UDC 615:546.815+623.454.87
DOI: https://doi.org/10.17721/3041-1491/2024.11-11

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A FOLLOW-UP STUDY ON THE LEAD EQUIVALENCE AND INTEGRITY OF PERSONAL PROTECTIVE EQUIPMENT USED IN CLINICAL PRACTICE

Introduction. *Personal radiation protective equipment (PRPE) means such vests and skirts, aprons, thyroid collars and other means reduce radiation exposure of personnel working with X-rays and gamma ray sources. The composition of PRPE worn by X-ray personnel to shield against secondary radiation is changing. Lead is being replaced by either lead-free or composite (lead with other high atomic numbered elements) materials. In clinical practice, PRPEs with different lead equivalents are used. PRPE from lead or lead-equivalent material (LEM) are essential in providing necessary shielding from secondary radiation exposure to workers.*

Methods. *Quality assessment of the PRPE was performed evaluating integrity and lead equivalence of more than 800 units, 0.25, 0.35, 0.5 and 1 mm LEM provided by ten manufacturers in the period 2022–2024.*

Results. *Siemens Luminos dRF MAX 3D radiography, Philips Incisive CT computed tomography, Philips BV Endura mobile C-arm, and FLOWD 8020 mobile protective clothing testing X-ray units were used for obtaining images of PRPE for checking the integrity and lead equivalence. A calibrated solid-state meter Piranha R&F/M 657 with RTI Dose Probe was used for checking the radiation attenuation. In order to check the integrity, PRPE were categorized into four categories: I (good quality), II (small cracks), III (large cracks not in critical areas and smaller than 5 cm^2), IV (very large cracks, cracks in critical areas, bigger than 5 cm^2). PRPE lead equivalence deviations were analysed and grouped into three categories: DI (less than 5 %), DII (less than 10 %), DIII (more than 10 %).*

Conclusions. *The results of the integrity tests showed that about 85 % of the PRPE were in good quality. The analysis of lead equivalence deviations showed that about 76 % of the PRPE met the criteria for category DI. The aim of the study was to evaluate the lead equivalence and the integrity of the PRPE used in clinical practice with different screening methods.*

Keywords: *personal radiation protective equipment, lead protective equipment, radiation protection.*

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Introduction

The total number of diagnostic and therapeutic procedures worldwide is constantly increasing (United Nations Scientific Committee on the Effects of Atomic Radiation, UNSCEAR) (UNSCEAR, 2021) and it may result in higher radiation exposure for interventional radiologists and other related medical staff. Personnel in departments equipped with X-ray modalities are required to wear personal radiation protective equipment (PRPE) to ensure adequate shielding from scattered radiation. Typically, PRPE including lead aprons, vests, skirts, and thyroid shields are made using lead powder-loaded sheets or lead-oxide on vinyl (McCaffrey et al., 2007; Peters et al., 2017). A typical 0.25 mm lead-impregnated apron weighs approximately 3.25 kg, while a 0.5 mm apron weighs around 4.95 kg, with some reaching up to 7 kg (Kim, Choi, & Jeon 2016; Warren-Forward et al., 2007; Zuguchi et al., 2008). This substantial weight can hinder efficient movement and performance of tasks, and prolonged use can lead to musculoskeletal pain and injuries, particularly affecting the spine (Goldstein, 2015; Klein, 2009; Moore et al., 1992). Due to these weight issues as well as environmental concerns, there has been a shift towards lightweight, non-lead or lead-composite materials incorporating elements such as cadmium, tin, iodine, barium, antimony, or tungsten (Aral, Duch, & Ardanuy, 2020; Klein et al., 2018; Yaffe et al., 1991). These composite materials offer the same level of attenuation as traditional lead aprons for X-ray energies ranging from 50 kVp to 125 kVp, but with a significant weight reduction of 20–30 % (Webster, 1966).

To assess the viability of employing PRPE, many hospitals and other organizations use W. Stam and M. Pillay (Stam, & Pillay, 2008) method which gives criteria to aid in determining when lead aprons should be discarded. The rejection criteria proposed by Lambert and McKeon can also be used (Lambert, & McKeon, 2001). However, there is a lack of uniform, specific, and actionable guidelines which can lead to inconsistencies in inspection practices. Therefore, institutions and hospitals develop their own procedures with regulation, such as rejection criteria, based on the literature and frequency of quality checks (Kellens et al., 2022).

It is important to test the integrity and the lead equivalence of every newly purchased apron before it is used by personnel. Common defects to look for include material non-uniformity, cracks, tailoring flaws, and discrepancies in the specified lead equivalence provided by manufacturers. Moreover, during usage, aprons are subject to normal wear and tear, as well as occasional mishandling or improper storage. PRPE can be inadvertently damaged when folded or dropped, causing sharp bends in the vinyl that result in deterioration, such as cracks or holes in the shielding material. Periodic inspections of PRPE are essential because the health and safety of both X-ray workers and patients rely on the integrity of this equipment. The aim of the study was to evaluate the lead equivalence and the integrity of the PRPE used in clinical practice with different screening methods.

Methods

General information: Quality assessment of 0.25, 0.35, 0.5 and 1 mm lead and lead-free PRPE from thirteen manufacturers was performed. X-ray units were used

for inspecting the integrity and lead equivalence: digital radiography Siemens Luminos dRF MAX 3D, computed tomography Philips Incisive CT, mobile C-arm Philips BV Endura and mobile apron screening system FLOWD 8020. The protocol parameters and modes used for the inspections are shown in Table 1. A calibrated solid-state meter Piranha R&F/M 657 with RTI Dose Probe was used for checking the radiation attenuation.

Table 1

The protocol parameters and modes used for inspections of PRPE

Manufacturer	Protocol	kV	mA	Field of view size	The attenuation evaluation method
Siemens Luminos dRF MAX 3D	Standard radiography and fluoroscopy	100	100	420 mm × 420 mm (radiography), 290 mm (fluoroscopy)	Solid-state meter; pixel values
Philips Incisive CT	CT scout view	100	50	500 mm	HU (Hounsfield units)
Philips BV Endura	Fluoroscopy	100	20	210 mm	Solid-state meter
FLOWD 8020	Standard	80–100	1,2–1,0	240 x 870 mm	Automatic

PRPE categorization and rejection criteria: In order to check the integrity, PRPE were categorized into four categories: I (good quality), II (small cracks), III (large cracks not in critical areas and smaller than 5 cm^2), IV (very large cracks, cracks in critical areas, bigger than 5 cm^2). PRPE lead equivalence deviations were analysed and grouped into three categories: DI (less than 5 %), DII (less than 10 %), DIII (more than 10 %). Pieces with a total defect area bigger than 5 cm^2 (IV category) in critical areas were rejected. An internal institutional rule allows to reject the PRPE that have breaks, tears and cracks in non-repairable areas.

Image and statistical analysis: Images were processed using ImageJ program packages. Data analysis was performed using "Microsoft EXCEL 2019" and "SPSS Statistics 2019" software.

Results

The inspection of PRPE is a multifaceted process essential for ensuring that protective gear continues to offer adequate protection against ionizing radiation. More than 800 units of PRPE were evaluated over two years. In particular, 278 thyroid collars, 194 vests, 190 skirts, 58 customized covering means, and 89 aprons were inspected. The results of the integrity tests showed that about 85.3 % of the PRPE were of good quality while the remaining had tears/cracks and were assigned to category II (9.8 %), III (3.8 %), and IV (1.1 %), respectively. The analysis of lead equivalence deviations revealed that 75.6 % of the PRPE met the criteria for category DI, 11.9 % for category

DII, while 12.5 % of the measured PRPE exceeded the lead equivalence amount specified by the manufacturers by more than 10 %. Detail results of PRPE integrity and lead equivalence are presented in Table 2 and Table 3. Moreover, the results indicated that all the X-ray units used for investigating the integrity and lead equivalency of PRPE had similar accuracy and could be used interchangeably. However, specialized apron screening system stood out for its practicality, large fields of view, automatic inspection protocol generation, reduced scan times, and close to the background dose rate exposure near the operating machine. Moreover, on-site PRPE inspections allow to minimize the disrupting the clinical work of departments where such PRPE are used. Depending on the PRPE units' number, the inspection of protective equipment takes about a couple of hours (including the handling and transportation to the inspection place). The risk of additional contamination of PRPE is also reduced, as inspections take place on the hospital's territory.

Table 2

Results of PRPE integrity deviation evaluations

Categories of PRPE integrity	Number of PRPE units	Percentage (%)
Category I (good quality)	690	85,3
Category II (small cracks)	79	9,8
Category III (large cracks not in critical areas and smaller than 5 cm^2	31	3,8
Category IV (very large cracks, cracks in critical areas, bigger than 5 cm^2)	9	1,1

Table 3

Results of PRPE lead equivalence deviation evaluations

Categories of PRPE integrity	Number of PRPE units	Percentage (%)
Category DI (less than 5 %)	612	75.6
Category DII (from 5 to 10 %)	96	11.9
Category DIII (more than 10 %)	101	12.5

Since the PRPEs were first visually inspected, damages, tears and cracks were found in most cases during these inspections. During usage, aprons are subject to normal wear and tear, as well as occasional mishandling or improper storage. This included inspection of buckles, loops and magnets, as well as inspection of the outer fabric. After this process, the PRPE were validated by inspection methods presented in Table 4. These techniques are essential for identifying cracks, voids, or inconsistencies within the protective material not visible to the naked eye. In addition, advanced inspection methods, as shown in Figure 1, play a crucial role in identifying hidden flaws that could compromise the protective function of the equipment, ensuring that only safe and effective PRPE remain in use.

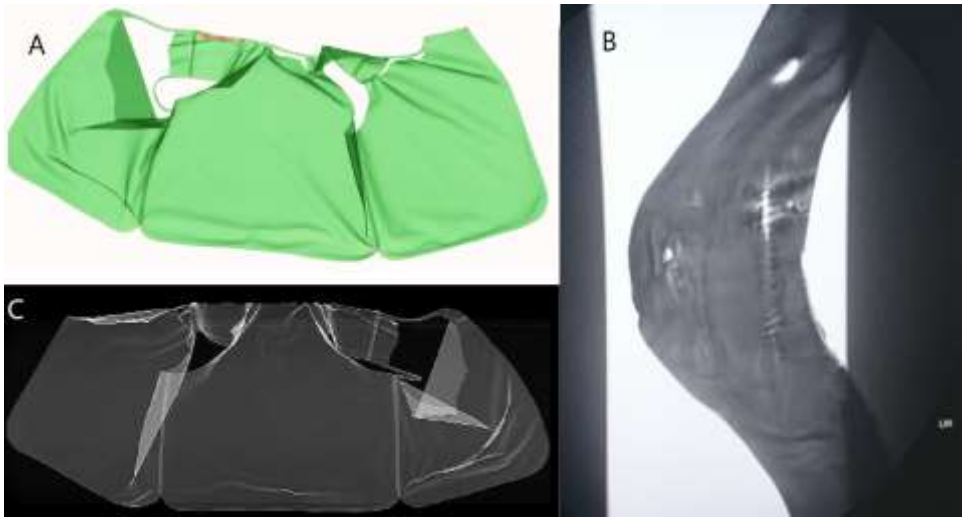


Fig. 1 Examples of cracks or tears in PRPE
(A – FLOWD 8020, B – fluoroscopy, C – CT images)

Table 4

Comparison of equipment use in PRPE inspection

Equipment	Inspection parameters	Advantages	Disadvantages
Computed Tomography	• Perform a topogram scan (scout view). • Always check the pixel resolution of the scout view, manufacturers have different pixel resolutions for the scout/planning view which can be lower than the stated scan resolution. In some cases, it reduces as the length of the scout view increases. A pixel resolution of 5mm may not demonstrate a tear < 5 mm. • Recommended exposure – 80 to 100 kV and a low mA setting to help protect the tube and lower the dose to the inspector.	• Eliminate the need for inspector presence in the X-ray room during exposure, thereby reducing personal dose exposure. • Speed of scans. • Having a permanent digital record of each apron. • The possibility of performing multiple aprons with a single scan. • No need of the calibrated solid-state meter.	• Unavailability of a scanner to perform testing as most facilities that have very busy schedules. • The scanning table might be too narrow and thus care must be taken to spread the apron on the table in a proper way. • CT resources (as the tube and detectors) are used. • HU must be analysed.

Equipment	Inspection parameters	Advantages	Disadvantages
Stationary X-ray and fluoroscopy	• Use fluoroscope's manual settings and low technique factors (e.g. 70–100 kVp). • Use remote controllable fluoroscopy unit. • Use maximum focus-film or focus-detector distance • Take a radiograph with manual settings and low exposure parameters (e.g. 70–100 kVp).	• Easily accessible in the hospitals. • Selection of different parameters.	• Additional radiation dose to the inspector (if there is no remote control). • Many fluoroscopy systems only work within pre-programmed protocols making it challenging to set optimised exposure factors for crack detection.
C-arm	• Use fluoroscope mode settings and low technique factors (e.g. 70-100 kVp).	• Easily accessible in the hospitals.	• Additional radiation dose to the inspector. • Small field of view. • Usually located in the operating room.
PRPE screening systems	• Direct performing of the PRPE inspection.	• Reduce the need to have dedicated personnel and equipment. • Have larger fields of view and much lower scan times. • Speed of scans. • The possibility of performing multiple units with a single scan. • No need of the calibrated solid-state meter. • Produce reports and might include an PRPE management system.	• Must be purchased separately.

Discussion and conclusions

Personal radiation protective equipment is crucial for the safety of hospital workers, and regular inspections are essential to ensure its effectiveness. It is recommended that PRPE integrity be checked after the purchase using computed tomography, fluoroscopy, radiography or dedicated protective clothing testing machines. Due to prolonged use of heavy PRPE during clinical procedures, the personnel often report physical strain, thus if LEM exceeds the declared value, PRPE weight may be higher. Special protective clothing testing machines enable to perform LEM QA in an efficient way. Calibrated radiographic, CT, C-arm

equipment could be used for acquiring images of integrity and lead equivalence, however, only qualified personnel can perform the evaluation. Dedicated personnel should ensure that both visual inspections and inspections by touch are performed regularly for signs of damage or prior misuse.

To maximize LEM PRPE life, personnel should hang PRPE correctly between the use, wear them correctly, ensuring that the workers wear the correct size, transport and clean the PRPE in correct way, as it recommended by the manufacturer. The repair of PRPE does not guarantee a long-term solution for prolonging the lifespan of the protecting mean.

Authors' contribution: all authors participated in the study design, original text writing and performing the measurements. Kirill Skovorodko is the corresponding first author, he performed the experimental work, wrote the manuscript text, analyzed and interpreted the data. Antonio Jreije was involved in all stages of preparing the manuscript: the analysis of data, the interpretation of data, and writing and reviewing of this manuscript. Inga Andriulevičiūtė contributed with experimental work, methodology, data analysis and provided helpful feedback and comments on the manuscript. Leonid Krynke was responsible for methodology, data analysis, the manuscript text writing. Birutė Gricienė was responsible for conceptualization of the article, she revised the manuscript and provided helpful comments and suggestions. All authors read and approved the final manuscript.

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Отримано редакцією збірника / Received: 27.08.24
Прорецензовано / Revised: 20.09.24
Схвалено до друку / Accepted: 23.10.24

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ПОДАЛЬШЕ ДОСЛІДЖЕННЯ ЕКВІВАЛЕНТНОСТІ СВИНЦЮ ТА ЦІЛІСНОСТІ ЗАСОБІВ ІНДИВІДУАЛЬНОГО ЗАХИСТУ, ЩО ВИКОРИСТОВУЮТЬСЯ В КЛІНІЧНІЙ ПРАКТИЦІ

В с т у п . ***Індивідуальні засоби радіаційного захисту (ЗІЗ) – це жилети та спідниці, фартухи, коміри та інші компоненти, що знижують радіаційне опромінення персоналу, який працює із джерелами рентгенівського та гамма-випромінювання. Складові ЗІЗ, який носять радіологічний персонал для захисту від вторинного випромінювання, змінюється. Свинець замінюють на безсвинцеві матеріалами або композити (свинець з іншими елементами з великим атомним номером). У клінічній практиці використовуються ЗІЗ з різним еквівалентом свинцю. ЗІЗ зі свинцю або із матеріалу з еквівалентом свинцю (МЕС) мають важливе значення для забезпечення необхідного захисту від вторинного опромінення працівників.***

М е т о д и . ***Визначення здатності ЗІЗ було проведено шляхом оцінювання стану цілісності та свинцевого еквіваленту для понад 800 засобів з МЕС 0,25, 0,35, 0,5 та 1 мм, наданих десятьма виробниками протягом 2022–2024 років.***

Результати. ***Для отримання зображень ЗІЗ і перевірки цілісності та еквівалента свинцю використовували мобільну випробувальну машину, призначену для контролю рівня захисту від рентгенівського випромінювання, FLOWD 8020, систему для хірургічної візуалізації Philips BV Endura mobile C-arm, комп'ютерний томограф Philips Incisive CT і цифрову рентгенівську систему Siemens Luminos dRF MAX 3D. Перевірку ослаблення випромінювання виконували за допомогою каліброваного твердотільного вимірювача Piranha R&F/M 657 із зовнішнім зондом RTI Dose Probe. Перевірку цілісності ЗІЗ було здійснено за чотирма категоріями: I (хороша якість), II (невеликі тріщини), III (великі тріщини не в критичних ділянках і площею менше 5 кв. см), IV (дуже великі тріщини, тріщини в критичних місцях, тріщини площею більше 5 кв. см). Відхилення значення еквівалентності свинцю були проаналізовані та ЗІЗ згруповані в три категорії: DI (менше 5 %), DII (менше 10 %), DIII (більше 10 %).***

Висновки. ***Результати випробувань на цілісність показали, що близько 85 % ЗІЗ мають належну якість. Аналіз відхилень еквівалентності свинцю показав, що близько 76 % ЗІЗ відповідали критеріям категорії DI. Метою дослідження було оцінити різними методами скринінгу еквівалентність свинцю та цілісність ЗІЗ, що використовується в клінічній практиці.***

Ключові слова: ***засоби індивідуального радіаційного захисту, свинцеві захисні засоби, радіаційний захист.***

Автори К. Сковородко, А. Йреіє, І. Андріулевічіуте, Л. Кринке та Б. Гріціене заявляють про відсутність конфлікту інтересів. Спонсори не брали участі в розробленні дослідження; у зборі, аналізі чи інтерпретації даних; у написанні рукопису; в рішенні про публікацію результатів.

The authors K. Skovorodko, A. Jreije, I. Andriulevičiūtė, L. Krynke and B. Gricienė declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses or interpretation of data; in the writing of the manuscript; in the decision to publish the results.