LABORATORY INVESTIGATIONS

Radiation-Shielding Devices: The Best Combination for Spine Interventional Procedures

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ABSTRACT

Purpose: Although many studies have examined the efficiency of various protective devices for reducing the dose of radiation exposure to physicians during interventional pain procedures, no study has compared the protective effect of these devices when they are used in combination. The purpose of this prospective experimental study was to determine the best combination of radiation-shielding devices.

Materials and Methods: Using anthropomorphic phantoms of a physician and patient, we measured the radiation protection efficiency (RPE) of each of the following protection methods and in combination during C-arm–guided simulated lumbar epidural injection: (a) personal protective equipment (PPE), (b) bedside curtain shield (Curtain), (c) x-ray tube filter (Filter), and (d) fluoroscopic collimation method (Collimation). We measured exposure doses using personal electronic dosimeters at the eye, thyroid, and gonad levels for 1 minute. Each experiment was repeated 15 times.

Results: The radiation exposure dose and RPE with the best single-, double-, and triple-protection methods were as follows: PPE for the single-protection method (11.82 μSv/min, 80.04%), PPE + Collimation for the double-combination method (4.68 μSv/min, 92.09%), and PPE + Collimation + Curtain for the triple-combination method (3.08 μSv/min, 93.39%). Additionally, PPE + Collimation + Curtain + Filter for the quadruple-combination method resulted in a radiation exposure and RPE of 2.91 μSv/min and 93.61%, respectively, compared with nonprotection.

Conclusions: The best single-, double-, and triple-protection method was PPE, PPE + Collimation, and PPE + Collimation + Curtain, respectively. While preparing protective equipment, we recommend prioritizing equipment in this order.

ABBREVIATIONS

Collimation = fluoroscopic collimation method, CSE = combined-sum effectivity, Curtain = bedside curtain shield, Filter = x-ray tube filter, NP = nonprotection, PED-IS = personal electronic dosimeters-intrinsically safe, PPE = personal protective equipment, RPE = radiation protection efficiency, SSE = single-sum effectivity

The development of and advances in interventional pain medicine have resulted in various procedures being conducted under fluoroscopic guidance (1). Because of the increasing frequency and complexity of interventional procedures, pain physicians are now at risk of exposure to higher levels of ionizing radiation than they were in the past. Therefore, occupational exposure protection has become an increasingly important issue (1–3). A single radiation exposure dose to a physician is lower than that to a patient; however, repeated radiation exposure from multiple procedures on multiple patients increases the physician’s accumulated exposure dose.

According to the linear nonthreshold model adopted by the International Commission on Radiological Protection, the probability of a radiation-induced stochastic effect (eg,
RESEARCH HIGHLIGHTS

- This phantom study was conducted to determine the performance of radiation-shielding devices for spinal interventional procedures.
- Radiation protection efficiency (RPE) was measured for the following tools individually and in combination: personal protective equipment (PPE), bedside Curtain shield, x-ray tube Filter, and fluoroscopic Collimation.
- The best protection methods were: single device, PPE (80% RPE); double protection, PPE + Collimation (92% RPE); and triple protection, PPE + Collimation + Curtain (93% RPE). The effect of the Filter was not significant.
- These findings may inform equipment prioritization for spinal and other procedures requiring the proceduralist to be close to the field.

STUDY DETAILS

Study type: Laboratory study

human phantom, with a life-size synthetic skeleton embedded in a radiological soft tissue substitute. The phantom physician (height, 165 cm) was constructed with a human skeleton cast inside a urethane material with the same effective atomic number as the soft tissue in the human body. Because this study involved no human subjects, it was exempted from institutional review board approval.

Simulation Procedure

During the experiment, the phantom patient was placed in the prone position on the operating table. To simulate a physician performing a procedure, the phantom physician was placed next to the operating table 45 cm from the central line of the phantom patient and turned 30° toward the fluoroscopic monitor to make the situation more realistic (Fig 1a). After placing a C-arm fluoroscope (Ziehm Vision RFD; Ziehm Imaging GmbH, Nuremberg, Germany) on the right side of the phantom patient, an x-ray tube was placed at the bottom and a flat-panel detector placed above the phantom patient. The distance between the flat-panel detector and phantom patient was 30 cm. The center of the fluoroscopic beam was directed toward the interlaminar space of the fifth lumbar and first sacral vertebrae at a cephalic angulation of 20° to align the lower endplate of the fifth lumbar vertebrae. To compare collimation and non-collimation situations, the manual exposure rate control mode was used for a tube voltage of 88 kVp and tube current of 17 mA as the C-arm fluoroscopic operating parameters. These fixed operating parameters were calculated using the automatic exposure rate control mode, enabling optimal image quality in the noncollimation situation.

Measurement of Radiation Exposure Dose

Radiation dosimeters (Personal Electronic Dosimeters-Intrinsically Safe [PED-IS]; Tracerco Ltd., Billingham, United Kingdom) were attached to the phantom physician at the eye, thyroid, and gonad levels to measure the dose of radiation exposure at the most vulnerable regions of the operator’s body (Fig 1b). The PED-ISs were placed at 153, 139, and 84 cm from the floor to represent the eye, thyroid, and gonad levels, respectively. All PED-ISs were attached to the physician phantom’s left side and located inside PPE. The PED-ISs were calibrated using a personal dose equivalent of Hp (10), which is a deep-tissue dose at 10 mm from the skin and is defined by the International Commission on Radiation Units and Measurements (4) as “a dosimeter reading of a dose at a depth of 10 mm below the body surface of the human body.” To measure the mean level of radiation exposure doses, each measurement was performed for 1 minute, and each experiment was repeated 15 times.

MATERIALS AND METHODS

Study Design

This prospective experimental study used an anthropomorphic phantom physician (Rando; The Phantom Laboratory Inc., Salem, New York) and an anthropomorphic phantom patient (whole-body phantom PBU60; Kyoto Kagaku Co., Ltd., Kyoto, Japan). The phantom patient was a life-size cancer or hereditary effect) increases in proportion to the dose, even at <100 mSv. Therefore, it is recommended that all physicians be provided optimal protection according to the “as low as reasonably achievable” (ALARA) principle (4).

Several studies (5–7) have shown that radiation exposure can be reduced through protection methods in the following 3 categories: personal protective equipment (PPE) used by individuals, proper operation of C-arm fluoroscopy, and protection devices attached to the operating table or x-ray tube. Although it would be ideal to use these protective devices simultaneously, most hospitals do not have all these protective devices in actual clinical settings. Aside from being inconvenient during procedures, it is less cost effective to use all of them simultaneously. Therefore, many physicians use a combination of several of these protective devices. However, because of the lack of recommendations regarding their use, difficulties persist while choosing a combination of protective devices.

Although there are many studies regarding the efficiency of each protective device for reducing the dose of radiation exposure to a physician, no study has compared the protective effect of these devices when used in combination during spinal interventional procedures. Therefore, the aim of this study was to determine the most efficient combination of shielding tools without reducing the generating capacity of the x-ray tube and interfering with interventional procedures.
The radiation doses were measured using a Geiger-Müller tube. To calculate the PED-IS measurement, a radiation-weighting factor was used and the tissue-weighting factor at the thyroid and gonad levels was excluded because only whole-body radiation exposure was considered.

**Radiation-Shielding Methods**

We tested the following 4 different radiation-shielding methods in this experiment (Fig 2): (a) PPE, (b) a fluoroscopic collimation method (hereafter referred to as Collimation), (c) a bedside curtain shield (hereafter referred to as Curtain), and (d) an x-ray tube filter (hereafter referred to as Filter). For PPE, apron-thyroid protection (N-XR-2; Nicemedica, Goyang, Korea) and x-ray protective goggles (XR-700 Extra Wide; Toray Medical Co., Ltd., Tokyo, Japan) were used. For Collimation, a ratio of 7:3 (70% field of view, 30% shielding) was set as a function of C-arm fluoroscopy. A Curtain (N-XR-g-6; Nicemedica) was used, which was attached to both sides of the operating bed. In addition, a Filter (CVP-2; MS Line ENG Co., Ltd., Seoul, Korea) was attached to the x-ray tube. The lead equivalent of the apron’s front side, goggles, and Curtain was 0.5, 0.07, and 0.5 mm Pb, respectively.

**Comparison of Radiation-Reduction Methods: Single, Double, Triple, and Quadruple Protection**

A total of 12 combinations were compared by combining the following 4 protection methods: 4 single-protection methods (PPE, Collimation, Curtain, and Filter), 3 double-protection methods (PPE + Collimation, PPE + Curtain, and PPE + Filter), 3 triple-protection methods (PPE + Collimation + Curtain, PPE + Collimation + Filter, and PPE + Curtain + Filter), and 1 quadruple-protection method (PPE + Collimation + Curtain + Filter). Measurements using no protective methods was used as a control reference value in this study.

**Single-effectivity (SSE), combined-effectivity (CSE), and radiation protection efficiency (RPE)** were measured in this study. SSE is a value that assumes double- and triple-protection methods based on the theoretical sum of the efficiency of each single-protection method. In contrast, CSE is used to directly measure the efficiency of double-, triple-, or quadruple-protection methods. RPE is expressed as a percentage and used as a value of the protection efficiency of each single- or combined-protection method in comparison with that of no protection. Measured directly, CSE and RPE can be thought of as the same value.

**Statistical Analysis**

The Kolmogorov-Smirnov test was used to analyze the normality of the data. The Kruskal-Wallis test, followed by the Mann-Whitney U test with Bonferroni correction, was used for a post hoc analysis comparing the dose of radiation exposure and RPE with each protection method. SPSS version 20 (IBM, Armonk, New York), was used for statistical analysis. All data were presented as mean ± standard deviation. P values <.05 were considered statistically significant.

**RESULTS**

Without any protection methods, the radiation exposure dose at the eye, thyroid, and gonad levels was 53.59 μSv/min ± 1.26, 22.97 μSv/min ± 0.44, and 132.57 μSv/min ± 2.4, respectively. Table 1 demonstrates the RPE and total average radiation dose in the 3 critical organs used for each protection method, alone or in combination, as described below.

**The Best Single-Protection Method**

The best single-protection method and the corresponding radiation exposure dose at the eye, thyroid, and gonad levels were PPE (19.08 μSv/min ± 0.54), PPE (3.32 μSv/
Figure 2. The location and application method for each protective item used for dose reduction. Personal protective equipment (a), fluoroscopic collimation method (b), bedside curtain shield (c), and x-ray tube filter (d).

Table 1. Comparison of Radiation Protection Efficiency and Total Average Radiation Dose for All Critical Organs for Each Protection Method

<table>
<thead>
<tr>
<th>Shielding strategy</th>
<th>Average radiation dose (μSv/min)</th>
<th>Radiation protection efficiency (%)</th>
<th>Total average</th>
<th>Eye</th>
<th>Thyroid</th>
<th>Gonad</th>
</tr>
</thead>
<tbody>
<tr>
<td>NP</td>
<td>69.72 ± 46.72</td>
<td>NA</td>
<td>80.04</td>
<td>64.40</td>
<td>85.55</td>
<td>90.16</td>
</tr>
<tr>
<td>PPE</td>
<td>11.82 ± 4.95</td>
<td>80.04</td>
<td>64.40</td>
<td>85.55</td>
<td>90.16</td>
<td></td>
</tr>
<tr>
<td>Collimation</td>
<td>29.3 ± 24.35</td>
<td>59.79</td>
<td>60.71</td>
<td>62.58</td>
<td>56.08</td>
<td></td>
</tr>
<tr>
<td>Curtain</td>
<td>28.95 ± 4.09</td>
<td>32.28</td>
<td>3.38</td>
<td>3.12</td>
<td>90.34</td>
<td></td>
</tr>
<tr>
<td>Filter</td>
<td>55.47 ± 39.45</td>
<td>17.40</td>
<td>8.28</td>
<td>18.16</td>
<td>25.75</td>
<td></td>
</tr>
<tr>
<td>PPE + Collimation</td>
<td>4.68 ± 1.93</td>
<td>92.09</td>
<td>85.58</td>
<td>94.48</td>
<td>96.20</td>
<td></td>
</tr>
<tr>
<td>PPE + Curtain</td>
<td>7.96 ± 0.8</td>
<td>83.01</td>
<td>63.79</td>
<td>86.23</td>
<td>99.02</td>
<td></td>
</tr>
<tr>
<td>PPE + Filter</td>
<td>10.13 ± 3.4</td>
<td>82.02</td>
<td>67.13</td>
<td>86.16</td>
<td>92.77</td>
<td></td>
</tr>
<tr>
<td>PPE + Collimation + Curtain</td>
<td>3.08 ± 0.35</td>
<td>93.39</td>
<td>86.05</td>
<td>94.48</td>
<td>99.63</td>
<td></td>
</tr>
<tr>
<td>PPE + Collimation + Filter</td>
<td>4.27 ± 1.46</td>
<td>92.47</td>
<td>86.16</td>
<td>94.32</td>
<td>96.92</td>
<td></td>
</tr>
<tr>
<td>PPE + Curtain + Filter</td>
<td>6.26 ± 0.82</td>
<td>86.37</td>
<td>71.53</td>
<td>88.19</td>
<td>99.38</td>
<td></td>
</tr>
<tr>
<td>PPE + Collimation + Curtain + Filter</td>
<td>2.91 ± 0.43</td>
<td>93.61</td>
<td>87.24</td>
<td>93.96</td>
<td>99.63</td>
<td></td>
</tr>
</tbody>
</table>

Values are presented as means ± standard deviation.
Collimation = fluoroscopic collimation method; Curtain = bedside curtain shield; Filter = x-ray tube filter; NA = not applicable; NP = no protection; PPE = personal protection equipment.
The Best Double-Protection Method

The best double-protection method and the corresponding radiation exposure dose at the eye, thyroid, and gonad levels were PPE + Collimation (7.73 μSv/min ± 0.5), PPE + Collimation (1.27 μSv/min ± 0.27), and PPE + Curtain (1.3 μSv/min ± 0.16), respectively (Fig 3b). All the double-protection methods were statistically significant compared with other double-protection methods individually at all the levels (all \( P < .001 \)), except between PPE + Curtain and PPE + Filter at the thyroid level (\( P = .870 \)).

The Best Triple-Protection Method

The best triple-protection method and the corresponding radiation exposure dose at the eye, thyroid, and gonad levels were PPE + Collimation + Filter (7.42 μSv/min ± 0.5), PPE + Collimation + Curtain (1.27 μSv/min ± 0.17), and PPE + Collimation + Curtain (0.49 μSv/min ± 0.14), respectively (Fig 3c). All the triple-protection methods were statistically significant compared with other triple-protection methods individually at all the levels (all \( P < .001 \)), except between PPE + Collimation + Filter and PPE + Collimation + Curtain at the eye (\( P = .744 \)) and thyroid levels (\( P = .267 \)).

Quadruple-Protection Method

With the quadruple-protection method, the radiation exposure dose at the eye, thyroid, and gonad levels was 6.84 μSv/min ± 1.26, 1.39 μSv/min ± 0.3, and 0.49 μSv/min ± 0.07, respectively (Fig 3c). The quadruple-protection

The Best Single-Protection Method

The best single-protection method and the corresponding radiation exposure dose at the eye, thyroid, and gonad levels were PPE (12.81 μSv/min ± 0.71), and Curtain (12.81 μSv/min ± 0.71), respectively (Fig 3a). All the single-protection methods were statistically significant compared with other single-protection methods individually at all the levels (all \( P < .001 \)), except between PPE and Curtain at the gonad level (\( P = .325 \)).
method was statistically significant compared with PPE + Curtain + Filter at all the levels (all $P < .001$), PPE + Collimation + Filter at the eye and gonad levels ($P = .003$ and $P < .001$, respectively), and PPE + Collimation + Curtain at the eye level ($P < .001$). However, there were no significant differences compared with PPE + Collimation + Filter at the thyroid level ($P = .461$) and PPE + Collimation + Curtain at the thyroid and gonad levels ($P = .217$ and $P = .902$, respectively).

Comparison of SSE and CSE for Each Protection Method

Seven combined protection methods (3 double-protection, 3 triple-protection, and 1 quadruple-protection methods) demonstrated higher SSE than CSE in all 3 critical organs (Table 2). The maximum and minimum differences between SSE and CSE were detected with PPE + Collimation + Curtain + Filter at the gonad level (162.68%) and PPE + Curtain at the thyroid level (2.43%), respectively.

DISCUSSION

This study helped identify the best radiation-shielding method for single-, double-, and triple-combination protection methods. PPE + Collimation exhibited a sufficiently effective average RPE to reduce the dose of radiation exposure in the 3 critical organs, with an average reduction of 92.09%. For PPE + Collimation + Curtain + Filter, the most effective average RPE was 93.61%, which was only a 1.52% greater reduction than that for PPE + Collimation.

This study compared single-protection methods with a combination of such methods to achieve optimal protection without reducing the generating capacity of the x-ray tube and interfering with interventional pain management procedures. This study did not consider subjective values, such as the operator’s skill or education level, in terms of radiation reduction. Therefore, this study can provide physicians with an objective index of optimized protection methods.

This study showed that PPE, consisting of apron-thyroid protection and x-ray protective goggles, represented essential protection methods for the 3 critical organs, similar to the findings of previous studies (8–11). Among the single-protection methods, the PPE used by the personnel during fluoroscopy had the greatest RPE at the eye and thyroid levels (64.4% and 85.55%, respectively). In addition, there was only a small difference in RPE between PPE and Curtain at the gonad level, and this was not statistically significant. Based on these findings, it can be inferred that if the lead equivalent of a protective device is 0.5 mm Pb, similar RPE can be achieved at the gonad level, regardless of how close the protective device is to the body. Although the x-ray protective goggles used in this study showed a lesser lead equivalent than those used in previous studies (12), at 0.07 mm Pb, the protective goggles used showed an RPE of 64.4%. Nevertheless, many physicians do not wear x-ray protective goggles during daily procedures and do not shield their thyroid tightly enough because it is uncomfortable and there is no immediate perception of gain in using them (13). Thus, physicians must be made aware of the risk of radiation exposure as well as the correct way to wear apron-thyroid protection and x-ray protective goggles because all 3 organs (eye, thyroid, and gonad) are vulnerable to radiation (14,15).

The use of Curtain showed the best RPE at the gonad level (90.34%) but the lowest RPE at the eye and thyroid levels (3.38% and 3.12%, respectively). These findings suggest that Curtain is specialized only in gonad protection, which is in accordance with the findings of previous studies (16–18). Because physicians are exposed to radiation throughout their bodies during interventional procedures, an average RPE of Curtain of 32.28% is not efficient compared with that of other single-protection methods. Therefore, we recommend that Curtain be installed in combination with other single-protection methods to enhance RPE.

In this study, Filter showed the lowest average RPE compared with other single-protection methods. Because tilting the angles of the C-arm fluoroscope to align the end plates of the spine is more common than the use of a vertical angle, the RPE of Filter is decreased when used in interventional pain procedures. Moreover, Filter was the most expensive among the protective devices used in this study.
Therefore, only Filter is recommended after all other protective devices in spinal interventions that use various angles (tilting, oblique, and lateral angles) of C-arm fluoroscopy.

The use of Collimation can reduce radiation exposure to all critical organs as well as to both physicians and patients (19–21). Collimation is an essential method of reducing radiation exposure doses without interrupting interventional procedures, maintaining the generating capacity of the x-ray tube and, most importantly, without incurring extra cost (19). In addition, the improved image quality observed might be related to decreased secondary scattered radiation (19). Therefore, Collimation is strongly recommended as an effective protection method for reducing radiation exposure doses in both the patients and physicians as well as enhancing image quality.

Before the discussion of double-, triple-, and quadruple-protection methods, it is necessary to compare the theoretically calculated SSE with the actually measured CSE. Because SSE does not reflect the limitations of the clinical environment, it is commonly higher than CSE. In addition, the higher RPE of the combined protection strategies consequently resulted in a greater difference between SSE and CSE. Each of the best protection methods showed an average difference value: 47.7% (PPE + Collimation), 78.54% (PPE + Collimation + Curtain), and 95.75% (PPE + Collimation + Curtain + Filter). Thus, it is important to measure the actual radiation exposure dose for each combined protection method because of differences between SSE and CSE.

Among the double-protection methods, the average RPE of PPE + Collimation was higher than that of the other protective methods. Moreover, there was only a small average RPE difference (0.99%) between PPE + Curtain and PPE + Filter. These findings indicated that Curtain and Filter were not more efficient than Collimation when combined with PPE. These results demonstrated that PPE + Collimation was the best double-protection method, even without incurring any additional cost for protection. Therefore, it is necessary to use PPE + Collimation actively during all interventional pain procedures.

In terms of the triple- or quadruple-protection methods, the average RPE of PPE + Collimation + Curtain was higher than that of the other protective methods. Moreover, there was only a small average RPE difference (0.99%) between PPE + Curtain and PPE + Filter. These findings indicated that Curtain and Filter were not more efficient than Collimation when combined with PPE. These results demonstrated that PPE + Collimation + Curtain was the best double-protection method, even without incurring any additional cost for protection. Therefore, it is necessary to use PPE + Collimation actively during all interventional pain procedures.

In conclusion, the best protection method and average RPE of the single-, double-, triple-, and quadruple-protection methods were PPE (80.04%), PPE + Collimation (92.09%), PPE + Collimation + Curtain (93.39%), and PPE + Collimation + Curtain + Filter (93.61%), respectively. These findings should be considered by individuals and by institutions investing resources into radiation protection.

REFERENCES


