Development of Nanocomposites for Protection from Ionizing Radiations in Biomedical Field in India: A Review

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Abstract

With the advancement in technology, ionizing radiations are widely used for various diagnoses and treatments in the biomedical field in India. X-rays, CT scans, nuclear imaging, and radiation therapies for the treatment of cancer are commonly in use. In some countries, the use of ionizing radiation is restricted by strict protocols. In contrast, in countries like India, due to a lack of awareness among patients and staff, exposure to ionizing radiation in the biomedical field is on the rise. Careless use of this technology is increasing. Doctors, nurses, and staff operating machinery that uses ionizing radiations, as well as patients, attendants, and relatives, are equally exposed to ionizing radiations. Protection from radiation is necessary for the present generation. While there may be no immediate effects in most cases, indirect harm due to DNA mutations may occur in the future. Radiations are necessary and mandatory in the treatment of patients with severe diseases, which is simply unavoidable. However, it is very important to use protective clothing and accessories for staff, patients, and their relatives. Nowadays, X-rays and CT scans with low-voltage radiation doses are being developed and used, which will cause less harm. However, it is simply not possible to avoid ionizing radiation entirely. To mitigate these dangers, lead aprons are already being used. Lead, with a high atomic number, blocks X-rays from penetrating human tissues and thus provides protection to staff. However, lead is heavy, susceptible to cracking, toxic, and uncomfortable to use. In India, there is an urgent need to develop lightweight, flexible lead-free materials for radiation protection. This

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review paper highlights the research done so far in the development of nanocomposites, which have shown tremendous potential to serve this purpose.

Keywords: Ionizing Radiations, Radiation Therapies, Nuclear Imaging, Lead Toxicity, Nanocomposites.

1. Introduction

When ionizing radiation travels through matter, it can ionize or charge it electrically. Radiation-induced electrical ions can alter normal biological functions in living tissues. These days, the widespread use of diagnostic imaging is increasing ionizing radiation exposure. Radiation-induced electrical ions can alter normal biological functions in living tissues (Reisz et al. 2014). Natural sources of radiation have always existed, originating from cosmic and terrestrial elements, as well as from the ingestion of radioactive substances found in food, water, and air. Human exposure also occurs due to artificial sources, such as nuclear power plants and medical imaging technologies. Artificial radiation, including X-rays and radiation utilized for cancer treatment and disease diagnosis, also exposes us (ATSDR 1999).

In this study, the term "radiation" refers to "ionizing" radiation, which has the ability to ionize or electrically charge something as it travels through it. Ionizing radiation is necessary for both diagnostic and therapeutic applications in the rapidly developing biomedical field (Safari et al. 2024). It is used in advanced biomedical imaging technologies including radiotherapy, CT scans, and X-rays to identify and cure diseases (Ahmadi 2023). If not handled appropriately, the same radiation poses serious hazards to patients and medical professionals. The airflow from nuclear and coal power plants releases tiny quantities of radioactive substances into the ecological environments thus exposing human beings. Human exposure occurs because of therapeutic X-rays and scanned radiation employed during disease diagnosis and cancer treatment (Hussain et al. 2022). In the rapidly advancing biomedical sector, the utilization of ionizing radiation considering diagnostic and therapeutic purposes is indispensable (Al-Saleh et al. 2023). Advanced biomedical imaging technologies, such as X-rays, CT scans, and radiotherapy rely on ionizing radiation to diagnose and treat illnesses (Hussain et al. 2022). This radiation poses significant risks to both patients and healthcare providers if not properly shielded. Lead-based compounds have long been the industry standard for radiation shielding because of their high density and radiation-attenuating capabilities (Nath Abhijitand Shah, 2019). However, safer substitutes must be developed due to lead toxicity and environmental risks (Mahalingam et al. 2025). Radiation protection is essential for the present generation. While immediate effects are rare in most cases, long-term DNA mutations can lead to future health risks (Kc and Abolfath 2022). The pressing demand for lead-free nanocomposite materials in radiation shielding is addressed in this research.

2. Radiation Protection

Large amounts of ionizing radiation have long been known to harm human tissues. As more was discovered overtime, scientists' concerns about the possibly harmful consequences of high radiation exposure grew. A good number of expert bodies were established in response to the necessity of regulating radiation exposure to determine what should be done (Nath Abhijitand Shah, 2019). The International X-ray and Radium Protection Committee, a separate non-governmental organization composed of subject-matter specialists, was founded in 1928. Its new name became the International Commission on Radiological Protection (ICRP). Its goal is to provide fundamental guidelines and suggestions for radiation protection (ATSDR 1999). National laws controlling the exposure of radiation workers and the general public are based on these guidelines and suggestions. Additionally, the International Atomic Energy Agency (IAEA) has included them in its Basic Safety Standards for Radiation Protection (Kc and Abolfath 2022), which were released in collaboration with the OECD Nuclear Energy Agency (NEA), the World Health Organization (WHO), and the International Labor Organization (ILO). These guidelines are applied globally to guarantee the safety and protection of the public and radiation workers (Safari et al. 2024).

The safety discipline learned from the field of radiation protection demonstrates two primary ways to serve as an example. Every exposure to radiation above natural background levels might trigger health effects according to the first assumption (Reisz et al. 2014). Second, it seeks to shield present-day behaviors from those that will affect future generations. Radiation risk from medical imaging: Ionizing radiation is the type of radiation and scattered radiation that you get from nuclear imaging, CT, and X-rays. These procedures carry a radiation risk to both radiology personnel and patients (Ahmadi 2023). One category of carcinogen is X-rays. Any possible drawbacks are greatly outweighed by the advantages of X-rays. When compared with other X-ray treatments, CT scans provide the highest amount of radiation. Because X-rays involve radiation being fired at the patient, scientists have expressed concern over the years about the potential health effects of these procedures (Hussain et al. 2022).

3. Types of Radiography in Medical Imaging

3.1 Radiography

Radiography functions as a crucial imaging technology that employs X-ray energy to create internal visualizations of the body for medical diagnostic purposes. Radiography serves as a non-invasive method that clinicians use to identify bone fractures, infections, tumors, and lung conditions. X-ray beams penetrate the body's structures, and differences in tissue absorption generate examination-quality images of all components, including bones and soft tissues (Hussain et al. 2022). The diagnostic potential of radiography improves significantly through three advanced imaging modalities especially CT, fluoroscopy, mammography (Mirzaei et al. 2019). CT imaging produces sectional displays while fluoroscopy shows moving pictures and mammography specializes in breast cancer screenings. Medical imaging through radiography serves extensive diagnostic purposes for the assessment of jaw and tooth conditions in dental practices (Safari et al. 2024). The application of industrial radiography plays an essential role in materials inspection, - structural flaw detection, and safety evaluation of construction and manufacturing operations (Engström et al. 2023). The process of radiography is considered safe but radiation exposure which increases after prolonged contact requires protective gear including lead aprons and limits time spent inside the scan room.

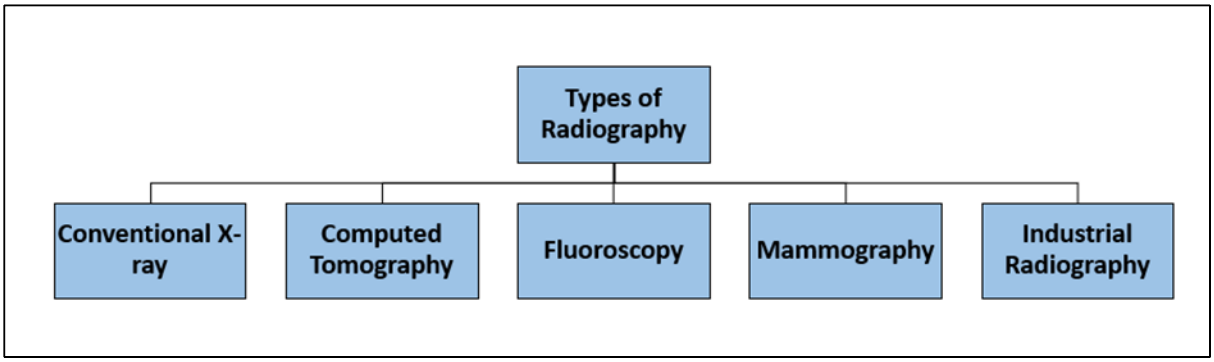

Figure 1. Types of Radiography

3.2 Importance of Radiation Protection

Protecting against radiation exposure proves essential for reducing the damage that ionizing radiation causes to patient's medical staff and nearby environments. The human body suffers severe consequences from long or overexposure to radiation which produces tissue damage and genetic mutations and elevates the risk of developing cancer (Al-Saleh et al. 2023). Medical imaging utilizes lead aprons together with thyroid shields and radiation monitoring devices to protect patients and radiographers from unnecessary radiation exposure. Acute diagnosis accuracy requires radiation doses that are only achievable at the lowest levels possible under reasonable circumstances (ALARA principle). Safety measures combined with effective equipment maintenance and correct protocol implementation form the essential components for stopping radiation mishaps. In industrial settings, radiation protection safeguards workers inspecting pipelines, aircraft parts, and construction materials (Nath Abhijitand Shah, 2019). The International Atomic Energy Agency (IAEA) along with the National Council on Radiation Protection and Measurements (NCRP) has developed guidelines that ensure the safe usage of radiation (Kc and Abolfath 2022). Effective radiation protection ensures both health preservation and establishes responsible behavior regarding radiological practices in medicine, industry, and research development. Radiation protection is important due to the following two unique and most important aspects:

- There is a chance that any elevated radiation level above the background will be harmful to one's health.
- It seeks to shield present-day activities from those that will affect future generations.

4. Shielding

In medical imaging using X-rays, there is an urgent requirement for shielding and protection for following in hospitals (Ahmadi 2023).

- Radiologists or doctors who are supposed to perform various procedures on different patients.
- Radiology staff who spend their entire time on duty in radiology labs to carry out X-rays and CT scans for various patients (Kim and Cho 2019).
- Patients or attendants who have come with the patients for an X-ray or CT scan (Mirzaei et al. 2019).

4.1 Shielding Principle

Protection shields represent the core method of radiation safety because these barriers create a defensive layer that stops radiation from reaching people. Protective measures with absorbing or blocking attributes inhibit radiation from causing harm to healthcare staff as well as patients and safeguard environmental integrity (Mirzaei et al. 2019). The effectiveness of shielding depends on the type of radiation and the material used. The intensity of the beam that comes from a material changes when an X-ray or gamma-ray beam passes through it (Hussain et al. 2022). The attenuation of the initial beam in the material, which is dependent on the penetrating properties of the beam and the physical properties of the material, is what causes the difference in intensity (Kim and Cho 2019). The weakening of an X-ray or gamma-ray beam as it passes through a material is known as attenuation (Fontainha et al. 2016). One of the following could be the reason for the reduction:

- Absorption, in which photon energy is converted to target or irradiated material atoms.
- Photon deflection from the beam, also known as scattering.

4.2 Lead as Shielding Material in Hospitals

The high density, low cost, easy processing, high atomic number, and best radiation-absorbing properties of lead (Pb) make hospitals rely on it as their primary material to block radiation particularly X-rays and gamma rays. The strong capability of radiation absorption in lead shields makes it crucial for radiology departments to protect both patients and healthcare personnel (Safari et al. 2024). Various lead shielding equipment illustrated in Figure 2, exists in different forms such as doors and aprons together with windows and thyroid shields for minimizing radiation exposure (Engström et al. 2023). Imaging staff members use portable lead screens and lead gloves to enhance their protection during radiologic procedures (Hussain et al. 2022). The amount of lead required for shielding depends on the type of radiation energy since stronger radiation needs thicker lead materials (Engström et al. 2023). Hospitals implement lead shielding according to protection guidelines throughout their diagnostic areas and operating environments as well as their nuclear medicine sections. The effectiveness of lead in blocking radiation comes with the essential need to handle and dispose of it safely because of its weight and toxicity (Mahalingam et al. 2025). The research into composite shielding materials attempts to deliver safer radiation protection through lighter-weight elements with equivalent efficiency (Kim and Cho 2019). Hospitals continue to use lead as their primary shielding material since it absorbs radiation better than any other substance. Although for a long period, lead was the best shield against ionizing radiation, there has recently been an increasing concern over the potential safety and health hazards associated with the use of lead (Hussain et al. 2022).

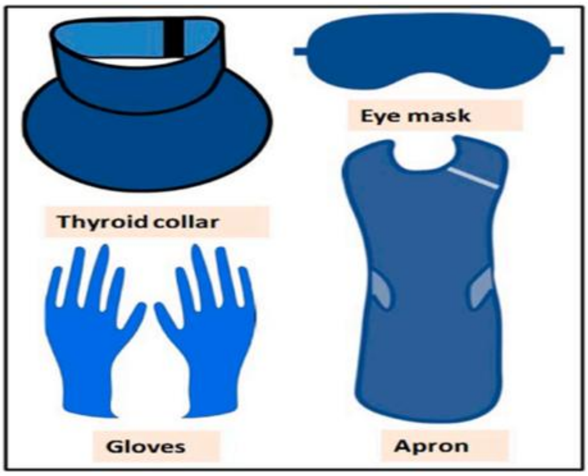

Figure 2. Schematic Diagram of Polymerization Various Types of Protective Garments used During Medical Diagnostic X-ray Techniques

4.3 Bad Effects of Lead Shields

Workers and patients can be adversely affected by lead exposure, which can negatively impact the biological systems of the human body. These hazards have been insidiously growing, prompting the need for more attention and awareness to be directed towards this issue (Engström et al. 2023). Lead toxicity and toxicokinetics include its movement through various parts of the body, such as blood, soft tissues, and bone (Hussain et al. 2022). Inorganic lead can enter the body through inhalation, ingestion, or skin contact, which can result in lead accumulation in various organs (Engström et al. 2023). The major drawbacks of lead shields are as follows:

1. **Lead Dust:** Any radiation shielding material that contains lead, including lead aprons, poses a health risk since lead dust can be released into the air and inadvertently consumed or inhaled by people.
2. **Bothersome Warmth:** The heavy and non-opaque nature of lead.
3. **Fatigue:** Fatigue is caused by its weight and warmth.
4. **Ache or Pain:** For radiologists who wear lead aprons and other lead shields, the main cause of low back discomfort is the constant overuse of the back muscles, which results in back pain.

According to the findings, lead aprons and thyroid collars are frequently uncomfortable to wear for extended periods of time, but only a tiny percentage of employees would be willing to forgo them in exchange for a slight increase in their risk of developing cancer in the future.

5. Requirements for New Shielding Material

Due to several health issues, such as toxicity, weight, and cracking, lead aprons and shields a classic shielding material used in medical applications are no longer in use. New shielding materials must be created in order to address these health issues (Hussain et al. 2022). Nanomaterials and polymers, for example, offer numerous advantages over lead aprons that overcome their drawbacks and offer adequate or superior shielding against ionizing radiation (Safari et al. 2024). Because of their notable chemical and physical characteristics, nanoparticles in various forms have recently drawn a lot of attention for radiation shielding applications. The basic requirements of new shielding materials are as follows:

1. Polymer composites containing micro- and nano-metal fillers that are flexible, lightweight, nontoxic, and ecologically friendly are needed for radiation shielding applications (Nambiar, Osei, and Yeow 2013).
2. Analysis is necessary to ascertain how shield thickness, tube voltage, nanofiller size, and nanofiller type affect dose reduction.
3. Because wearing an apron for an extended period of time is required, the weight of the apron should be decreased and the degree of comfort for doctors should be raised (Mahalingam et al. 2025).

6. Types of Lead-Free Materials (Nanomaterials, composites, and polymers) Identified for Research for Radiation Shielding

6.1 Titanium oxide (TiO2)

Titanium oxide's low cost and good photochemical stability make it a potential and popular semiconductor material. Its photostability, light dispersion, and potent UV light-flattering sunscreen qualities have led to its employment as a pigment and paint ingredient (Mahalingam et al. 2025). One of the materials that has been studied the most recently for energy and environmental purposes is TiO2.

6.2 Bismuth (Bi)

The diamagnetic semimetal bismuth (Bi) possesses a number of characteristics, including strong heat conductivity, magnetoresistance, and anisotropic electronic activity. Being the most non-radioactive element, bismuth has a variety of advantages over other high atomic number elements, including minimal toxicity, strong biocompatibility, cost-effectiveness, and an excellent nuclear sensitization possibility. Furthermore, at 100 keV, Bismuth exhibits a very high X-ray attenuation coefficient of μ=5.74 cm2/g, strong absorption, and X-ray opacity (Maghrabi et al. 2016).

6.3 Polymethyl methacrylate (PMMA)

A thermoplastic polymer with an amorphous and linear structure, PMMAis appropriate for a variety of applications due to its many appealing qualities. PMMA is more readily available, simpler to prepare, and less expensive to manufacture using non-volatile liquids and inexpensive monomers than other polymers (Al-Saleh et al. 2023).

7. Preparation for Polymer Composites

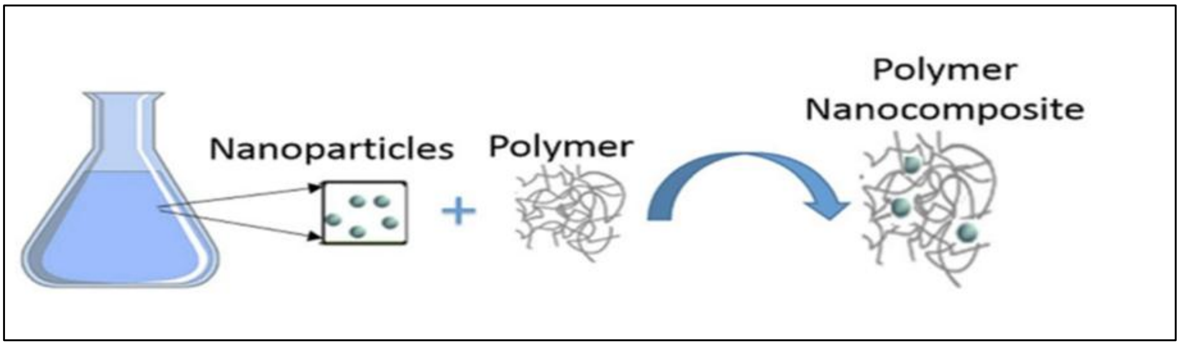

Figure 3. Schematic Diagram of Polymerization

The chemical process of polymerization creates vast, repeating molecular structures called polymers by joining tiny molecules described in Figure 3. The production method serves as a necessary chemical process for making diverse synthetic materials alongside natural materials that people routinely use (Huang et al. 2019; Rahaman, Mostafizur, and Aldalbahi 2019). The polymerization reaction operates through two essential processes: the first involves linking double-bond monomers, while the second mechanism involves condensation polymerization, which releases small molecules such as water during monomer union (e.g., polyethylene and polystyrene; nylon and polyester) (Nambiar et al. 2013). This production method functions across industries to create plastics, rubber items, adhesives, and artificial fiber materials (Stabik, Dybowska, and Chomiak 2010). Those developing from polymer science research have established sustainable polymers that degrade and recycle easily.

A lot of work is put into creating high-quality polymer matrix nanocomposites in a new, difficult field. High atomic number nanopowders of TiO2 bismuth, tungsten, barium sulfate, barium carbonate, etc. (Fontainha et al. 2016). have produced a range of outcomes when combined with different polymers. Combination, thickness, and molecule proportion all influence attenuation for varying X-ray machine voltages. Improved flexibility has demonstrated effective qualities as a substitute for non-lead aprons. These substances are also non-toxic, meaning they don't harm the body. The review found that single metal shields composed of bismuth powder performed better in terms of X-ray attenuation than shields constructed of tungsten or barium sulfate. Furthermore, compared to single-metal shields, the usage of two metals in a shield was linked to greater attenuation and dosage reduction (Huang et al. 2019). The particle size, the proportion of metal employed in the shield, and the tube voltage (kV) are some of the variables that influence how well shields reduce X-ray exposure. Therefore, it is anticipated that when shields are constructed, a higher metal ratio, a lower tube potential (kV), and smaller nanoparticle size could boost X-ray attenuation (Stabik et al. 2010). Bismuth-tungsten shields were shown to have the best potential for radiation protection among the shields under study (Maghrabi et al. 2016).

8. Attenuation/Radiation Protection Efficiency (%)

After a critical literature survey, some nanocomposites and polymers that show good percent attenuation of photon beam are enumerated below (Huang et al. 2019): -

Table 1. Comparison of Attenuation of X Rays of variable KVRange when Passed through Various Nanomaterials with Various Thickness

Sl. no	Authors [No. of reference]	Nanoparticles /Polymer composite	Size (nm)	Polymer	Thickness (mm)	Tube voltage (KV)	Attenuation/Radiation Protection efficiency(%)
1	Kholoud S. Al-mugren (Al-mugren et al. 2024)	HDPE (High-Density Polyethylene) with 15% of MoC (Molybdenm carbide)	5.36 µm	HDPE	3 mm	30 - 50 KV	94.04 % – 70 %
2	Kholoud S. Al-mugren (Al-mugren et al. 2024)	HDPE (high-density polyethylene) with 15% of WC	~300 nm	HDPE	2.8 mm	30 - 5P KV	91.73% - 63.58%

		(Tungsten Carbide)					
3	Nambiar et al. (Nambiar et al. 2013)	bismuth oxide (BO)	90–210 nm	Polydimethylsiloxane (PDMS)	1.3 mm	40–150 K V	86% at 60 KV
4	Maghrabi et al. (Maghrabi et al. 2016)	Bismuth oxide Bi2O3	10 µm	Polyvinyl chloride (PVC)	1.03 mm	80 KV	Maximum attenuation 67% at 80 KV
5	Aghaz et al. (Aghaz et al. 2016)	Tungsten dioxide WO3	100 nm Less than 20 µm	EPVC polymer matrix	1 ± 0.2 mm	100 KV	40% – 41.2 7% at 70 KV with 60 wt% of WO3
6	Fontainha et al. (Fontainha et al. 2016)	Zirconia ZrO2	100 nm	Poly(vinylidene fluoride–trifluoro ethylene)	1.0 mm	40 KV	60% with 10% ZrO2 at 40 KV

Table 1 shows a comparison of various materials with various thicknesses. Results of maximum attenuation on various KV X-ray sources are displayed in the table.

When the shielding materials referred to in sl no 1 and 2 were created and sliced into disks, it was discovered that they were lighter than lead. These composites offer a non-toxic and portable substitute for conventional shielding materials like lead, and they greatly improve X-ray attenuation, especially in low-energy regions (Aghaz et al. 2016). By employing a thicker shield or raising the percentage of heavy metal concentration, the HDPE +MoC composite, in particular, shows better shielding capabilities at 50 keV than other manufactured samples, indicating its potential for a safer medical diagnostic environment (Al-mugren et al. 2024). At sl no 3 Bismuth Oxide(BO) Nanopowder with 1.3mm thickness showed 86% attenuation at 60KV, whereas when BI2O3 was used at 1.03 mm thickness showed maximum attenuation at 67% at 80 KV (Nambiar et al. 2013) (Maghrabi et al. 2016). At sl no5 Tungsten Dioxide with 1 mm thickness showed 40 – 41 % attenuation at 70 KV (Aghaz et al. 2016). At sl no6 Zirconia ZrO with 1.0 mm thickness showed 60 % attenuation at 40 KV (Fontainha et al. 2016).

Due to the remarkable chemical and physical properties of nanoparticles in a variety of forms, including polymers of different types (i.e., nanocomposites), they present an enticing alternative to lead in ionizing radiation shielding with a great deal of attention for applications. The mechanical characteristics of the nanocomposites, their stability, durability, and resistance to environmental conditions, as well as the cytotoxicity of the nanomaterials, should all be taken into account when employing them as a novel radiation shielding materials.

9. Conclusion

The development of sustainable radiation shielding materials is required due to biomedical research involving ever-increasing ionizing radiation levels. Despite their effectiveness, traditional lead-based shielding methods' high toxicity and weight density cause serious health problems and environmental harm. Because nanocomposites have several advantageous qualities, including increased flexibility and weight reduction, as well as superior radiation-blocking capabilities, research on them is underway for additional shielding products. Bismuth oxide, tungsten dioxide, and titanium oxide nanomaterials are effective radiation-resistant materials without the use of lead when applied to polymer structures. These composites offer radiation protection and a solution to lead toxicity issues, making long-term clinical tools safer for patients and healthcare providers. Modern protective wearables made of polymer-based nanocomposites offer superior shielding efficacy along with increased comfort and mobility.

Future studies should concentrate on optimizing the scale-up of nanocomposite manufacturing and conducting extensive durability and reliability testing to guarantee performance. The biomedical industry can raise safety standards by creating lightweight, inexpensive, and ecologically friendly radiation shielding materials for long-term, sustainable medical practice.

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