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Comparison of Experiments and Simulations to Estimate Deviations in Lead Equivalent in Radiation-Protection Devices

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Abstract

Background/Objectives: The purpose was to estimate deviation in lead equivalents when radiation-protection devices were exposed to the energy range that encompasses medical diagnostic conditions through an experimental and a simulation(GATE).

Methods/Statistical analyses: Deviations in lead equivalent of 0.25, 0.50, 0.75, and 1.00 mmPb were made at thicknesses of 0.02, 0.02, 0.03, and 0.05 mmPb, respectively, to irradiate the energy corresponding to a tube voltage of 90, 100, 110, and 120 kV with a distance (SDD) of 100 cm between the source and detector. Results were normalized for each reference lead equivalent by comparing and analyzing between the experiment and the simulation.

Findings: Experiments and simulations showed that lower lead equivalents of radiation-protection devices and higher tube voltages were associated with greater differences in radiation penetration rates, depending on unit thickness deviation. For the lead equivalent of 0.25 mmPb, the difference between experiment and simulation for all energy levels averaged 2.59% when deviation occurred at 0.02 mmPb intervals, 2.56% for 0.50 mmPb, 1.29% for 0.75 mmPb, and 1.91% for 1.00 mmPb. These results confirm for each parameter that the rate of penetration that a radiation-protection device wearer can receive in the event of a lead equivalent deviation is significantly increased. Studies on shielding by lead equivalent that evaluated X-rays and γ-rays, which are a mono energy, and studies assessing the degree of harm caused by deviation in lead equivalent in terms of radiation dose are needed.

Improvements/Applications: In this study, we propose a reliability evaluation method for verification and development of shielding materials using simulation tools when experimental options are restricted due to conditions.

***Keywords*:** Radiation-protection devices, Lead equivalent, Deviation, GATE, Comparison

1. Introduction

Photons (X, γ-rays) are a type of electromagnetic wave and are defined as electromagnetic radiation. Radiation with both wave and particle properties gradually loses energy and passes through material after interaction with constituent atoms of the material when they collide. These radiation effects are both non-stochastic and stochastic and can be harmful to the human body. Non-stochastic effects include the presence of threshold values and an apparent causal relationship between exposure dose and disability degree, resulting in loss of function, failure, and death of tissues or organs. Stochastic effects are typical of cancer incidence and genetic disorders because they do not have a threshold and the probability of exposure and disability are proportional but have nothing to do with disability degree.

Radiation-protection devices are important medical equipment that can protect the human body from scattered radiation, and are commercially available in various shapes and lead equivalents depending on the target area and energy used by medical personnel, practitioners, and patients. The number of radiation-involved applications is increasing annually in various fields, including industry and medical care, which highlights the need to manufacture safe and effective radiation-protection devices for human use.

Several studies have demonstrated the importance of radiation-protection devices in industrial and medical fields in which radiation is commonly used. Yoo et al. quantitatively examined the uniformity and shielding rate of several aprons used in general hospitals. They found that the shielding rate of the upper apron part was reduced when stored on a hanger[1-3]. Concern persists over the non-uniformity of lead equivalent in devices that determine the degree of shielding to the human body, and the resulting difference in radiation penetration is not known.

Therefore, in this study, radiation-protection devices with lead equivalents of 0.25, 0.50, 0.75, and 1.00 mmPb, which are widely sold on the market, were set to unit-thickness deviations of 0.02, 0.02, 0.03, and 0.05 mmPb, respectively, in an environment where they were exposed to the photo energy range of diagnostic contexts. We also experimented with a number of lead sheets of 0.03 mm–0.05 mm, and conducted Monte Carlo simulations using the GATE (Geant4 application for tomographic emission, v8.0) tool, which is based on Geant4 code.

2. Materials and Methods

Radiation-protection devices used in various fields are subject to lead equivalents of varying values from 0.25 mmPb to 1.00 mmPb, depending on the target area and photon energy used. In the experiments and simulations conducted in this study, thickness parameters were changed and the differences in the radiation penetration rate were compared by decreasing the lead equivalent in units of 0.02, 0.02, 0.03, and 0.05 mmPb, respectively (Table 1). Additionally, the tube voltage was set to 90, 100, 110, and 120 kV; all values fall within the 40 kV–150 kV diagnostic energy range. Simulations used the energy spectrum calculation program, TASMIP (Tungsten anode spectral model using interpolating polynomials). The distance (SDD) between the source and the detector was set to 100 cm.

Table 1: Thickness parameters for reference lead equivalent of radiation-protection devices

Lead equivalent (mmPb)			
0.25	0.50	0.75	1.00
0.23	0.48	0.72	0.95
0.21	0.46	0.69	0.90
0.19	0.44	0.66	0.85
	0.42	0.63	0.80

2.1. *Monte Carlo Simulation (GATE)*

To compare with the experimental output, Monte Carlo simulation general code, Geant4-based GATE version 8.0, was used. Originally developed to simulate high-energy physical experiments, Geant4 codes are widely used in many modern medical and industrial fields, including space navigation, radiation defense, and biology, but they are built using C++ language, which limits their accessibility to the general public. To overcome these limitations, GATE was developed in 2004 for the healthcare arena and has been continuously updated and remains highly reliable[4,5].

In the simulations for this study, the detector was set up as a virtual substance consisting of a full absorber (density = 999.9 g/cm^3) and placed behind the lead phantom to detect lead-penetrated radiation. The release angle of the source was then adjusted into the detector to minimize radiation leakage from the beam[6].

2.2. *Experiment*

The X-ray tube for digital radiography (DR) used in the experiment was the LTN-25(E7239X) (TOSHIBA Japan; Figure 1). Errors were minimized by entering the various equipment characteristics into the GATE simulation code, including inherent filtering (0.9 mmAl) and a series of operating tube voltages within the range of 40 kV–125 kV.

Figure 1. X-ray tube (LTN-25(E7239X), TOSHIBA, JAPAN)

Radiation dose (rate) is mainly measured using either semiconductor detectors with a solid or gas ionization reaction, ion chamber, proportional counter, and Geiger-Muller (GM) counter or with a thermoluminescence dosimeter (TLD) and scintillator dosimeters based on luminescence principles of materials. In this experiment, a multi-function meter using gas ionization (IBA, Germany), was used (Figure 2).

Figure 2. MagicMax Universal multimeter, IBA, GERMANY

After fixing the distance between the source and the detector to 100 cm (Figure 3), the default values for lead equivalent at 0 mmPb (when lead sheet was not taken into account) were measured first, and density (11.34 g/cm^3), size (10 x 10 cm^2, overlapping with lead sheets of 0.03 mm–0.05 mm thickness), and average values for lead equivalent were recorded three times from the same structure.

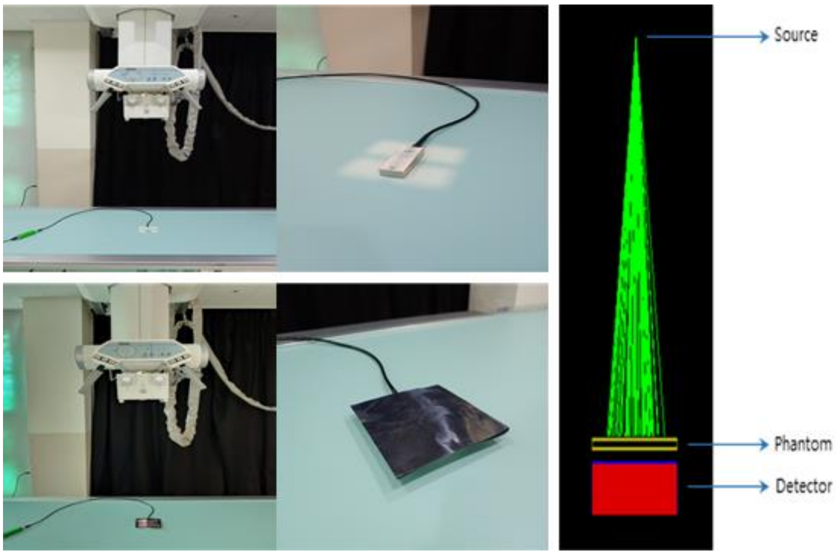


Figure 3. Experiment (left) and GATE (right) structures for measuring penetration rates

3. Results and Discussion

The radiation penetration rate by unit of thickness deviation from the reference lead equivalent of the radiation-protection devices was compared and analyzed between the experimental and GATE outputs, and the results were normalized for each reference lead equivalent.

At 0.25 mmPb, results were obtained by gradually decreasing the lead equivalent by the 0.02 mmPb unit thickness deviation (Table 2). Experiments showed a 13.8% increase in the radiation penetration rate at 0.23 mmPb, 20.4% at 0.21 mmPb, and 41.5% at 0.19 mmPb, compared with the 0.25 mmPb at 90 kV reference, respectively. For GATE simulations, increases were 11.1%, 23.8%, and 38.6%. At 100 kV tube voltage, the experiment yielded 12.5%, 27.9%, and 36.1% increases for 0.23 mmPb, 0.21 mmPb, and 0.19 mmPb respectively, and increased widths of 10.4%, 22.2%, and 35.8% were observed from GATE simulations. Tube voltage at 110 kV yielded 12.5%, 27.7%, and 34.9% increases for the experiments, and 10.1%, 21.6%, and 34.8% for the GATE simulations. For each lead equivalent, tube voltage at 120 kV yielded penetration rate increases of 10.2%, 25.1%, and 32.9% for the experiments and 10.0%, 21.3%, and 34.3% for GATE simulations.

Table 2: Comparison of penetration rate (%) errors with changes in unit thickness deviation by 0.02 mm (Lead equivalent reference = 0.25 mmPb)

kV / mmPb	90		100		110		120	
	Ex	GATE	Ex	GATE	Ex	GATE	Ex	GATE
0.23	13.8	11.1	12.5	10.4	12.5	10.1	10.2	10.0
0.21	20.4	23.8	27.9	22.2	27.7	21.6	25.1	21.3
0.19	41.5	38.6	36.1	35.8	34.9	34.8	32.9	34.3

The increases in the radiation penetration rates in the experiments and GATE simulations according to a thickness deviation of 0.02 mmPb from the reference lead equivalent of 0.25 mmPb were similar (Figure 4), with a maximum error of 6.1% and a minimum error of 0.1%.

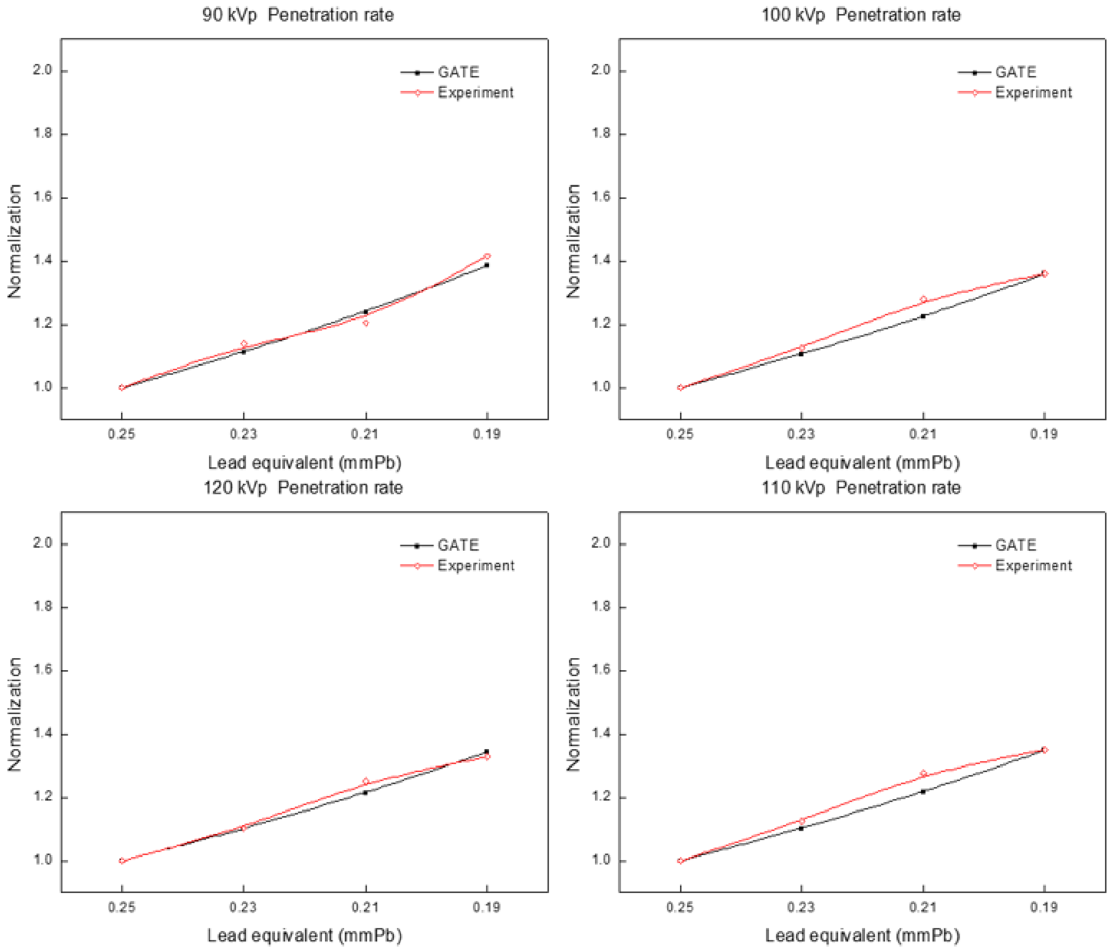


Figure 4. Comparison of penetration rate errors with changes in unit thickness deviation by 0.02 mm (Lead equivalent reference = 0.25 mmPb)

Likewise, in the case of a lead equivalent of 0.50 mmPb, results were obtained by gradually decreasing the lead equivalent by 0.02 mmPb of unit thickness (Table 3). Experiments yielded an 11.4% increase at a radiation penetration rate of 0.48 mmPb, 15.9% at 0.46 mmPb, 29.8% at 0.44 mmPb, and 43.4% at 0.42 mmPb, compared with 0.50 mmPb at 90 kV, respectively. Meanwhile, GATE simulations yielded increases of 8.3%, 17.3%, 27.3%, and 38.4%, respectively. At 100 kV of tube voltage, the experiments yielded 10.5%, 13.8%, 27.8%, and 38.6% increases for 0.48 mmPb, 0.46 mmPb, 0.44 mmPb, and 0.42 mmPb respectively. Increased widths of 7.9%, 16.5%, 25.9%, and 36.3% were observed in GATE simulations. Tube voltage at 110 kV yielded 11.1%, 14.1%, 27.1%, and 38.5% increases in the experiments, while GATE simulations yielded 7.7%, 16.2%, 25.5%, and 35.8% increases. Finally, tube voltage at 120 kV yielded increases in penetration rates of 11.3%, 15.0%, 27.8%, and 38.6% for experiments and 7.8%, 16.3%, 25.7%, and 35.9% for GATE simulations.

Table 3: Comparison of penetration rate (%) errors with changes in unit thickness deviation by 0.02 mm (Lead equivalent reference = 0.50 mmPb)

kV mmPb	90		100		110		120	
	Ex	GATE	Ex	GATE	Ex	GATE	Ex	GATE
0.48	11.4	8.3	10.5	7.9	11.1	7.7	11.3	7.8
0.46	15.9	17.3	13.8	16.5	14.1	16.2	15.0	16.3
0.44	29.8	27.3	27.8	25.9	27.1	25.5	27.8	25.7
0.42	43.4	38.4	38.6	36.3	38.5	35.8	38.6	35.9

The increases in the radiation penetration rates in experiments and GATE simulations according to thickness deviations ranging from 0.02 mmPb from 0.50 mmPb were similar (Figure 5) and yielded maximum and minimum errors of 5.0% and 1.3%, respectively.

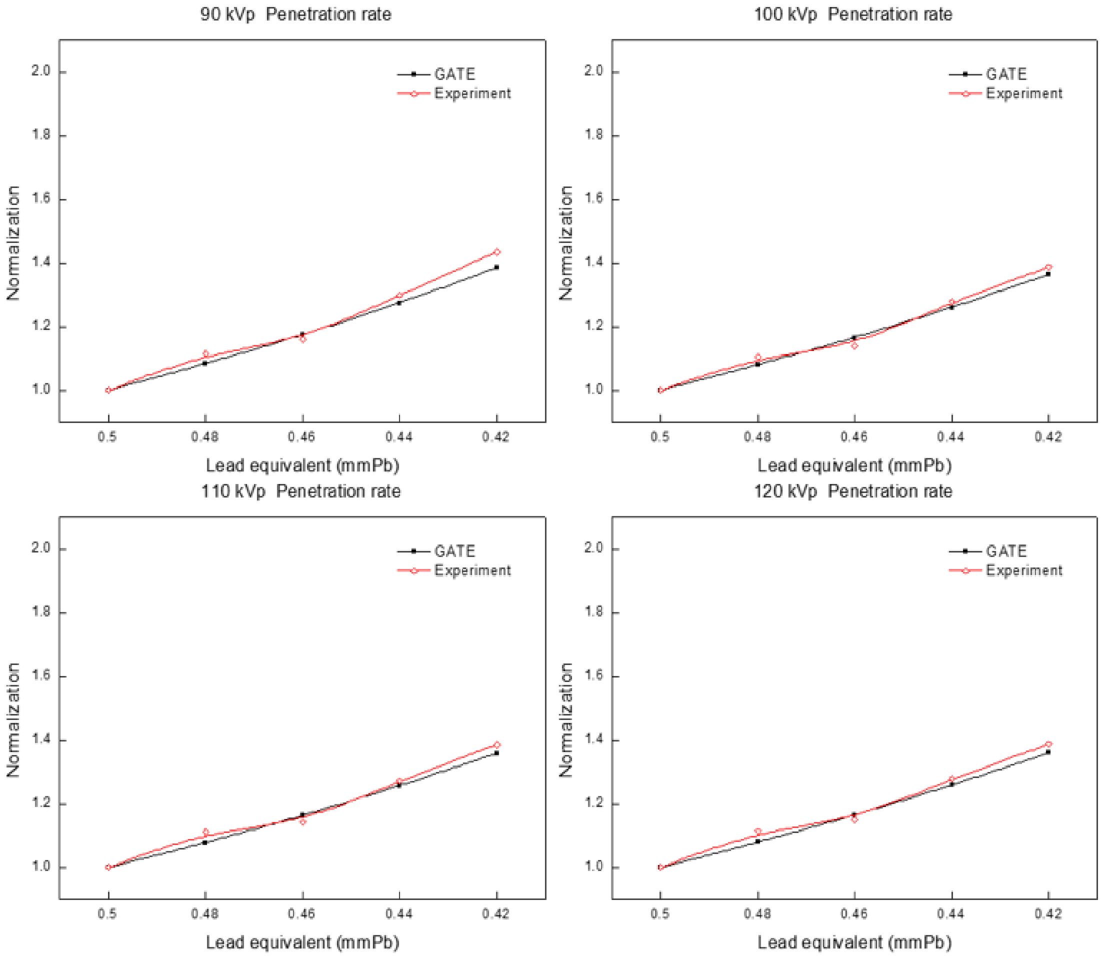


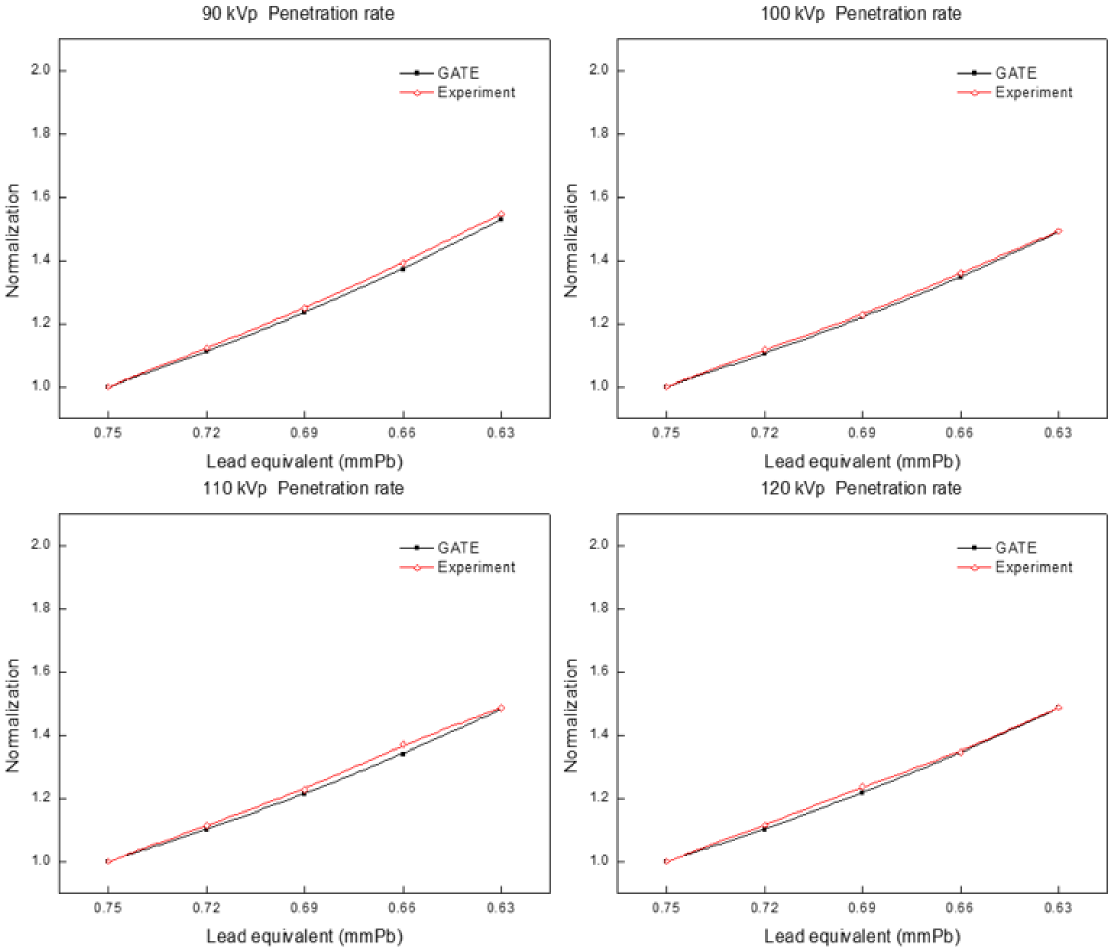
Figure 5. Comparison of penetration rate errors with changes in unit thickness deviation by 0.02 mm (Lead equivalent reference = 0.50 mmPb)

Using the lead equivalent reference of 0.75 mmPb, deviations in unit thickness of 0.03 mmPb were experimentally explored and simulated (Table 4), and accounted for a shielding rate that was higher than the previous lead equivalent. Experiments with 90 kV tube voltage yielded 12.2% increases at 0.72 mmPb, 24.7% at 0.69 mmPb, 39.2% at 0.66 mmPb, and 54.8% at 0.63 mmPb, compared with 0.75 mmPb. Meanwhile, GATE simulations yielded increases in the radiation penetration rate of 11.0%, 23.3%, 37.2%, and 52.8%. At 100 kV tube voltage, 11.7%, 22.6%, 36.0%, and 49.2% increases were observed from each lead equivalent reference of 0.72 mmPb, 0.69 mmPb, 0.66 mmPb, and 0.63 mmPb, respectively. GATE simulations yielded 10.3%, 21.8%, 34.5%, and 49.0% increases for the respective lead equivalent values. At 110 kV, the experiments yielded increases of 11.5%, 22.7%, 37.0%, 48.7%, and GATE simulations yielded increases of 10.1%, 21.4%, 34.0% and 48.2%. Finally, at 120 kV tube voltage, experiments yielded 11.5%, 23.6%, 34.6%, 48.8% increases and GATE simulations yielded 10.2%, 21.6%, 34.3%, and 48.5% increases.

Table 4: Comparison of penetration rate (%) errors with changes in unit thickness deviation by 0.03 mm (Lead equivalent reference = 0.75 mmPb)

kV / mmPb	90		100		110		120	
	Ex	GATE	Ex	GATE	Ex	GATE	Ex	GATE
0.72	12.2	11.0	11.7	10.3	11.5	10.1	11.5	10.2
0.69	24.7	23.3	22.6	21.8	22.7	21.4	23.6	21.6
0.66	39.2	37.2	36.0	34.5	37.0	34.0	34.6	34.3
0.63	54.8	52.8	49.2	49.0	48.7	48.2	48.8	48.5

The increases in the penetration rates in experiments and GATE simulations according to a thickness deviation of 0.03 mmPb compared with the reference lead equivalent of 0.75 mmPb were similar (Figure 6), yielding maximum and minimum errors of 3.0% and 0.2%, respectively.



90 kVp Penetration rate

100 kVp Penetration rate

110 kVp Penetration rate

120 kVp Penetration rate

Figure 6. Comparison of penetration rate errors with changes in unit thickness deviation by 0.03 mm (Lead equivalent reference = 0.75 mmPb)

Experiments and GATE simulations were conducted using the 1.00 mmPb lead equivalent reference for each 0.05-mmPb unit thickness deviation, taking into account the high shielding rate of the lead equivalent. At 90 kV tube voltage, for the lead equivalent values 0.95 mmPb, 0.90 mmPb, 0.85 mmPb, and 0.80 mmPb, experiments yielded increases of 17.5%, 41.3%, 61.4%, and 88.1%, respectively, and GATE simulations yielded increases of 17.0%, 36.7%, 60.7%, and 89.5%. At 100 kV tube voltage, experiments yielded increases of 16.7%, 37.8%, 56.7%, 80.4%, and GATE simulations yielded increases of 16.1%, 34.9%, 57.4%, and 84.1%. At 110 kV tube voltage, experiments yielded increases of 15.1%, 36.6%, 53.6%, and 78.1%, and GATE simulations yielded increases of 15.5%, 34.1%, 55.8%, and 81.5%. Finally, at 120 kV tube voltage, experiments yielded increases of 16.3%, 37.8%, 55.0%, and 80.3%, and GATE simulations yielded increases of 15.5%, 33.8%, 55.8%, and 81.7%.

Table 5: Comparison of penetration rate (%) errors with changes in unit thickness deviation by 0.05 mm (Lead equivalent reference = 1.00 mmPb)

kV / mmPb	90		100		110		120	
	Ex	GATE	Ex	GATE	Ex	GATE	Ex	GATE
0.95	17.5	17.0	16.7	16.1	15.1	15.5	16.3	15.5
0.90	41.3	36.7	37.8	34.9	36.6	34.1	37.8	33.8
0.85	61.4	60.7	56.7	57.4	53.6	55.8	55.0	55.8
0.80	88.1	89.5	80.4	84.1	78.1	81.5	80.3	81.7

The increases in radiation penetration rates in experiments and GATE simulations according to a thickness deviation of 0.05 mmPb compared with the reference lead equivalent of 1.00 mmPb were similar (Figure 7), and they yield maximum and minimum errors of 4.6% and 0.4%, respectively.

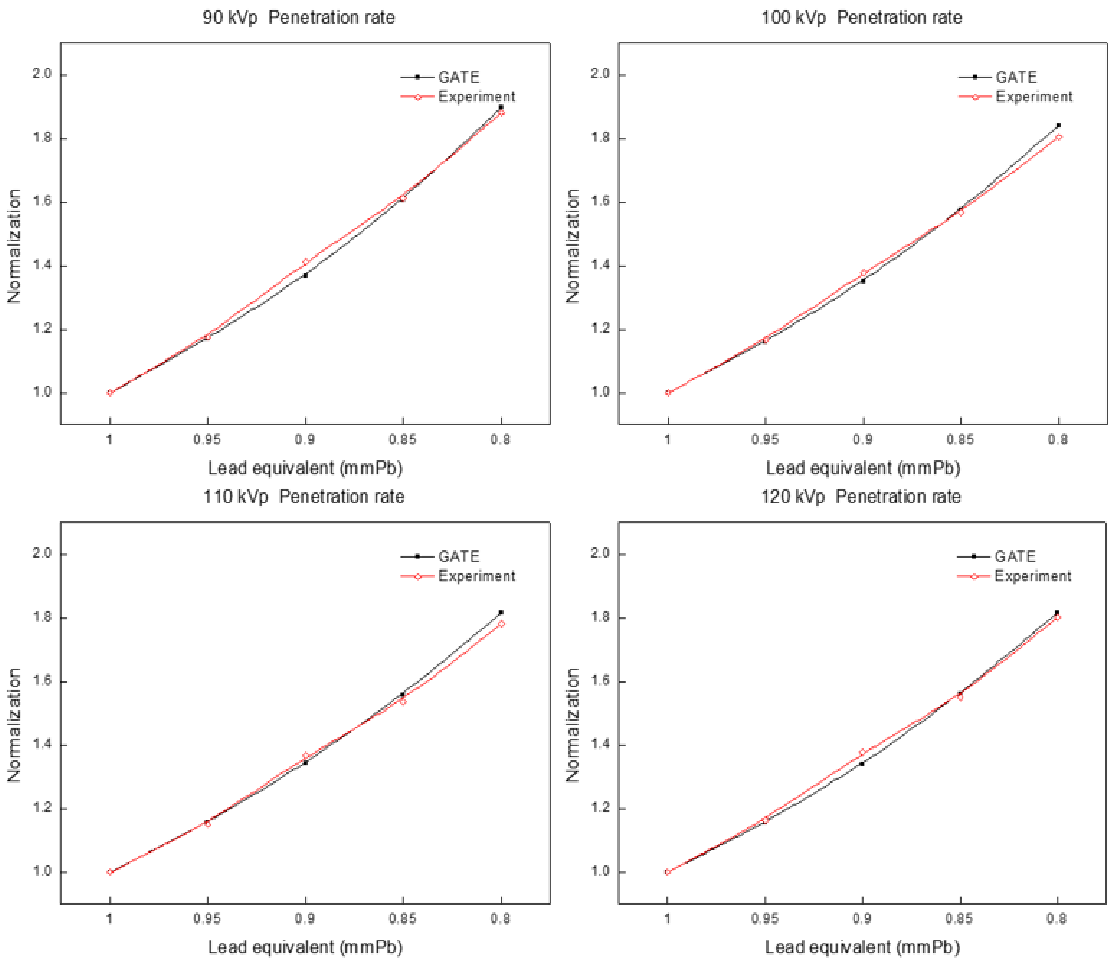


Figure 7. Comparison of penetration rate errors with changes in unit thickness deviation by 0.05 mm (Lead equivalent reference = 1.00 mmPb)

The purpose of this study was to compare and analyze the lead equivalents of commercially available radiation-protection devices through both experimental methods and GATE simulations. For a lead equivalent of 0.25 mmPb, which is 10%–20%, radiation penetration in the diagnostic energy range was observed to increase by an average of 11.3%, 23.8%, and 36.1% for each 0.02-mmPb deviation in thickness, and by an average of 9.5%, 15.6%, 27.1%, and 38.2% for each 0.50-mmPb unit deviation. The lead equivalent reference of 0.75 mmPb increased by an average of 11.1%, 22.7%, 35.9%, and 50.0% for each unit deviation and the lead equivalent of 1.00 mmPb increased by an average of 16.2%, 36.6%, 57.1%, and 83.0%[7].

It was also shown that as lead equivalents of the radiation-protection devices decreased and as tube voltage increased, the difference in radiation penetration rates increased according to unit thickness deviation. These results confirmed for each lead equivalent parameter that when deviation thickness occurs in the lead equivalent of shielding devices for specific target areas and of various energies, the penetration rate, which can have a harmful effect on the human body, can increase greatly.

The average error rate between the experiments and GATE simulations is surprisingly consistent (2.05%), given the numerous factors that can affect radiation penetration rate results, such as Monte Carlo simulation codes, differences in calculation methods, and errors in stochastic statistical variations[8-10].

4. Conclusion

Radiation plays an important role in a variety of occupations, including industry and health care, however, radiation exposure can also have harmful effects that must be considered. Radiation-protection devices are the first line of protection for people in all fields that utilize radiation, and wearing this essential protective gear is recommended to prevent scattered radiation exposure. Comparative studies of experiments and Monte Carlo simulations (GATE) provided an opportunity to verify through simulation tools if future conditions constrain experimental environments. This study also demonstrated a reliable evaluation method for verifying and developing shielding materials. Future studies on shielding by lead equivalent should take into account mono-energy gamma rays and X-rays, and they should assess the degree of harm caused by errors in lead equivalents in terms of radiation dose.

5. Acknowledgment

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