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Development of an Electromagnetic Radiation Screening System using Push-Shield Door for Radiation Safety

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This study evaluates radiation exposure risks associated with baggage jamming in X-ray security inspection systems and proposes a new push-type shielding door mechanism to mitigate such exposure. Using the Monte Carlo code MCNPX v2.7 and the HDRK-Man computational phantom, simulations were conducted to estimate leakage and operator dose rates under various obstruction scenarios. The results demonstrated that when the lead curtain was fully open due to baggage jam, operator exposure reached up to 22.69 μSv/hr, exceeding public dose limits. Implementation of the newly designed shielding door reduced this dose to 0.06 μSv/hr, achieving a 99.7% reduction in exposure. The proposed system not only ensures compliance with domestic radiation safety regulations but also improves operational efficiency and inspection stability.

Keywords : electro-magnetic radiation, X-ray scan system, radiation safety, Computed simulation, dose optimization

1. Introduction

X-ray security inspection systems are widely operated at airports, seaports, and terminals to detect hazardous items such as guns, knives, explosives, illegal drugs, and prohibited goods including certain plants and foods. In recent years, due to increasing concerns about industrial technology leakage and various forms of terrorism, these inspection systems have also been deployed in major public institutions, crowded facilities, and courier companies handling large volumes of parcels.

The general operating principle of a security X-ray scanner is as follows: when a baggage item is placed on the conveyor belt, the belt moves the item through a lead-shielded curtain toward the detection area. Once the entry sensor is triggered, the X-ray tube emits radiation that passes through the item and is detected by the detector, which reconstructs the image for analysis. During this process, the operator visually monitors the baggage and guides individuals as necessary [1, 2].

However, differences in baggage shape and size can cause mechanical issues such as curtain entanglement or belt jams. When this occurs, the entry sensor may continue to recognize the presence of baggage, causing continuous X-ray emission. In such cases, the lead curtain may rest on top of the baggage, and radiation leakage can occur through gaps or low-density materials such as cardboard boxes. This may lead to unnecessary radiation exposure to nearby operators. These incidents are relatively common, particularly when the items are large but lightweight. Consequently, scattered radiation may penetrate through the baggage and leak toward the operator, increasing the risk of exposure [3].

In this study, to scientifically evaluate such exposure scenarios, we used MCNPX (Monte Carlo N-Particle eXtended) v2.7, developed by Los Alamos National Laboratory (USA), and the HDRK-Man computational phantom, developed based on the average Korean adult male and certified by the International Commission on Radiological Protection (ICRP) [4-6]. We assessed both the leakage radiation dose and the corresponding occupational exposure dose to the operator. Furthermore, we designed a push-type shielding door system that fundamentally resolves this issue by minimizing worker exposure while maintaining compliance with domestic radiation safety regulations and operational efficiency.

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2. Materials and Methods

2.1. Geometric Modeling of the X-ray Security Inspection System

As shown in Fig. 1, the X-ray scanner setup used in this study represents a commonly used 160 kV, 0.6 mA cabinet-type system in Korea, certified under the Nuclear Safety Act (surface dose ≤ 10 μSv/hr). X-rays are generated by a tungsten target, and their generation efficiency is approximately 1 to 2% at 150 kV or higher. The internal shielding curtain was modeled with a lead-equivalent thickness of 0.5 mm Pb. The operational process is as follows: the item (A) moves on the conveyor belt, passes through the shielding curtain (B), and activates the entry sensor (C), triggering the X-ray generation (D). The transmitted X-rays are then detected (E) and reconstructed into an image (F). Typically, two security personnel are involved — Operator A monitors the X-ray image, while Operator B stands near the entry point (position A) to visually observe and assist with baggage flow and passenger movement.

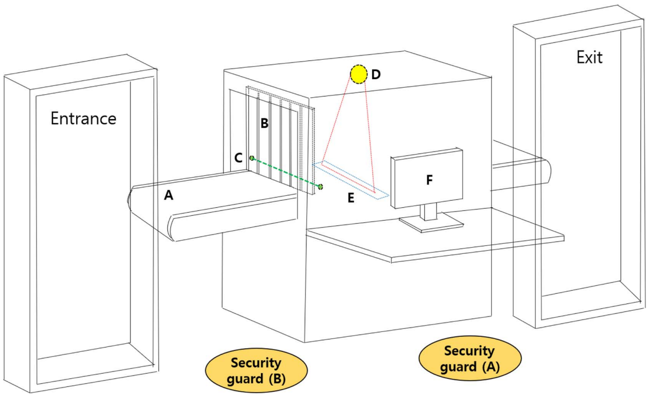

Fig. 1. (Color online) Example of the structure and security personnel positions of an X-ray security screening system.

2.2. Evaluation of Radiation Exposure in Baggage Jamming Scenarios

For conservative estimation, a large, low-density cardboard box was modeled as being stuck in the lead curtain. The curtain opening ratio was varied from 0% (fully closed) to 100% (fully open) in 20% increments, and the corresponding dose rate at the equipment surface and at the worker's position was simulated. As shown in Fig. 2, the radiation exposure was evaluated using MCNPX v2.7 coupled with the HDRK-Man phantom to determine both leakage radiation and operator dose under various obstruction conditions. The position of the proximity worker is -80 cm in the x-axis and 50 cm in the z-axis from the center of the x-ray source. The worker's radiation dose is calculated as the Tally 6 value (Jerk/g) in the simulation, which represents the energy absorbed per unit mass per photon. This value, in turn, is divided by the simulated value to obtain the normalized factor (NF) for the number of photons irradiated to the target, as

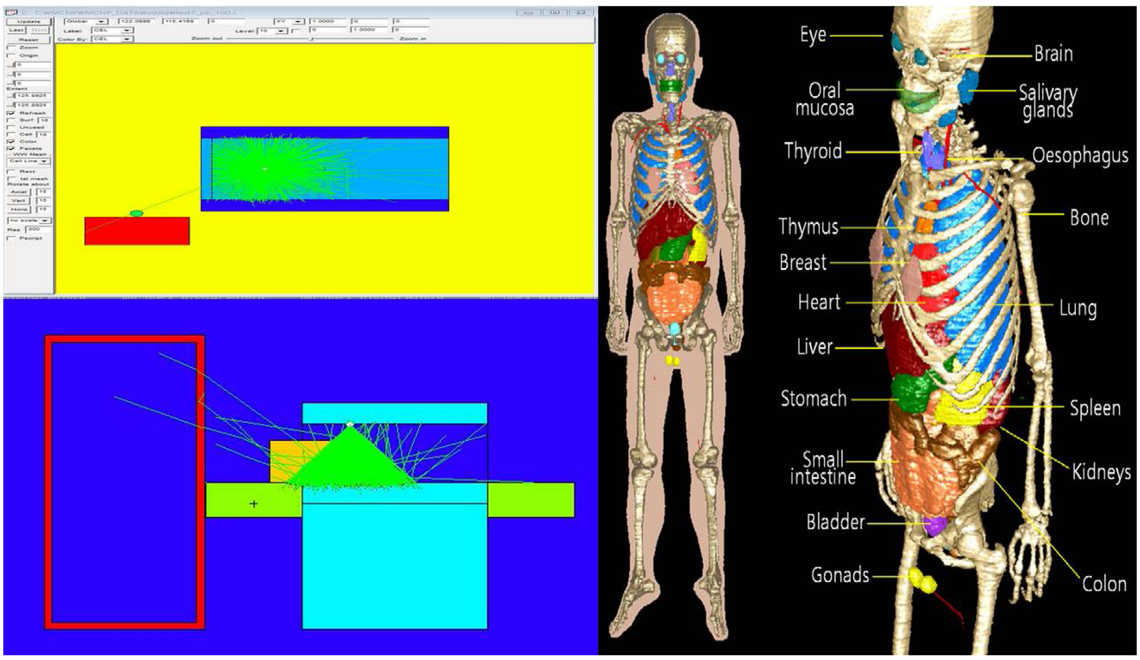

Fig. 2. (Color online) Monte Carlo simulation setup using MCNPX v2.7 (Los Alamos National Laboratory) and HDRK-Man computational phantom (Korean adult male, Hanyang Univ., Prof. Kim).

calculated by dividing the measured air kerma value under the same X-ray irradiation conditions by the simulated value. This value is the ratio of the actual measured value to the quantitative concept of the probability value per simulated photon. Finally, the effective dose was calculated by applying the tissue weighting factor value of ICRP 103 for each organ to the simulated absorbed dose value.

2.3. Design and Shielding Performance Evaluation of the Push-Type Shielding Door

The proposed push-type shielding door system aims to automatically push jammed baggage into the inspection tunnel while minimizing operator radiation exposure. Therefore, it must ensure sufficient structural strength, comply with shielding performance standards defined by the Nuclear Safety Act, and maintain lightweight design for cost and mechanical efficiency. The optimal shielding material composition and thickness were determined using MCNPX simulations.

3. Results and Discussion

3.1. Operator Exposure Evaluation under Baggage Jamming Conditions

As shown in Table 1, when baggage was jammed, the measured radiation dose rate at the scanner's entrance surface was 0.22 mSv/hr with the lead curtain fully open and 0.01 mSv/hr when fully closed approximately a 32-fold difference. As shown in Table 2, at the operator's position, the corresponding dose rates were 22.69 μSv/hr (open) and 0.7 μSv/hr (closed), again showing a 32-fold variation. Assuming an operator works 1 hour/day, 200 days/year under the worst-case (fully open) condition, the annual dose would reach 4.5 mSv, exceeding the 1 mSv/year limit for members of the public under the Nuclear

Table 1. Radiation dose rate at the X-ray scanner entrance surface according to lead curtain opening.

Open ratio of lead curtain (%)	Photon praction (Jerk/g/hr)	mSv/hr	uSv/hr
100%	1.44.E-22	0.22	215.22
80%	1.42.E-22	0.21	212.78
60%	1.37.E-22	0.20	204.14
40%	1.18.E-22	0.18	176.17
20%	9.06.E-23	0.14	135.37
0%	4.54.E-24	0.01	6.79
Max-Min	1.39.E-22	0.21	208.43
Max/Min	31.71		

Table 2. Operator B radiation dose rate according to lead curtain opening.

Open ratio of lead curtain (%)	mSv/hr	uSv/hr
100%	0.023	22.69
80%	0.022	22.39
60%	0.022	21.71
40%	0.017	17.22
20%	0.009	9.21
0%	0.001	0.71

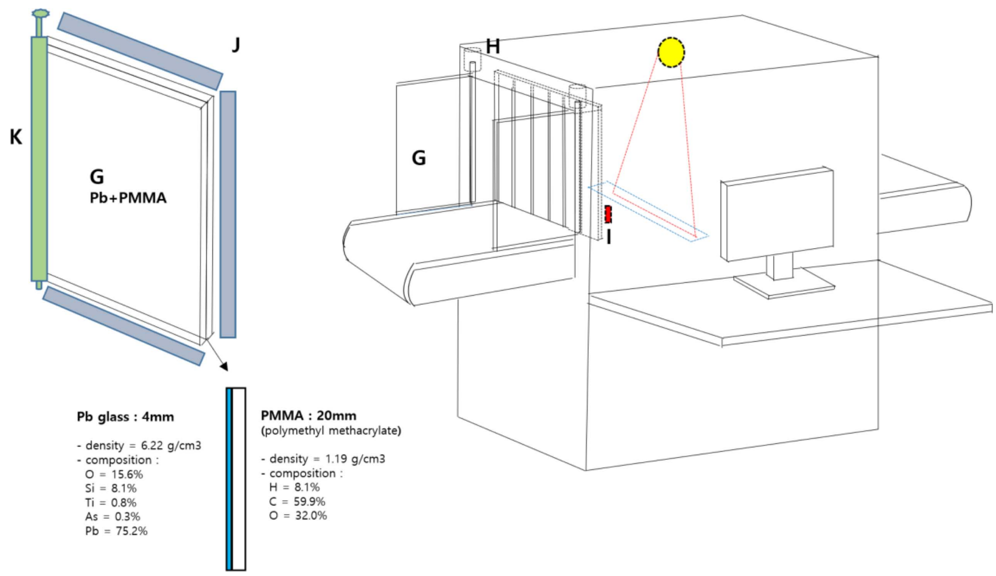

Fig. 3. (Color online) X-ray security inspection system with push-type shielding door: operational process when a baggage jam occurs.

Safety Act by approximately 4.5 times.

Although such X-ray inspection devices are regulated, they are classified as reportable devices rather than licensed sources, leading to less stringent operational and exposure management. Given that even low-energy radiation can cause significant cumulative effects with repeated exposure, there is a high potential risk of over-exposure accidents. Recent domestic cases of occupational radiation overexposure during maintenance work further emphasize the need for safer inspection system designs.

3.2. Shielding Performance Evaluation Results of the Push Shielding Door

As shown in Fig. 3, the newly developed push-type shielding door operates automatically when the entry sensor detects baggage but the motion sensor (I) does not, indicating a jam. The door, driven by an electric motor, gently pushes the baggage inward to resume smooth inspection. When the continuous mode is activated, the door can also operate independently of the motion sensor for maintenance or repeated inspection tasks as designed in Fig. 4.

Since lead glass is expensive, the door structure was optimized via simulation to meet the surface dose limit of 10 μSv/hr, qualifying it as a fully shielded type. As shown in Table 3, the final configuration consisted of 4 mm lead glass (Pb 75.2%, O 15.6%, Si 8.1%, Ti 0.8%, As 0.3%) and 20 mm PMMA (polymethyl methacrylate), supported by stainless steel framing connected to the motor shaft. To minimize impact and leakage, 0.5 cm thick Bi-containing rubber was attached to the remaining three sides of the door. This study was conducted based on the composition of the most commonly used radiation shielding lead glass. Future research is warranted to explore the optimal effects of varying the composition of lead glass.

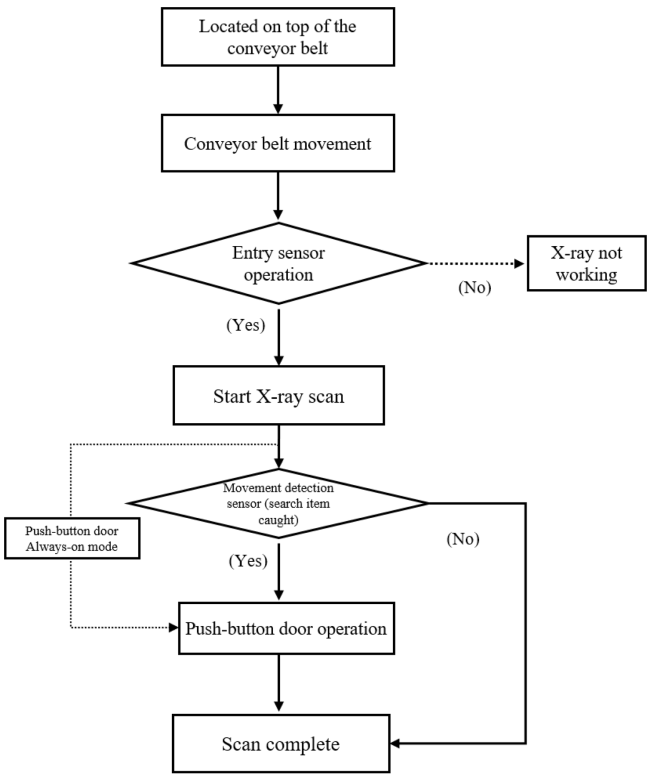

Fig. 4. Operational process of the X-ray inspection system with push-type/electric shielding door.

This X-ray inspection system is regulated under the Nuclear Safety Act of the Republic of Korea; however, it is classified as a “reportable” rather than a “licensable” device, resulting in a relatively lower level of regulatory control. The system can also be operated by non-experts, and it is excluded from the legal requirements for radiation exposure management. Consequently, any operational or movement error of the system could potentially lead to radiation overexposure accidents.

Although the radiation energy generated by the device is relatively low, repeated and continuous unnecessary exposure can accumulate over time, posing significant health risks. In fact, a serious radiation accident was recently reported in a domestic company, where a worker was exposed to radiation for an extended period during maintenance work on a reportable X-ray device. These incidents highlight the urgent need for research aimed at improving the safety of X-ray inspection systems.

Therefore, this study aims to develop an efficient and safe X-ray inspection system designed to prevent luggage transport errors at shielding curtains, reduce worker radiation exposure, and enhance image quality. The outcomes of this research have been filed for a Korean patent (Patent no. 10-2025-0122841) and are currently under registration review [7].

Table 3. Evaluation of radiation dose rate for selecting optimal lead glass thickness.

Thickness of lead glass (mm)	Photon praction (Jerk/g/hr)	mSv/hr	uSv/hr
1	1.29.E-32	0.02	19.28
2	3.69.E-33	0.006	5.523
3	1.02.E-33	0.002	1.521
4	4.19.E-34	0.001	0.627
5	2.29.E-34	0.000	0.343
6	1.72.E-34	0.000	0.257
7	1.67.E-34	0.000	0.249
8	1.48.E-34	0.000	0.222
9	1.06.E-34	0.000	0.159
10	6.03.E-35	0.000	0.090

Table 4. Maximum operator dose rate before and after push-type shielding door installation.

Open ratio of lead curtain (%)	mSv/hr	uSv/hr
Before Pb glass door installation	0.023	22.69
After Pb glass door installation	0.00006	0.06
difference in value	0.023	22.627
shielding ratio	99.7%	

4. Conclusion

This study proposed a novel X-ray security inspection system to mitigate radiation exposure caused by baggage jams and conveyor malfunctions. As shown in Table 4, under conventional systems, the maximum measured operator dose rate reached 22.69 μSv/hr, whereas the application of the new system reduced it to 0.06 μSv/hr, achieving a 99.7% shielding efficiency. In addition to substantially lowering occupational radiation exposure, the system is expected to enhance image stability by reducing irregular motion errors during inspection.

Acknowledgments

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