Comparative Analysis of Effectiveness of Traditional Lead Aprons versus Newer Generation Lead-free Aprons in Radiation Protection

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Abstract

The comparative effectiveness of traditional lead aprons versus newer generation lead-free alternatives in radiation protection is a critical area of investigation in medical safety. While lead aprons have long been the standard, concerns over weight and mobility have spurred interest in lead-free options, which incorporate materials such as antimony, bismuth, and barium sulfate. Understanding the relative performance of these apron types is essential for optimizing radiation protection protocols in medical settings. Relevant studies were identified through electronic database searches, with inclusion criteria focusing on comparative evaluations of apron types in terms of radiation shielding effectiveness and durability. Data extraction and risk of bias were performed to analyze key findings across the selected studies. Analysis of the included eleven studies revealed promising results for lead-free aprons, demonstrating comparable radiation protection to traditional lead aprons. In addition, thinner lead-free aprons were proven to be adequate for shielding while concerns related to weight and mobility. The systematic review highlights the evolving landscape of radiation protection in medical settings, with newer-generation lead-free aprons presenting promising alternatives to traditional lead aprons. In addition, shields composed of combined metals demonstrated more substantial attenuation and dose reduction in comparison to single-metal shields.

Keywords: Aprons, efficacy, lead-free, radiation, safety, transmission

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Introduction

Radiation exposure is known to have a negative effect on human health. Ionizing radiation, especially X-rays used in diagnostic medical imaging, is a critical concern requiring adherence to radiation protection standards.[1] When human living tissue absorbs energy, it can induce biological effects across various levels, reaching from tissues down to cells and deoxyribonucleic acid. These effects may not always be immediately observable in the body, yet they can still manifest within the biological system.[2] However, efforts are dedicated to shielding radiosensitive organs and minimizing scatter radiation exposure to personnel, aiming to reduce doses from both primary and secondary radiation. Reduction of these risks involves employing appropriate protective equipment, including radiation protective aprons.[3]

Conventionally, lead aprons have been essential in diagnostic radiology and interventional procedures due to their exceptional effectiveness in reducing radiation doses for both patients and operators.[4] Recommended lead-equivalent thickness for these protective aprons is at least 0.25 mm for X-rays up to 100 kV and 0.35 mm for X-rays exceeding 100 kV. Radiation personnel are advised a minimum Pbeq of 0.5 mm.[5]

Despite their efficacy, lead aprons are often found to be cumbersome and uncomfortable, particularly during prolonged use, with frequent bending or mishandling leading to splits and gaps in the protective layers, thereby reducing their effectiveness against scattered ionizing radiation and contributing to the onset of back pain among wearers. This necessitates the need for an alternative protective material that is lead-free, providing enhanced protection while minimizing

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adverse outcomes. Therefore, lead-free alternatives utilizing lighter materials like antimony, tin, and barium have emerged to tackle this problem.[6]

Certain nonlead materials may have improved attenuation capacities depending on photon energy because of their K-edge. Moreover, materials of various sizes, including micro- and nano-sized particles, have demonstrated sufficient efficacy in X-ray attenuation. While a variety of materials are utilized as shields, have shown promising potential for radiation protection.[7,8]

Regular radiographic evaluations are conducted on these shields to maintain ongoing protection, identifying any gaps or cracks. Aprons with marked defects are swiftly withdrawn from circulation to uphold safety standards.[9] Similarly, phantom studies have been undertaken to assess patient and personnel dose using thermoluminescent dosimeters. The maintenance protocol for protective aprons remains a significant challenge, with proper handling before and after use observed to prolong their lifespan.[10] Due to the scarcity of studies present in the literature, the review intended to compare the traditional lead aprons versus newer generation lead-free aprons in radiation protection.

Table 1: Search terms used

Lead aprons
Lead-free aprons
Radiation protection
Dose reduction
Transmission
X-ray transmission
Efficacy
Absorbance

Table 2: Summary of the search strategy used

Items	Specifications
Date of search	February 2014 to February 2024
Databases and other sources searched	PubMed, Google Scholar, Scopus, Wiley, PubMed Central
Search terms used	Refer Table 1
Inclusion criteria	Articles published between the last ten years, Articles written in English language, Original articles and review articles about lead and lead-free aprons, Human studies
Exclusion criteria	Non-English articles, Studies reporting a very small sample size, Incomplete articles, Duplicate articles, Incomplete abstracts, Letter to editor, book, or chapter

Methodology

In the present review, the electronic database was performed to gather studies on lead and lead-free aprons for the comparative analysis. The studies were selected based on the author's assessment of their credibility, relevance to the topic, and alignment with current radiation protection management strategies. The search utilized specific terms listed in Table 1, and an overview of the search strategy can be found in Table 2. In addition, the review incorporated further articles by examining the bibliographies of the initially selected studies.

Data collection

Initially, the search strategy outlined earlier was implemented. Subsequently, all articles in databases underwent screening based on their titles and abstracts to determine eligibility for further review. Selected studies were thoroughly examined and evaluated, with only those meeting all inclusion criteria considered for full-text analysis. Reviewers categorized and assessed data across various parameters.

Quality assessment

After conducting a thorough database search, the selected articles were organized into an Excel spreadsheet. Subsequently, duplicate articles were identified and removed. Following this, two authors independently evaluated the full-text publications and abstracts. Each publication was reviewed by both authors to determine its suitability for inclusion in the study.

Statistical analysis

In accordance with Cochrane Review criteria, the study utilized RevMan 5.4.1 to assess bias risk. This tool comprised two parts addressing six key domains, with corresponding tables titled "Risk of Bias" for each domain. Entries for each study typically commenced with a summary of the study's conduct. In addition, the tool enabled users to assign bias risk ratings as low, unclear, or high for each entry.

Results

The current systematic review retrieved 942 articles in its initial search. After eliminating 39 duplicate or triplicate publications and removing 392 articles for various reasons, including irrelevance, incomplete data, and missing parameters, 608 publications remained for header and abstract screening. Among these, 274 were excluded due to incomplete data, irrelevance to the present study, or other factors. Subsequently, 334 articles met the inclusion criteria and underwent full-text examination. Of these, 68 papers were eliminated for being case studies or case series, whereas 132 articles were found irrelevant to the study, and 26 were identified as letters to editors. In addition, 97 articles were excluded for various other reasons. A total of 11 studies were included after thorough screening and analysis [Figure 1]. The review included articles published within the timeframe from 2014 to 2024.

Study characteristics

A total of 11 studies were included in the systematic review, providing information on both lead and lead-free aprons along with their respective outcomes as summarized in Table 3.

We evaluated individual studies for selection bias (randomization process), performance bias (blinding of participants and personnel), attrition bias (incomplete outcome data), selective reporting (reporting bias), and other potential biases. These

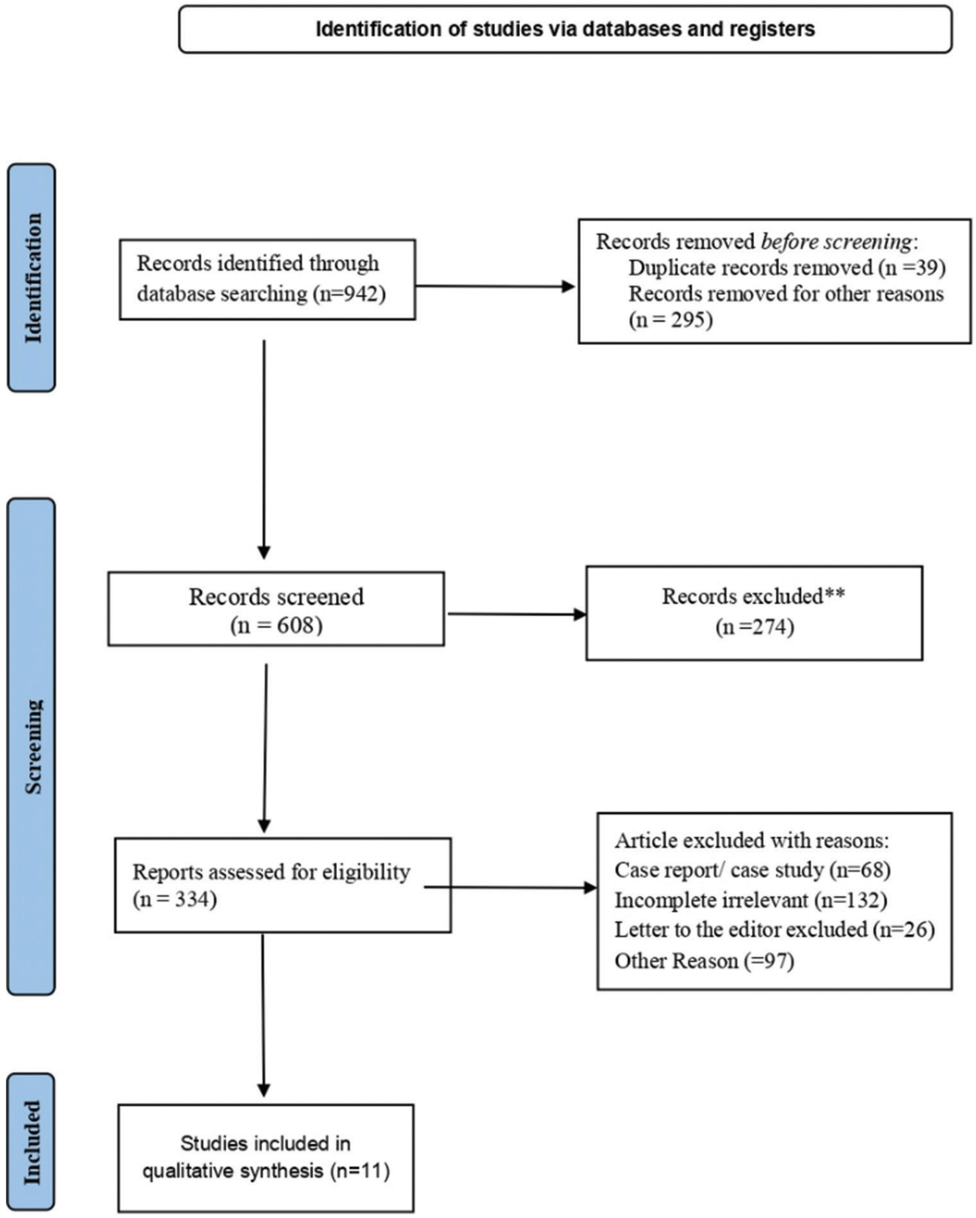

Figure 1: PRISMA flow diagram

studies were categorized as having low, unclear, or high risk across the various domains and criteria assessed. The overall risk assessment for each of the 11 included research studies was indicated as low risk (+), high risk (−), or unclear risk (?), as illustrated in Figure 2. We provided a thorough summary of the bias assessment for these studies. Notably, we identified significant methodological shortcomings in at least one bias domain across all studies. Among the most notable concerns were inadequate or absent randomization (resulting in a high risk representing 58% of the trials), with low risk (44%) and unclear risk noted in the remaining 44% of trials, as depicted in Figure 3.

Discussion

The study systematically compared the effectiveness of traditional lead aprons to newer generation lead-free aprons in radiation protection, specifically assessing their efficacy in reducing radiation exposure. Currently, radiation safety is of paramount concern as the frequency of minimally invasive procedures performed in catheterization labs continues to rise.[17] Effective methods for radiation protection include maintaining distance, limiting exposure time, and employing shielding, with lead aprons serving as a common shielding approach. Yet, for optimal protection, lead aprons must be well-maintained and correctly worn. Ensuring the integrity and efficacy of lead aprons requires proper care and maintenance. Routine quality assurance assessments are imperative for identifying any potential concerns regarding the integrity of the lead aprons.[16]

Shielding medical X-rays within the diagnostic range in medical imaging primarily involves blocking direct X-rays, a

Table 3: Characteristics of studies included

Author	Type of apron	Design/ number of years used	Thickness	Device	Tube Voltage	Outcomes
Huet *et al*.[11]	Lead free and light lead apron	Masks and caps	0.5 and 1.2 mm	Radiation devices	80 kV (X-ray energy spectrum)	Both lead and lead-free caps and masks showed potential for safeguarding certain areas of the brain, with masks possibly providing additional protection to the eye lens Lead-free aprons were found to provide similar levels of protection as lead aprons, whereas the zero gravity system demonstrated substantial dose reduction for all covered organs
Ijabor *et al*.[12]	Lead apron	Front and back and 3–11 years	0.5, 0.25 and 0.35 mm	CT and conventional radiograph	100–150 kV and 50–150 kV	The protective aprons were determined to be intact; however, broad lines were observed on all of them The absorbance and TF were comparable to findings in most studies and were deemed sufficient
Hayre *et al*.[13]	Lead-rubber apron	-	0.35 mm	Scattered ionizing radiation	1–20 µGy/s	The lead-rubber apron exhibited a significant reduction in radiation doses to key organs, including the left breast by 98% (0.0083 mGy), the right breast by 99.9% (0.0000 mGy), and the spleen by 99.9% (0.0262 mGy) Scattered radiation was reduced to both eyes, despite not being directly shielded
Omojola *et al*.[14]	Lead	Front and back and 9.3 years	0.25, 0.35 and 0.50 mm	X-ray mobile unit	125 kV	Radiographs indicated that protective aprons A and C were defect-free The estimated annual skin dose for physicians using protective aprons of 0.25, 0.35, and 0.50 mm thickness stayed under 500 mSv/year, with absorption rates for 0.25 mm aprons consistently under 90%
Lu *et al*.[15]	Lead and lead-free apron	Front and back	0.25 and 0.35 mm	X-ray machine	50–70 kVp	The front panel performance of the apron in scattering radiation varied by 38-fold, despite all being labeled as 0.5 mm lead equivalent 56% of the aprons demonstrated a difference in scatter transmission of at least 49% when tested at 50 and 70 kVp
Uche *et al*.[16]	Lead apron	Front and back and 3–12 years	0.35 mm	Fluoroscopy and conventional X-rays	50–20 kVp and 100 kVp	Physical examination revealed that 7 out of 9 aprons (77.78%) were deemed to be in good condition. However, the qualitative assessment indicated that only 4 out of 9 lead aprons (44.4%) were in good condition The efficiency of lead aprons was found to correlate positively with the KVp but negatively with lead thickness
Livingstone *et al*.[17]	Lead rubber, lead vinyl, and lead free	Skirt and vest, single side and wrap around	0.5, 0.25 and 0.35 mm	-	-	The majority of the IR reported experiencing increased physical strain when using single-sided lead rubber aprons Aprons featuring with a bi-layer blend of low- and high-atomic-weight textiles will effectively protect the wearer while also minimizing physical strain
Peters *et al*.[18]	LC, NL, and NL-BL	Front and back	0.5, 0.25 and 0.35 mm	Inverse broad beam geometry	70, 90 and 110 kVp	An uncertainty of 0.58% was present when determining the transmission values Between the LC, NL, and NL-BL groups, there were no statistically significant differences found for any combination of specified lead equivalency and tube voltage

Contd...

Table 3: Contd...

Author	Type of apron	Design/ number of years used	Thickness	Device	Tube Voltage	Outcomes
Kazempour *et al*. (2015)[19]	Lead containing (Pb-Si and Pb-EPVC) and Lead free (W-Si, W-Sn, Ba- EPVC, W-Sn-Cd- EPVC)	Front and back	-	Monte Carlo simulation (MCNP)	40, 60, 90 and 120 kVp	Lead shields provide superior protection at energies below 40 kVp. The W-Sn-Ba-EPVC composite offers exceptional attenuation at 120 kVp, outperforming earlier lead-based materials, while W-Sn-Cd-EPVC demonstrates optimal radiation attenuation at 60 and 90 kVp Shields free of lead have been shown to be completely effective in protecting against X-ray energy between 60 and 120 kVp
Kim *et al*.[20]	Lead and Lead free (Al, Cu, and Sn)	-	0.039, 0.095, 0.22, 0.15, 0.21 and 0.29 mm	Radiography system	60 kVp and 100 kVp	At 0.5 m, 86%, 1.0 m, and 1.5 m, the rate of shielding space scattering rays is 80%, 97%, and 96%, respectively When compared to existing lead aprons, which usually weigh more than 4 kg, it is possible to lower the weight of the apron to 1/5 with the intention of shielding low-intensity radiations and dispersing X-rays. This confirms the possibility of producing lightweight aprons specifically designed for shielding low-dose radiations
Mori *et al*.[21]	Lead and lead-free	Upper and lower	0.25, 0.35 and 0.50 mm	X-rays	50, 60, 80, 100 and 120 kVp	For IVR operators, the 0.25-mm thick aprons equal to lead proven to be effective enough. But the nonlead, 0.50-mm thick apron comparable to lead was considered excessively hefty The 0.35-mm lead apron is effective against the high-energy X-rays that are common in CT scans, and it has been shown to be useful for CT nurses In the experimental setting, there is a 20% variation in the transmission rate of protective aprons even within the limited effective energy range of 33–50 keV

TF: Transmission factors, CT: Computed tomography, IR: Interventional radiologists, KVp: Kilovoltage peak, LC: Lead composite, NL: Non-lead single layer, NL-BL: Non-lead bilayer, MCNP: Monte Carlo n-particle transport

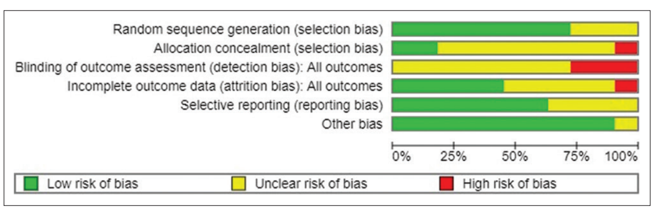

Figure 2: Representing the percentage risk of bias of included studies

critical aspect for ensuring effective protection.[20] In a study, researchers analyzed 63 lead aprons and discovered that 62.5% of them had one or more defects, with defect sizes varying from 1 to 8 cm.[22] Bjørkås *et al*. examined the integrity of 10 lead aprons with thicknesses of 0.25, 0.35, and 0.50 mm and found that 70% had defects, including cracks and tears near critical organs, while only 30% were defect free.[23]

Hyun *et al*. reported that 0.5 mm lead aprons blocked slightly more than 1/3rd of the radiation scattered toward the surgeon. Thus, employing reduced radiation techniques (e.g., utilizing robotic guidance) proves to be effective approach in decreasing radiation exposure compared to solely relying on protection provided by lead aprons.[24] Uche *et al*.[16] in their study revealed that the physical examination indicated that 77.78% of the aprons were in good condition, and qualitative assessment revealed that only 44.4% of the lead aprons met the criteria for being in good condition. Furthermore, the efficacy of lead aprons was observed to rise with increasing KVp and decline with thicker lead, aligning with findings consistent with those of Oyar and Kışlalıoğlu,[25] where 68.2% were deemed defective.

Another study by Haussen *et al*. reported a fourfold increase in the cumulative dose when using a lead apron (in conjunction with lead glasses, a thyroid shield, and a hanging shield at the groin) compared to a weightless protection garment like the zero-gravity system.[26] In addition, Gilligan *et al*. demonstrated a further reduction in radiation dose through the use of enhanced acrylic shielding.[27]

In recent years, lead-free aprons containing antimony, bismuth, and barium sulfate have become commercially

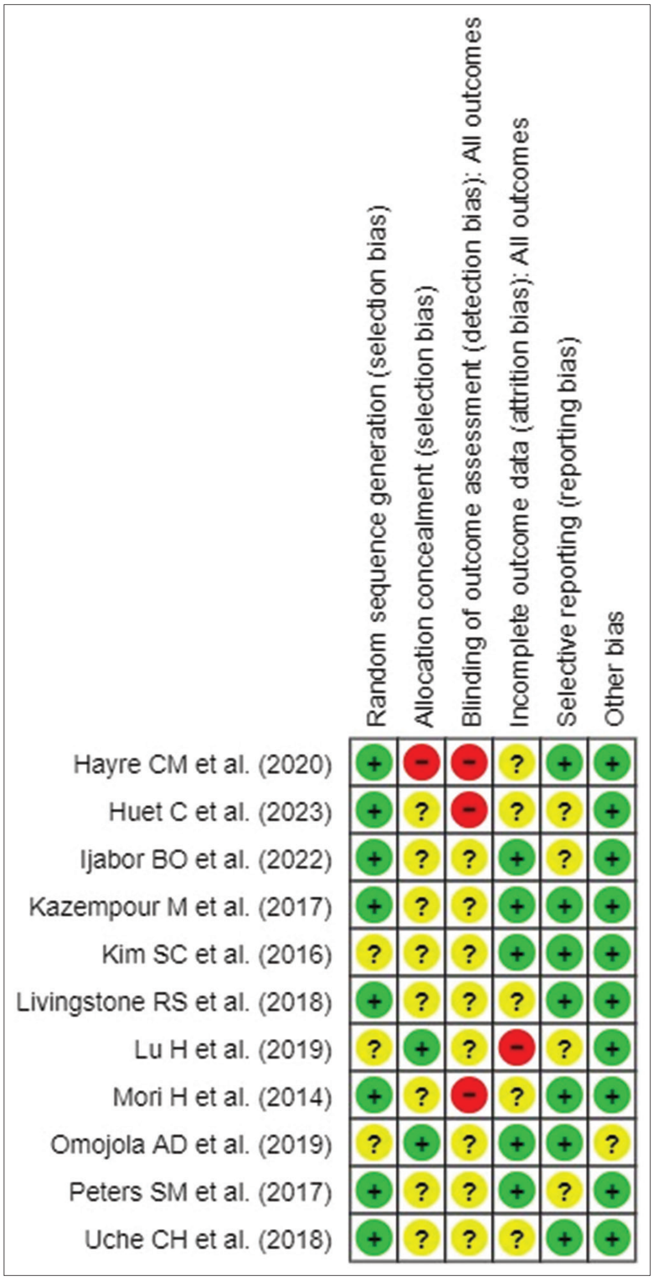

Figure 3: Illustrating the risk of bias of included studies

available. Typically, these aprons weigh between 2 and 4.5 kg, varying based on their dimensions. Certain manufacturers of lead-free aprons integrate a bi-layer design utilizing materials with low and high atomic weights, aligned with k-edges, potentially offering 20% more effective protection compared to lead.[28] The radiation attenuation provided by protectors with lead equivalent thicknesses of 0.3 mm and 0.6 mm was 78.1% – 78.5% and 90.4% – 90.8%, respectively. Maintaining a distance of 5 cm from the edge of the table reduced radiation exposure by 33.3% – 36.1%.[29] According to Kim *et al*.'s study, radiation protection increased from 24% to 76% when the thickness of the BaSO4 and Bi powder shield was changed from 0.15 to 0.29 mm.[20]

Studies suggest that increasing the weight percentage of Bi, W, or BaSO4 in a shielding material can achieve the required attenuation with a thinner layer. An increased concentration of particles per unit volume of the shield enhances attenuation while reducing beam energy significantly. However, a higher percentage of materials like Bi can compromise the shield's flexibility and increase the risk of cracking. Thongpool *et al*.[30] reported that increasing the weight percentage of BaSO4 in the shielding material from 0.2% to 0.8% resulted in a rise in the linear attenuation coefficient from 0.085 to 1.189. Another study on W-based shields with a thickness of 0.3 mm and an 80% weight percentage of W showed attenuation rates of 65%, 53%, 48%, and 46% at 60, 80, 100, and 120 kVp, respectively. The results indicated that as the kVp increased from 60 to 120, the attenuation decreased from 65% to 46%.[31]

Conclusion

The current systematic review emphasizes the evolving landscape of radiation protection in medical settings. Lead-free aprons, incorporating materials such as antimony, bismuth, and barium sulfate, have shown promising results in providing radiation protection comparable to lead aprons. While traditional lead aprons remain prevalent, the emergence of lead-free alternatives, coupled with innovative designs, presents promising avenues for enhancing radiation safety. Innovative approaches such as the zero-gravity system and improved acrylic shielding have shown significant reductions in radiation dose compared to traditional lead aprons. The efficacy of protective aprons varies depending on the energy range of the radiation being shielded. Different materials and thicknesses may be optimal for shielding against low-energy X-rays compared to high-energy ones. These advancements provide comparable effectiveness, potential dose reduction, and improved comfort for healthcare professionals. Thus, further research and development are crucial for optimizing radiation protection strategies and ensuring the well-being of medical personnel.

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Conflicts of interest

There are no conflicts of interest.

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