз үшін:

Абылқасымов Ә., Такеда Й., Такахира Х., Тамакума Ю., Кудо Т., Йокояма С. Монте-Карло әдісіне негізделген PHITS симуляциялық кодын қолдану арқылы ядролық медицина медбикелеріне арналған радиациялық дозаны бағалау // Ғылым және Денсаулық сақтау. 2026. Vol.28 (1), Б. 13-20. *doi 10.34689/SH.2026.28.1.002*

Introduction

Radioactive iodine (^{131}I) therapy is a well-established and highly effective modality for the treatment of differentiated thyroid carcinoma, including cases with distant metastases [2]. Its therapeutic effect is based on the selective uptake of iodine by thyroid cells, allowing targeted radiation delivery to residual thyroid tissue or metastatic lesions while limiting systemic toxicity. Owing to its clinical efficacy, ^{131}I continues to play a central role in thyroid cancer management worldwide [3]. In Japan, its use remains distinctive compared with other countries, with a steady increase in inpatient cases over the past two decades [1,3,6-10].

Despite these therapeutic advantages, ^{131}I is a β- and γ-emitting radionuclide with a physical half-life of approximately eight days. While β-particles (Emax=0.606 MeV) provide the desired dose to thyroid tissue and are absorbed within the patient's body, γ-photons (364 keV) are highly penetrating and represent the main contributor to external exposure in clinical settings. Consequently, patients treated with ^{131}I can serve as a radiation source to healthcare workers, caregivers and the public. To mitigate radiation risks, strict regulatory guidelines have been established to ensure safe administration and handling of ^{131}I. The Ministry of Health, Labour and Welfare of Japan has implemented stringent regulations governing the use of radioactive materials and the discharge of patients following RAI therapy [3]. Compliance with these regulations necessitates the development of dedicated shielded facilities, specialized waste disposal systems and protective protocols for medical staff working in nuclear medicine departments. Furthermore, behavioural restrictions for treated patients are crucial to minimize secondary radiation exposure to their families and the surrounding environment.

However, accurately estimating and visualizing radiation dose distributions within an isolated therapy room remains challenging. Experimental dosimetry provides essential information, yet its utility is often limited by restricted accessibility, insufficient spatial resolution, and the inability to account for dynamic patient behaviour. Therefore, Monte Carlo–based simulations have become an important complementary tool for investigating photon transport, optimizing shielding, and improving workflow design.

In this study, we employ PHITS (Particle and Heavy Ion Transport code System) to simulate the spatial and temporal distribution of radiation from patients undergoing ^{131}I therapy [11]. A detailed combinatorial geometry model of a dedicated therapy room including walls, shielding structures, furniture and the patient as the radiation source was constructed to calculate dose distributions at occupationally relevant locations. Integrating simulated data with measured dosimetry enables a comprehensive evaluation of exposure scenarios and supports the development of practical recommendations for room layout, shielding, and staff positioning in accordance with the ALARA principle [4].

Materials and Methods

Study subject and setting

This study is a simulation-based dosimetric research integrating Monte Carlo radiation transport modelling with observational analysis of clinical workflow data. Study investigates the radiation dose distribution in an isolated patient's room used for ^{131}I radioisotope therapy in patients with thyroid cancer after total thyroidectomy and based on data obtained from the ^{131}I therapy isolation room at Nagasaki University Hospital between June 2022 and April 2024, following the methodology by previous research (*Takahira H.),* The 9th International Symposium of the Network-type Joint Usage/Research Center for Radiation Disaster Medical Science, 2025). The patient's room consists of a main living area, a bathroom with a toilet and

washstand. Patients undergoing ^{131}I therapy received oral doses ranging from 1.1 GBq to 5.5 GBq and remained in the room for two nights and three days. The radioiodine capsules were administrated between 10:00 and 11:00 am on the admission day.

Dosimeters

In this study, seven personal D-Shuttle dosimeters (Chiyoda Technol Co., Ltd) were used to examine the dose equivalent. The D-Shuttle dosimeter is a small (68 mm x 32 mm x 14 mm) and very light (23 g.) Si-diode-based personal gamma-ray dosimeter. Personal dose equivalent recordings can be provided every hour for a long time. Measured dose could read via a USB connection to a PC equipped with the dedicated software. Radiation dose measurements were recorded in microsieverts (μSv/2 min.) using personal D-Shuttle dosimeters placed in key locations, including the head and foot sides of the bed, near the wall, side table, in front of the entrance, washstand and bathroom. Measurements were taken every 2 minutes over three consecutive days period to ensure comprehensive monitoring of real radiation exposure. After data scanning for dose distribution calculating analysis microsieverts per 2 minutes (μSv/2 min.) were converted to microsieverts per seconds (μSv/sec.)

Nursing procedures tracking

Based on the previous research data, all procedures performed by nurses were systematically recorded in patient management diaries to assess the frequency and duration of nursing procedures in the ^{131}I therapy isolation room. The dataset included the date (month and day), number of nurses (five in total), start time, end time, total duration (in minutes), type and number of procedures performed per day. However, the distance between the nurse and patient was not measured, and therefore to assess potential radiation exposure it was classified as close-contacted and distant contacted procedures based on the nurse's proximity to the patient during the procedure.

PHITS simulation: ^{131}I source and patient room modelling

PHITS (version 3.34) was used to model β- and γ-emissions from ^{131}I using Monte Carlo particle transport. Particle interactions including scattering, absorption and transmission were sampled from established physical probability distributions. Source spectra were generated using the radionuclide mode in PHITS, incorporating the full β-energy distribution (Emax = 0.606 MeV; mean = 0.192 MeV) and dominant γ- lines (364 keV) as defined in ICRP Publication 107. To enable integration with the room geometry and patient phantom model, radiation sources were implemented using simplified geometric representations. The β- and γ- sources were defined under identical conditions to allow direct comparison of emission characteristics. Each source was modelled as a 1-cm radius emission region positioned along the z-axis (-10 cm $\leq z \leq -10$ cm) with isotropic particle release. Energy distributions were derived from tabulated nuclear decay data. All simulations were normalized to the physical half-life of ^{131}I, ensuring consistent decay scaling across β- and γ- radiation fields.

To achieve realistic modelling of patient activation, the full geometry of the ^{131}I isolation room was reconstructed in PHITS, including all major structural and furnishing elements relevant to photon and electron transport. The room was implemented as a rectangular enclosure (420 × 230 × 215 cm) composed of concrete (density 2.2 g/cm³). An internal bathroom was modeled with composite plastic-aluminium walls, and additional room components including the hospital bed, washstand, water-filled sink, and lead-shielded corner wagon were defined using material densities consistent with their physical counterparts. Seven dosimeter volumes were placed at clinically relevant positions (head and foot of bed, wall side, side table, entrance, washstand, and bathroom). Their geometry followed manufacturer specifications to ensure accurate dose scoring. A 0.5-cm lead barrier was included near the entrance to account for localized shielding. All geometries were defined using rectangular parallelepiped (RPP) surfaces to maintain computational efficiency and compatibility with PHITS geometry handling. To ensure statistical stability, simulations employed an extended maximum number of particle histories (10^6–10^8). Full geometry rendering and execution required approximately 1.5 hours of computation time.

PHITS simulation: Phantom modelling with ^{131}I radiation source

For Monte Carlo-based dose estimation, an anatomically realistic adult male mesh-type computational phantom (MRCP-AM, ICRP Publication 145) was implemented in PHITS. This phantom provides detailed representation of human anatomy, including organ shapes, tissue heterogeneity, and body contour, allowing for more accurate modelling of photon scattering and absorption processes relevant to ^{131}I therapy. The radioactive source was placed in the thyroid region and defined using the PHITS built-in radionuclide mode, which incorporates the complete β- and γ-emission spectra of ^{131}I.

The phantom was positioned within a rectangular room geometry replicating the clinical layout to account for scattering, attenuation, and shielding from walls and furniture. Dose scoring was performed using a combination of mesh-based T-track tallies and region-based T-deposit tallies to evaluate spatial and anatomical energy deposition. All results were normalized per primary source particle and reported in Gy per particle or converted to dose rate (μSv/s) where applicable. Visualization of the phantom and room geometry was enabled (gshow = 1) for verification of spatial alignment. Simulations were performed using 10^6 particle histories per batch, with a total of 10^7 primary photons to ensure statistical stability and maintain relative errors within acceptable ranges for radiation protection calculations.

Measurements and PHITS simulation data calculation

Dosimeter readings recorded in microsieverts per 2 minutes (μSv/2 min) were converted to microsieverts per second (μSv/s) for compatibility with PHITS output units. PHITS simulations produced dose rates in picosieverts per second (pSv/s), which were converted to sieverts per second (Sv/s) and subsequently to microsieverts per second per becquerel (μSv/s/Bq). These values were then scaled to the administered activity (1.1–5.5 GBq). Final dose-rate distributions are reported as mean ± SD and maximum values. All numerical analyses were performed using Microsoft Excel.

Ethical approval

This study used the anonymized data of the study approved by the Ethics committee of Nagasaki University

(Approval number 22051615). Written informed consent was waived by the Ethics Committee, as the study did not involve direct patient participation and included only anonymized observational workflow data and computational simulations. The study was conducted with the knowledge and approval of the hospital administration, and permission was granted for the analysis and publication of the results.

Results

Evaluation of radiation dose rates across seven measured locations using the mesh-type MRCP-AM phantom demonstrated a clear and consistent decline over the 72-hour period (Figure 1, Figure 2). As expected, the highest dose rates were observed in the areas closest to the patient bed, particularly at the wall side and head side.

At the wall side of the bed, the dose rate decreased from 0.0513 μSv/s during the first 24 hours to 0.0409 μSv/s at 24-48 hours, and further to 0.0251 μSv/s at 48-72 hours. This corresponded to a 20.2% reduction in the first interval and a total decline of 38.7% by 72 hours. A similar pattern was seen at the head side of the bed, where the dose rate decreased from 0.0338 μSv/s to 0.0270 μSv/s and then to 0.0166 μSv/s, resulting in an overall 50.9% reduction across the 72-hour period. The foot side of the bed also showed relatively high initial values (0.0268 μSv/s), which decreased to 0.0216 μSv/s and 0.0134 μSv/s by 72 hours, corresponding to a 49.9% total decline.

Across all near-bed locations, dose rates demonstrated a comparable reduction pattern: approximately 19-21% during the first 24–48 hours, followed by a more pronounced 38-40% decrease between 48-72 hours. The side table also exhibited moderate dose levels, decreasing from 0.0064 μSv/s to 0.0050 μSv/s and 0.0030 μSv/s over the same intervals, with an overall reduction of 51.7%.

Dose distribution using mesh-type phantom (MRCP-AM).

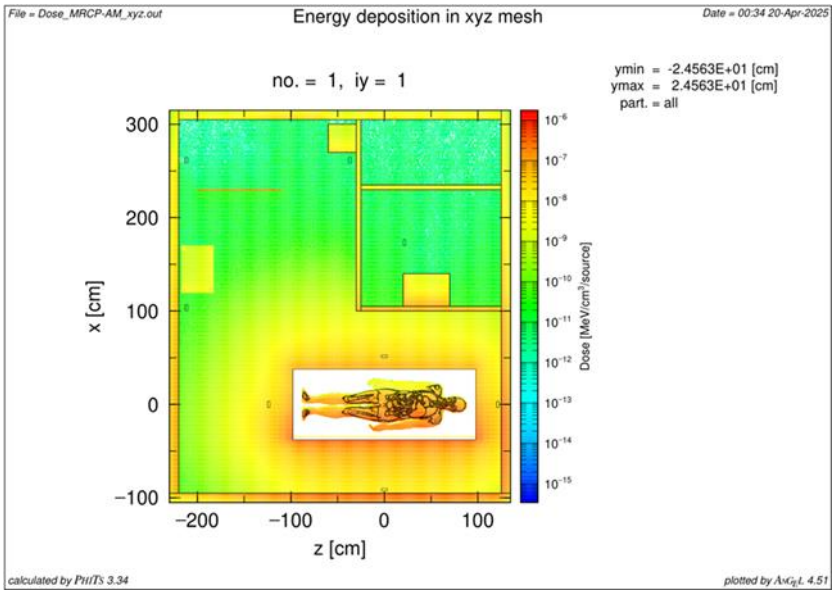

Figure 1. Spatial distribution of equivalent dose rate H(10) for photons and electrons emitted from ^{131}I represented by a human body MRCP phantom model (male, weight 73 kg, height 176 cm) with rectangular source (maxcas=10^7). Simulation performed using PHITS 3.34.

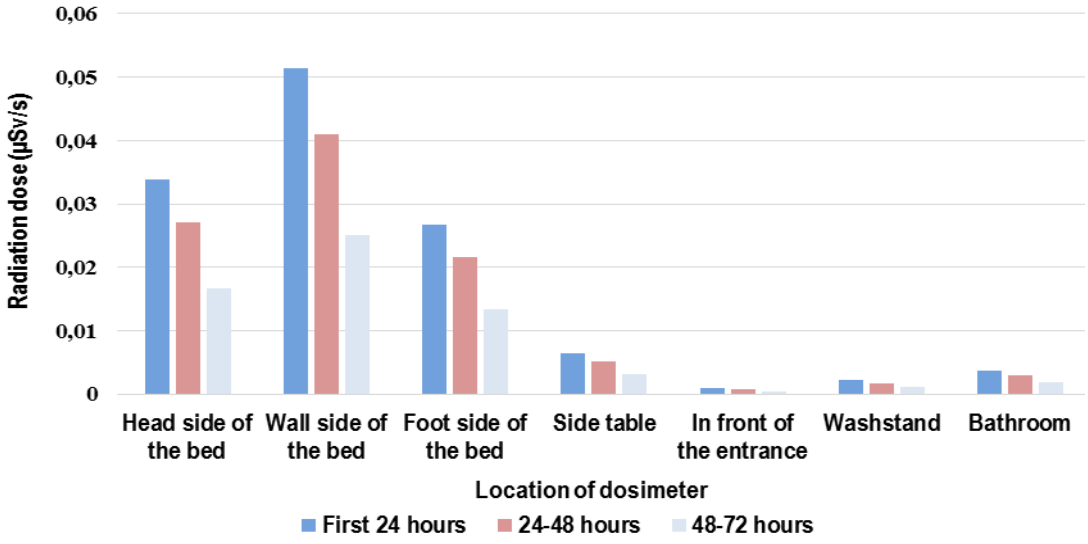

Figure 2. Analysis of ^{131}I radiation dose distribution from PHITS simulation (μSv/s) using a human body MRCP phantom model (male, weight 73 kg, height 176 cm) with rectangular source (maxcas=10^7) over three consecutive days.

Distant locations, including the washstand, bathroom, and entrance, recorded the lowest dose rates. At the washstand, values decreased from 0.0022 μSv/s to 0.0017 μSv/s and 0.0010 μSv/s, representing a total reduction of 52.6%. A similar trend was observed in the bathroom (0.0037 → 0.0029 → 0.0018 μSv/s; 51.9% total decline). The lowest exposure occurred in front of the entrance, where the dose rate dropped from 0.0008 μSv/s to 0.0007 μSv/s and 0.0004 μSv/s, corresponding to a 51.1% decline.

Overall, all measurement points followed the same temporal pattern: a moderate ~20% reduction during the first 24-48 hours, followed by a sharper 38-40% decrease during the subsequent 48–72 hours, resulting in a total 50-52% reduction over 72 hours. Relative error values for all simulated doses ranged from 1.8% to 3.7%.

Using the MRCP-AM adult male phantom (73 kg, 176 cm) with a rectangular ^{131}I source (maxcas = 10^7), the highest average dose rate across the entire period was recorded at the wall side of the bed (0.0391 μSv/s). Moderate values were registered at the head and foot sides (0.0258 μSv/s and 0.0206 μSv/s), while the lowest averages were observed at the side table (0.0048 μSv/s), bathroom (0.0028 μSv/s), washstand (0.0016 μSv/s), and entrance (0.0006 μSv/s). The high stability of the results was ensured by the use of 10 million particle histories, with reliability primarily determined by the number of particle histories rather than by multiple simulation runs.

Comparison between calculation and measured dosimeter data

Table 1.

Radiation dose rates (μSv/s) in various locations of the isolated patient room following ^{131}I administration.

	First 24 hours		24 ~ 48 hours		48 ~ 72 hours	
	Max (μSv/s)	Mean±SD	Max (μSv/s)	Mean±SD	Max (μSv/s)	Mean±SD
Bed (Head side)	0.0407	0.0106±0.012	0.0340	0.0130±0.009	0.0135	0.0030±0.004
Bed (Wall side)	0.1329	0.0159±0.020	0.0669	0.0124±0.008	0.0189	0.0026±0.003
Bed (Foot side)	0.0646	0.0111±0.014	0.0244	0.0081±0.003	0.0095	0.0014±0.001
Near side table	0.0775	0.0082±0.017	0.0392	0.0047±0.007	1.2925	0.0034±0.052
Entrance	0.0209	0.0026±0.003	0.0089	0.0017±0.001	0.9050	0.0023±0.038
Washstand	0.0316	0.0017±0.002	0.0145	0.0013±0.001	0.0060	0.0003±0.001
Bathroom	0.0237	0.0029±0.003	0.0200	0.0021±0.002	0.0061	0.0006±0.001

The dosimeters data during the first 24 hours revealed the highest radiation dose at the wall side of the bed recording a peak value approximately 3.3 times higher than the head side and 2.1 times higher than the foot side of the bed. Compared to the bathroom, the dose at the wall side of the bed was approximately 5.6 times greater. Even the side table, located slightly away from the patient, had a dose 3.3 times higher than the in front of the entrance location. The dose rate at the wall side of the bed was approximately 4.2 times higher than that measured near the washstand. From 24 to 48 hours, despite a general reduction in dose rates was observed across all seven locations, the wall side of the bed still maintained the highest average value. At this period of time, the wall side dose was 7.5 times higher than at the entrance and 3.3 times higher than at the washstand. The bathroom dose remained approximately 3.3 times lower than the wall side. By 48-72 hours period, although maximum peaks were recorded near the side table and in front of the entrance location, the average dose levels stayed low. The wall side and head side of the bed continued to show moderately elevated values. The wall side of the bed dose was still about 3 times higher than the bathroom and over 7 times higher than in front of the entrance location. The washstand and bathroom remained among the lowest exposure zones throughout the observation period. The three-day average dose was 0.0089 μSv/s at the head side of the bed, 0.0103 μSv/s at the wall side of the bed, 0.0069 μSv/s at the foot side of the bed, 0.0054 μSv/s at the side table, 0.0022 μSv/s at the location in front of the entrance, 0.0011 μSv/s at the washstand, and 0.0019 μSv/s in the bathroom. Elevated dose rate at side table and in front of the entrance locations during 48-72 hours period was considered anomalous and possibly due to temporary patient proximity or local contamination, as it was inconsistent with physical decay trends and simulation data.

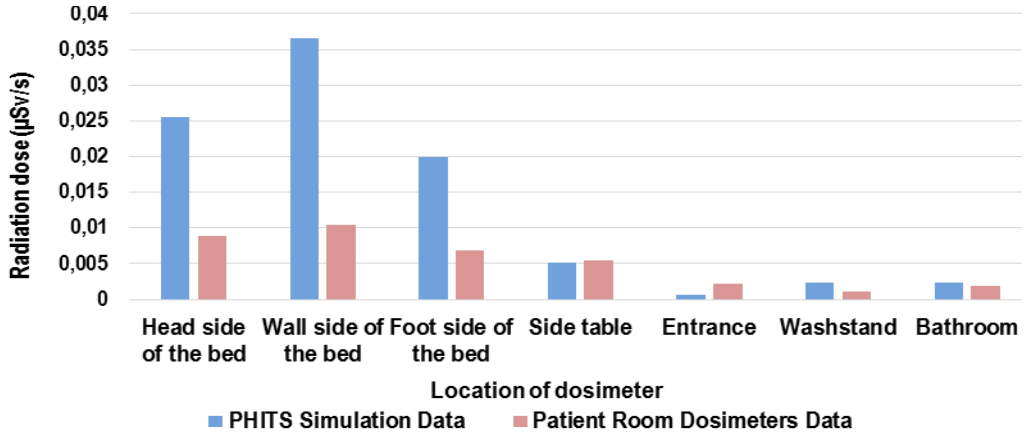

Figure 3. Analysis of ^{131}I radiation dose from dosimeters and PHITS simulation (μSv/s) using a human body MRCP phantom model (male, weight 73 kg, height 176 cm) with rectangular source (maxcas=10^7).

In analysis of ^{131}I radiation dose distribution using a human body phantom model the three-day average exposure comparison showed that PHITS-simulated doses were generally higher than dosimeters measurements. At the wall side of the bed, the estimated dose by PHITS simulation result was significantly higher than that measured by dosimeters (0.0366 μSv/s vs. 0.0103 μSv/s). At the head side and foot side of the bed, PHITS simulation results also predicted significantly higher doses compared to dosimeters calculation results (0.0254 μSv/s vs. 0.0089 μSv/s and 0.0198 μSv/s vs. 0.0069 μSv/s). In contrast, at the location of side table there was no significant difference observed between PHITS simulation result and dosimeters calculation data (0.0034 μSv/s vs. 0.0054 μSv/s). For more distant locations, such as in front of the entrance, washstand and bathroom, PHITS simulation results remained slightly higher but without significant difference (0.0006 μSv/s vs. 0.0022 μSv/s; 0.0023 μSv/s vs. 0.0011 μSv/s; 0.0024 μSv/s vs. 0.0019 μSv/s).

Time-based analysis of nursing procedures in the isolated patient room

Based on the previous study data, we analyzed the average time spent by nurses performing various manipulations in the ^{131}I administered patient room, presented at Figure 4, which shows the percentage of nursing procedures grouped by their duration intervals. The horizontal axis shows the percentage of total time spent in the room. The vertical axis shows the duration of nursing procedures in minutes. An analysis of nursing activity durations revealed that 8.2% of nurses spent 20-29 minutes inside the ^{131}I isolated patient room. Meanwhile, 24.4% stayed for 10- 19 minutes, 43% for 5-9 minutes, and 24.4% spent less than 5 minutes. The percentages correspond to the number of procedures that fell within each time bracket, rather than the share of total time spent in the isolated room. These time durations were extracted from nurse's diaries that included both the starting and ending time of each recorded activity.

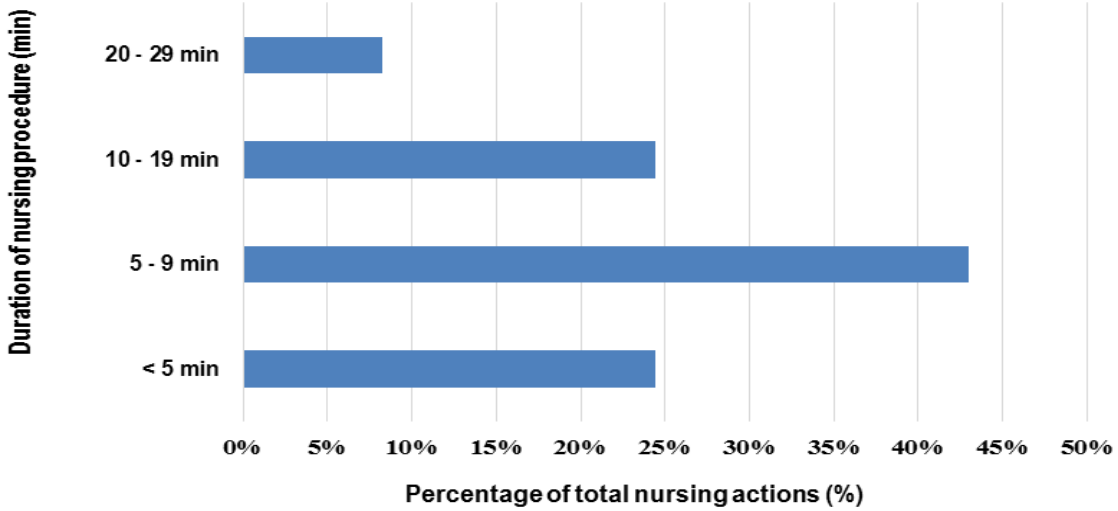

Figure 4. Distribution of nursing procedures by duration in the isolated patient room.

Discussion

This study provides a comprehensive assessment of the spatial and temporal characteristics of radiation exposure in a ^{131}I therapy isolation room by integrating Monte Carlo-based PHITS simulations with long-term dosimeter measurements. Using an anatomically realistic ICRP MRCP-AM mesh phantom allowed for a more accurate representation of patient anatomy, tissue composition, and scattering behaviour, all of which are essential for evaluating occupational exposure risks. These findings are particularly relevant for nuclear medicine practice in Japan, where outpatient ablation with 1,110 MBq remains widely used and where medical staff frequently perform close-contact procedures in the early post-administration phase [3].

Across all simulations, dose rates declined predictably over the 72-hour period, with an initial reduction of approximately 20-30% between 24 and 48 hours, followed by a more pronounced 38-40% decrease up to 72 hours. This pattern corresponds well with the physical decay of ^{131}I and supports the reliability of the simulation parameters. The spatial distribution obtained with the MRCP-AM phantom demonstrated clearly elevated dose levels in near-bed regions, with progressively lower exposures toward the periphery of the room. These results highlight the importance of anatomical realism for accurate near-field dose estimation, as simplified representations of the human body typically underestimate exposure in areas where staff are most likely to work.

Comparison of PHITS output with dosimeter measurements further illustrated the complexity of real-world radiation environments. PHITS tended to overestimate doses near the bed particularly at the wall, head, and foot sides likely due to factors not fully captured in the simulation, including micro-shielding from furniture, variations in wall composition, patient movement, and self-shielding effects. In contrast, simulated and measured values were in close agreement at more distant locations such as the washstand, bathroom, and entrance, where room geometry is simpler and environmental influences are minimal. These observations indicate that while PHITS provides reliable far-field predictions, refinement of near-field modelling remains necessary for accurately characterizing staff exposure.

A key methodological limitation is that PHITS assumes a static patient. Real clinical scenarios involve patient movement, changes in posture, and the potential spread of radioactive contamination through bodily fluids, factors that cannot be reproduced in the simulation. Previous studies have shown that the bathroom and washstand may become contaminated

during ^{131}I therapy, yet such secondary pathways were not represented in our simulation framework [5]. As a result, these areas appeared less irradiated in simulated dose maps than would be expected based on clinical observations. Incorporating patient mobility and contamination dynamics into future modelling approaches would enhance the realism and applicability of simulation-based dose assessments.

Analysis of nursing activity revealed that staff behaviour plays a central role in shaping cumulative occupational dose. Both simulation and measured data showed that exposure peaks within the first 1–13 hours after radioiodine administration, emphasizing the need to minimize room entry and reduce time spent near the patient during this critical period. Although the majority of procedures lasted less than 10 minutes, approximately one-third exceeded this duration, particularly tasks requiring close contact such as patient monitoring, intravenous line management, and supervision of ^{131}I ingestion. Standardizing workflow, optimizing scheduling, and expanding the use of remote monitoring could meaningfully reduce exposure. Psychological factors, including anxiety about radiation well documented in post-Fukushima nursing surveys - may also influence staff behaviour and lead to unnecessarily prolonged interactions [12].

Overall, the combined simulation and measurement results confirm that while fundamental radiation protection principles remain effective, clinical practice can be further optimized to reduce occupational dose. Indirect radiation pathways, variability in staff behaviour, and the influence of room layout all underscore the need for ongoing evaluation and refinement of safety protocols. High-fidelity Monte Carlo simulations, when validated by empirical data, represent a valuable tool for improving workflow, enhancing room design, and strengthening radiation protection strategies in nuclear medicine.

Conclusion

This study demonstrates that the PHITS system can reliably estimate the spatial and temporal distribution of ^{131}I radiation in an isolation room. Although some discrepancies appeared near the bedside mainly due to geometric simplifications and phantom limitations the agreement between simulations and dosimeter data was strong at distant locations, confirming the model's overall validity for safety planning. Both simulation and measurements showed that radiation levels are highest during the first 1-13 hours after administration, emphasizing the need to minimize staff presence in this critical period. Optimizing workflow, reducing time spent near the patient, and applying appropriate shielding can further reduce occupational exposure for healthcare personnel.

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