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Alternative Uses of Lead-Free Materials for Medical Radiation Protection: A Review

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ABSTRACT

In light of its great density and potent radiation-blocking properties, lead has long been the main material used for radiation shielding in medical applications. However, attempts to discover safer and lighter alternatives have been motivated by its toxicity, environmental hazards, high weight, and disposal difficulties. Numerous lead-free shielding solutions, including tungsten, bismuth, barium sulfate, antimony, and polymer-based nanocomposites, have been developed as a result of advances in material science and are appropriate for both diagnostic and therapeutic imaging. Using articles that are indexed in the PubMed and Scopus databases, this review gathers and examines recent research on various substitute materials. Research shows that composites made on tungsten and bismuth have attenuation efficiencies similar to those of traditional lead aprons, but they are more flexible, durable, and less hazardous. Heavy metal oxide-reinforced polymer composites have also demonstrated great potential in the development of lightweight personal protective equipment, including as gloves, shielding curtains, thyroid collars, and aprons. Moreover, textile-based shielding systems and multilayer nanocomposites have become cutting-edge methods for improving radiation attenuation effectiveness. There are still issues with manufacturing costs, mechanical stability, uniformity, and long-term durability despite promising advancements. Sustainable and multipurpose shielding materials with enhanced attenuation performance and ergonomic qualities appropriate for regular clinical usage should be the focus of future research. The advancements, benefits, drawbacks, and prospects for lead-free radiation shielding materials in medical settings are highlighted in this review.

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Introduction

Radiation exposure among medical personnel and patients has dramatically grown as a result of medical imaging modalities such Computed Tomography (CT), fluoroscopy, mammography, and interventional radiology [1]. Radiation protection is an important consideration in diagnostic radiology to safeguard the safety of patients, healthcare personnel, and the general public. Lead has long been utilized as a shielding material due to its high atomic number, density, and ability to attenuate radiation. However, worries about the long-term health impacts of toxicity, environmental disease, and the heavy weight of lead have prompted the quest for new lead-free shielding materials. Lead-free multilayered polymer composites and non-lead nanocomposite shields have been proposed as effective replacement materials for traditional lead-based and single metal shields.

Using high-density and atomic-number elements such as bismuth, barium, gadolinium, and tungsten significantly improves composite shielding ability. Because of their high atomic number and excellent radiation attenuation capacity, lead-based shielding materials have historically been utilized extensively [2]. Hospitals and diagnostic facilities continue to use lead aprons, thyroid shields, gloves, and protective barriers as conventional radiation protection equipment [3]. These experts, who routinely work in radiation-exposed situations, rely on lead aprons to safeguard themselves. These aprons' weight and inflexibility put tremendous strain on the spine and musculoskeletal system, resulting un chronic pain and discomfort.

As a result, healthcare institutions and radiation safety authorities must address this employment hazard and investigate alternate protective aprons or ergonomic solutions to reduce the long-term health impacts on radiation workers [4]. A study of the three groups of cardiologists, orthopedic surgeons, and rheumatologists revealed that cardiologists have greater complaints about low back discomfort [5]. A 15-pound lead apron exerts up to 300 pounds per square inch of strain on the spinal discs.

Lead has a number of drawbacks despite its efficacy, such as toxicity, weight, lack of flexibility, and potential for environmental pollution [6]. Neurological, hematological, renal, and reproductive problems can result from prolonged exposure to lead [7]. Lead-containing material recycling and disposal also provide environmental issues [8]. As a result, scientists have concentrated on creating non-toxic, lightweight, flexible, and environmentally friendly substitutes for radiation shielding applications [9]. The advantages of using polymer matrix materials for radiation shielding include flexibility, chemical stability, lightweight, low maintenance, good workability, low cost, and so on.

As a result, efforts have been undertaken to strengthen polymers with appropriate fillers and additives, resulting in the creation of Polymer Matrix Composites [PMCs] as effective and efficient shielding materials. In addition to their shielding properties, these fillers increase the physico-mechanical properties of PMCs. Polymer-based composites combined with high Z micro/nanoparticles are commonly used in experiments to replace lead-based shielding materials. Polymer composites combined with metallic nanoparticles display greater shielding performance compared to those loaded with microparticles due to the arrangement of atoms having various absorption edges and the large surface area of nanoparticles. Shielding in Computed Tomography (CT) reduces radiation exposure to radiosensitive tissues during imaging processes. Shielding can be divided into two types: in-plane and out-of-plane [10]. In-plane shielding is positioned directly within the scanning field to protect organs in the primary beam, such as the eyes, during head CT scans.

Out-of-plane shielding is placed outside the scan field to limit scattered radiation exposure to organs outside than the region of interest, such as the gonads, during chest CT scans. While in-plane shielding is successful in dose reduction, it may degrade image quality due to increased noise and artifacts, whereas out-of-plane shielding has little influence on image quality [10].

Gamma rays are high-intensity ionizing radiation that can harm live cells by slowing down and transferring energy to them. Lead and concrete were utilized as radiation shielding materials.

However, it demonstrates that lead toxicity is a significant environmental illness with terrible consequences for the human body. As a result, there is an urgent need to develop a sustainable radiation shielding material to protect humans and the environment from the harmful effects of radiation. The best radiation shielding materials have a high atomic number and density, such as tungsten and concrete. There have been several experimental and theoretical studies conducted on radiation shielding materials.

Substances with good attenuation qualities that are appropriate for medical radiation shielding include tungsten, bismuth, barium sulfate, tin, antimony, and rare-earth composites, according to recent research [1-6]. The most frequent shielding materials used in CT imaging are bismuth and lead. Bismuth shielding is made of bismuth-impregnated latex and is extensively used to protect superficial radiosensitive organs such as the breasts, eyes, and thyroid because of its lightweight nature and effective X-ray attenuation properties, Bismuth shields have been proven in studies to reduce doses significantly, with Vollmar and Kalender (2008) reporting breast dose reductions of 42.8%-47.8%.

However, bismuth shielding can cause picture noise, distortions, and changes in CT number correctness. To reduce these effects, a thin foam spacer can be inserted between the shield and the patient, increasing image quality and maintaining radiation protection. Advanced multilayer composites and textile-based shielding systems with improved performance have been made possible by nanotechnology and polymer engineering [9]. Glass materials are suitable alternatives to lead and concrete because of their physical and optical qualities, which may be easily altered by composition and manufacturing technique.

Nowadays, glasses and glass-ceramics are used in radiation shielding applications. Furthermore, glasses can be doped with significant amounts of heavy metals such as Bi_2O_3, PbO, WO_3, and MoO_3, in order to render them an effective lead-free radiation shielding. Lead exposure is mostly caused by inhalation and ingestion when handling lead shielding materials such as lead bricks and lead aprons. Airborne lead dust formed during movement or damage to shielding materials can enter the respiratory tract, while contaminated hands may result in unintentional ingestion.

Lead can also cross the placenta during pregnancy, influencing fetal development. Lead is slowly eliminated and accumulates in the body, thus prolonged exposure may have harmful consequences on the hematological, cardiovascular, neurological, immunological, and reproductive systems. Heavy weight and continuous use of lead aprons in radiology departments may contribute to musculoskeletal diseases such as low back pain, myalgia, and tendonitis among technologists. Furthermore, broken or cracked lead aprons may lose their protective function, necessitating frequent quality checks. Chronic lead exposure can also harm reproductive health by reducing sperm quality in males and increasing the chance of miscarriage, preterm, and developmental abnormalities in females. Ionizing radiation, particularly X-rays used in medical imaging, can have a negative biological impact on tissues, cells, and DNA, making radiation shielding critical for both patients and healthcare professionals. Lead aprons have long been employed for their superior radiation attenuation qualities, with suggested lead-equivalent thicknesses ranging from 0.25 mm to 0.5 mm depending on the exposure conditions.

However, standard lead aprons are heavy, uncomfortable to wear for long periods of time, and can develop cracks or holes with frequent bending, diminishing their protective effectiveness and leading to musculoskeletal disorders such as back discomfort. To address these restrictions, lead-free protective compounds comprising lighter elements including antimony, tin, and barium have been created. Lead-based radiation protection solutions, such as lead aprons and shielding materials, are critical for protecting patients and healthcare staff from hazardous X-ray radiation during medical procedures. Unseen rays, such as X-rays, gamma rays, neutrons, and beta rays, can penetrate surfaces and cause radiation damage. Hospitals, nuclear power plants, particle accelerators, industrial radiography, and other sources use and generate these ionizing radiations. It is critical to safeguard the public, patients, and the environment against dangerous radiation.

Radiation shielding materials are used to prevent the harmful spread of radiation. The thickness of the radiation shield varies depending on the energy, type of radiation, and attenuation properties of the shield. To protect against X-rays, 1 to 2.3mm thick lead sheets are used on the walls of X-ray rooms, CT scanner rooms, and so on. However, 10 MeV radiation bunkers are built using 450 mm thick lead or 2300 mm broad concrete. Both lightweight (2.3g/cc) and heavyweight (>2.6 g/cc) concretes are extensively utilized to construct radiation shielding structures in radiotherapy bunkers, nuclear power plants, sterilizing plants, and so on. However, these have intrinsic disadvantages like as taking up space, being pricey, non-refillable, and thermally unstable.

Red mud is a hazardous alumina manufacturing waste that is very alkaline and contains heavy element leaching. Globally, 170 million tonnes of red mud are generated each year and left underutilized in disposal plants due to lack methods for large-scale usages These shielding materials are commonly used in dentistry clinics, hospitals, laboratories, nuclear plants, and radioactive material transportation to reduce radiation exposure. Excessive radiation exposure can cause microscopic damage to cells and tissues, resulting in immediate symptoms like skin burns and radiation sickness, as well as long-term problems including cancer and cardiovascular disease.

Lead's high atomic number and density make it an excellent attenuator of X-rays and gamma rays, absorbing and dispersing radiation energy. Lead shielding, lead bricks, lead lining, lead containers, and lead cabinets are examples of common lead-based radiation protection methods. Lead-lined doors, mobile screens, partitions, walls, windows, and lead bricks are all traditional ways to build protective barriers in radiation situations. Lead brick shielding, for example, offers better radiation protection than lead-lined drywall or plywood due to its high molecular density and non-porous structure, making it ideal for building radiation-shielded walls and partitions. Despite its efficiency, lead is a hazardous element that can endanger environmental and occupational health if not handled and maintained appropriately. Lead and mercury are naturally occurring heavy metals and prevalent environmental pollutants that, when exposed to high levels, can pose serious health hazards. Individuals may get exposed by occupational, environmental, or unintentional means, prompting many individuals to seek medical attention for suspected heavy metal toxicity.

These metals can harm several organ systems, including the neurological, cardiovascular, renal, and reproductive systems. As a result, clinicians must be able to recognize the signs and symptoms of poisoning, conduct appropriate laboratory examinations, appropriately interpret exposure levels, and determine when chelation therapy is required. Although severe toxicity still occurs, many suspected instances may not result in clinically significant poisoning, emphasizing the significance of accurate diagnosis and evidence-based care.

Metal exposure, particularly lead exposure, is still a common problem that is linked to past and present industrial practices. While the poisonous characteristics of metals are well understood, exposure to metals is simply one of several factors that contribute to elevated blood metal concentrations and the resulting health repercussions in people. Geochemical, biochemical, and physiological aspects influence the pace and extent of metal absorption. In youngsters, the interplay of these elements can be significant, especially if biochemical and physiological processes have not evolved to adult status. Such immaturity poses a higher risk to metal-exposed youngsters since they may be more sensitive to heightened absorption, particularly through the oral route.

The current study examines the literature on substitute lead-free materials for medical radiation shielding and talks about their uses, benefits, efficacy, and prospects. The comparative effectiveness of classic lead aprons against newer generation lead-free alternatives in radiation shielding is an important subject of study in medical safety. While lead aprons have long been the norm, concerns about weight and mobility have sparked research in lead-free alternatives that use elements like antimony, bismuth, and barium sulfate. Understanding the relative efficacy of these apron kinds is critical for improving radiation protection strategies in medical settings. Relevant studies were discovered using electronic database searches, with inclusion criteria centered on comparative evaluations of apron types in terms of radiation shielding performance and durability. Lead-free aprons provide equal radiation protection to standard lead aprons. In addition, thinner lead-free aprons were shown to be adequate for shielding, despite concerns about weight and mobility.

The systematic review focuses on the changing landscape of radiation protection in medical settings, with newer-generation lead-free aprons offering viable alternatives to older lead aprons. Furthermore, coupled metal shields displayed greater attenuation and dosage reduction than single-metal shields. Radiology is an important aspect of occupational medicine because it helps detect and evaluate work-related ailments, including respiratory problems, musculoskeletal conditions, and solvent-induced brain and liver disorders. Barium is a silvery-white metal that occurs naturally and is utilized extensively in both industry and medicine. Barium-based materials are being researched as alternatives to lead for radiation shielding due to their eco-friendliness.

In particular, barium sulfate has demonstrated encouraging shielding qualities without the health risks of lead. Studies have combined barium sulfate with materials like silicon, tungsten, molybdenum, and rubber to create flexible radiation shielding sheets. At various energy levels (30–150 kVp), these shields showed good radiation protection, with shielding performance on par with lead of the same thickness. Barium-based compounds are regarded as promising environmentally acceptable shielding materials for radiology and nuclear medicine applications because of their adaptability, reduced toxicity, and affordability. Radiological imaging, which compares exposed people to non-exposed persons, provides an objective tool for diagnosing occupational diseases, determining disease progression, and monitoring workplace dangers.

Because of their better sensitivity and diagnostic accuracy, advanced imaging techniques such as High-Resolution Computed Tomography (HRCT), Magnetic Resonance Imaging (MRI), and Magnetic Resonance Spectroscopy (MRS) are increasingly being utilized to detect occupational health concerns early on. Effective occupational health evaluation thus necessitates close collaboration between occupational health services and well-equipped imaging departments. Radiology is an important aspect of occupational medicine because it helps detect and evaluate work-related ailments, including respiratory problems, musculoskeletal conditions, and solvent-induced brain and liver disorders. Uncoated metallic lead is frequently used for radiation shielding in radiology, nuclear medicine, research, and industrial applications due to its strong radiation attenuation capabilities.

However, lead shielding may provide occupational health hazards due to the discharge of lead dust from oxidized or cleaned surfaces during handling and installation. Workers can inhale airborne lead particles, which poses a risk of lead toxicity. Studies have demonstrated that putting a polyurethane coating considerably minimizes lead dust dispersion and contamination. Although most worker exposures remain within the authorized occupational exposure limits, there is still a risk of overexposure during major shielding projects, emphasizing the significance of proper coating, ventilation, and safety precautions. A study on the remediation of buildings with degraded lead-based paint compared various cleaning procedures and their impact on worker lead exposure. Dry scraping and sweeping were used, as well as wet scraping with HEPA vacuuming and exhaust ventilation [11].

The results revealed that all approaches provided potential occupational health hazards, with certain airborne lead levels above OSHA exposure standards. Wet scraping combined with HEPA vacuuming resulted in the lowest lead exposure, however extra ventilation unexpectedly raised airborne lead concentrations. The study stressed the significance of appropriate cleaning methods and engineering measures to limit occupational lead exposure.

Materials and Methods

Method for Accessing Publications

The PubMed and Scopus databases were used to conduct a thorough literature search. Lead-free radiation shielding, "medical radiation protection," "tungsten shielding," "bismuth shielding," "polymer nanocomposites," and "X-ray attenuation materials" were among the keywords utilized.

Selection Norms
Included were research publications, review articles, and experimental investigations that were published in English between 2010 and 2026. Research on lead-free attenuation materials and medical radiation shielding applications was chosen.

Retrieval of Data
Relevant information about medicinal uses, attenuation efficiency, flexibility, toxicity, and shielding materials was extracted and methodically examined.

Results and Discussion
Lead-Free Radiation Shielding Materials Should Be Required
Lead's high atomic number and density allow it to be an efficient radiation attenuator.[2] Nevertheless, the hunt for alternatives that are more secure has been spurred by environmental contamination and occupational exposure [3]. The goal for modern radiation protection is to create shielding materials that are ergonomic and lightweight without reducing attenuation effectiveness [1].

Shielding Materials based on Tungsten
Tungsten's great density and superior radiation attenuation features render it one of the most viable substitutes for lead [4]. Composites made of tungsten and polymers indicate good shielding effectiveness while lowering material toxicity and increasing flexibility [1].

According to recent research, lightweight and flexible radiation shields appropriate for medical protective clothing were created by incorporating tungsten oxide nanoparticles into polyvinyl chloride matrices [12]. Tungsten powder-containing textile coatings also demonstrated notable attenuation performance measured on par via conventional lead aprons [13].
Tungsten Shield Applications
- Aprons that protect against radiation
- Transportable shielding curtains
- Barriers in the CT room
- Protective apparel for interventional radiology

Radiation Protection Using Bismuth
Bismuth is a desirable substitute for lead due to its high atomic number and low toxicity [10]. To minimize radiation exposure to radiosensitive organs such the thyroid, breast, and eyes, bismuth shields are frequently employed in CT imaging.

According to studies, bismuth oxide nanoparticles implemented in silicone and polymer matrix substrates offer increased flexibility and shielding effectiveness [10]. Composites based on bismuth also lower patient dosage without sacrificing adequate image quality. When employed in CT imaging, bismuth is an efficient radiation shielding material that lowers the exposure to radiosensitive organs such the thyroid, breast, and eye lens. It offers a considerable dosage decrease and is lightweight and simple to use. However, CT exposure control systems and image quality may be impacted by its use. Because radiation doses above 50 mGy can reach breast tissue, raising the long-term risk of radiation-induced cancer, breast shielding is particularly crucial in chest CT scans.

Benefits of Bismuth
- Less harmful than lead
- Adaptable composite construction
- In diagnostic radiology, effective attenuation
- Safer disposal for the environment Polymer Nanocomposites and Multilayer Structures.

Heavy metal oxide-reinforced polymer-based nanocomposites are a significant development in radiation shielding technology [1]. Because of the synergistic interactions between layered interfaces, multilayer composites containing tungsten and bismuth showed better attenuation efficiency [1].

Nanocomposites have a Number of Benefits
- The construction is lightweight
- Flexibility in mechanics
- Enhanced comfort for medical personnel
- Increased robustness

The "blind absorption zone" connected to conventional lead shielding is also lessened by sophisticated multilayer shielding systems [1].

Radiation Shielding Using Textiles
There has been a lot of interest in flexible textile-based shielding materials covered with powdered tungsten, bismuth, and barium sulfate [13]. These materials lessen the physical strain that heavy lead aprons generate and increase wearer comfort [13].
Currently, research is being done on radiation-protective fabrics for:
- Aprons for surgery
- Gloves for protection
- Thyroid collars
- Shielding gadgets for children Challenges and Limitations

Although lead-free materials demonstrate promising attenuation performance, several Limitations Remain:
- High manufacturing costs
- Difficulty in large-scale production
- Mechanical wear and durability concerns
- Limited standardization guidelines
- Reduced shielding efficiency at certain energy levels

Further research is necessary to optimize filler concentration, nanostructure design, and multilayer architecture to improve shielding performance [1].

Future Perspectives
It is anticipated that future radiation shielding technology will concentrate on:
- Eco-friendly, sustainable materials
- Composites improved by nanotechnology
- Wearable radiation shields with intelligence
- Protective systems with many functions that are hybrid
- Shielding materials that are recyclable and biocompatible

According to recent evaluations, innovative structural engineering techniques like nanofiber-based reinforcement and core-shell topologies may further enhance mechanical performance and shielding effectiveness.

Conclusion
In radiation therapy and medical imaging, lead-free radiation shielding materials have shown promise as substitutes for traditional lead-based protective systems. Composites composed of tungsten, bismuth, and polymers exhibit good attenuation qualities while reducing toxicity & increasing flexibility. For healthcare personnel, textile-based and multilayer nanocomposite shielding solutions provide improved comfort and ergonomic advantages. Ongoing developments in nanotechnology and material science are anticipated to hasten the creation of safer and more sustainable radiation shielding materials, despite a number of persistent

issues with cost, durability, and standardization. For broader acceptance in the medical sector settings, future research should give priority to clinical validation, long-term performance analysis, and environmentally friendly methods of production [14-18].

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