Limitations of Conventional Thyroid Collars and Emerging Design Solutions: A Narrative Review

Running Title: *Limitations of Thyroid Collars*

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Abstract

Background: The thyroid gland is highly radiosensitive and is at considerable risk of occupational exposure in radiological and interventional procedures. Conventional thyroid collars are widely used due to their ability to attenuate scattered radiation; however, their design limitations may compromise both protective efficacy and user compliance in clinical settings. **Objective:** This narrative review aims to critically evaluate the limitations of conventional thyroid collars and synthesize emerging design solutions to improve radiation protection and ergonomic performance. **Methods:** A comprehensive narrative review was conducted using literature retrieved from PubMed, Scopus, Web of Science, and Google Scholar. Studies published between 2000 and 2026 were included, focusing on shielding design, material properties, ergonomic factors, and radiation attenuation. Articles were selected based on predefined criteria, and findings were synthesized using a qualitative thematic approach and a total of 60 studies were included. **Results:** Evidence indicates that conventional thyroid collars, despite adequate attenuation, are limited by poor anatomical fit, leading to gaps and potential radiation leakage. Ergonomic challenges, including excessive weight, uneven load distribution, and thermal discomfort, contribute to reduced compliance and increased risk of musculoskeletal disorders. Additionally, collar design may interfere with imaging, particularly during thoracic CT examinations. Emerging solutions—such as anatomically contoured designs, lightweight lead-free materials, improved fastening mechanisms, and weight redistribution systems—demonstrate enhanced fit, comfort, and usability. **Conclusion:** While conventional collars provide essential baseline protection, design-focused innovations are necessary to improve both safety and user compliance. Further standardization and clinical validation are required for broader implementation.

Keywords: *Radiation Protection; Thyroid Shielding; Thyroid Collar; Lead-Free Shielding; Radiation Safety Devices*

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1. Introduction

The use of ionizing radiation in modern medical imaging and interventional procedures has significantly enhanced diagnostic accuracy and therapeutic precision (1). However, it has also raised concerns regarding occupational radiation exposure among healthcare professionals. Among radiosensitive organs, the thyroid gland is particularly vulnerable due to its superficial anatomical location and high cellular sensitivity to ionizing radiation (2). Even low-dose, repeated exposure over time has been associated with an increased risk of radiation-induced thyroid dysfunction and malignancy, making effective protection of this gland a critical component of radiation safety protocols (3).

In routine radiological practice, especially in fluoroscopy-guided interventions, computed tomography (CT), and interventional radiology procedures, healthcare workers are frequently exposed to scatter radiation (4). To mitigate this risk, thyroid shielding devices, commonly in the form of conventional thyroid collars-are widely used as part of standard personal protective equipment (5). These collars are typically designed with lead or lead-equivalent materials to attenuate scattered X-rays and reduce radiation dose to the thyroid region. Their effectiveness in reducing radiation exposure has been well documented, leading to their widespread acceptance and routine use in clinical settings (6).

Despite their protective efficacy in terms of radiation attenuation, conventional thyroid collars exhibit several notable design limitations that may compromise their overall effectiveness and user compliance (6). Most commercially available collars follow a “one-size-fits-all” design approach, which often fails to accommodate individual variations in neck anatomy (7). This can result in inadequate coverage, particularly at the lateral and posterior aspects of the neck, creating potential pathways for radiation leakage. Furthermore, the weight and rigidity of traditional lead-based materials can impose significant ergonomic burden on the cervical spine, contributing to discomfort and long-term musculoskeletal strain among users, especially during prolonged procedures (8).

In addition to fit and ergonomic concerns, issues such as poor ventilation, heat retention, material degradation, and limited durability further reduce the practicality and lifespan of conventional thyroid collars (8). These factors may lead to reduced compliance among healthcare workers, ultimately diminishing the effectiveness of radiation protection strategies. Moreover, advancements in material science and biomedical engineering have highlighted the potential for improved designs that address these limitations through lightweight composites, anatomically contoured structures, and enhanced ergonomic features (8).

Given these challenges, there is a growing need to critically evaluate the shortcomings of conventional thyroid collars and to explore next-generation shielding systems that can optimize both protective performance and user comfort. Therefore, this narrative review aims to critically evaluate the limitations of conventional thyroid collars and synthesize next-generation shielding systems to improve radiation protection and ergonomic performance.

2. Methods

2.1 Study Design

This study was conducted as a narrative review aimed at critically evaluating the limitations of conventional thyroid collars and summarizing emerging design solutions in radiation protection. A qualitative synthesis approach was adopted to integrate findings from multidisciplinary domains, including radiology, biomedical engineering, ergonomics, and material science. The study selection process is illustrated using a PRISMA flow diagram.

2.2 Data Sources and Search Strategy

A comprehensive literature search was performed using the following electronic databases: PubMed, Scopus, Web of Science and Google Scholar. The search covered publications from 2000 to 2026, with emphasis on studies published in the last 10 years.

Search Keywords and Boolean combinations included: Radiation Protection; Thyroid Shielding; Thyroid Collar; Ergonomics; Occupational Exposure

2.3 Inclusion Criteria

Studies were included if they: Focused on thyroid radiation protection devices, discussed design, material, or ergonomic aspects of shielding, reported on radiation attenuation or leakage, addressed occupational safety or musculoskeletal impact, were published in peer-reviewed journals and were written in English.

2.4 Exclusion Criteria

Studies were excluded if they: Focused solely on patient shielding without relevance to thyroid collars, were case reports, editorials, or non-scientific articles, lacked sufficient methodological detail and were duplicate publications.

2.5 Study Selection Process

Relevant articles were identified through database searching and screened based on titles and abstracts. Full-text articles were then reviewed for eligibility. Additional studies were identified through manual reference screening of selected articles to ensure comprehensive coverage and a total of 60 studies were included.

2.6 Data Extraction and Thematic Analysis

Key information extracted from selected studies included: Type of thyroid shielding device, Material composition, Lead equivalence (Pb eq), Design characteristics, Ergonomic considerations, Reported limitations and Proposed innovations.

The extracted data were thematically categorized into: Limitations of conventional thyroid collars, Biomechanical and ergonomic considerations and Emerging design and material innovations.

2.7 Synthesis Approach

A qualitative narrative synthesis was performed to: Compare findings across studies, identify recurring limitations in conventional designs, highlight trends in emerging technologies and Establish gaps in current literature. No quantitative meta-analysis was conducted due to heterogeneity in study designs, methodologies, and outcome measures.

2.8 Reporting Standards

Although this study is a narrative review, efforts were made to ensure methodological transparency and rigor in line with principles of the PRISMA framework, as illustrated in Figure 1.

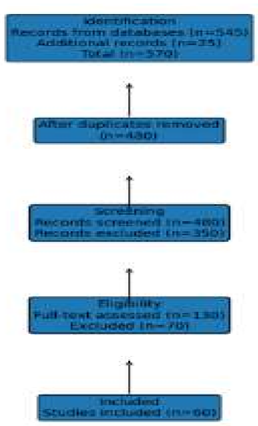

Figure 1: PRISMA flow diagram illustrating the process of literature identification, screening, eligibility assessment, and inclusion of studies.

3. Overview of Thyroid Radiation Protection

3.1 Thyroid Radiosensitivity and Occupational Risk

The thyroid gland is one of the most radiosensitive organs in the human body, primarily due to its superficial anatomical location and high mitotic activity of follicular cells (9). Exposure to ionizing radiation, even at relatively low doses, has been associated with an increased risk of thyroid dysfunction and malignancies, particularly papillary thyroid carcinoma (10). The biological effects of radiation on the thyroid can be broadly categorized into deterministic and stochastic effects. Deterministic effects, such as hypothyroidism, occur above a threshold dose, whereas stochastic effects, including carcinogenesis, have no threshold and increase in probability with cumulative exposure (11).

In radiological practice, occupational exposure to scatter radiation represents a significant concern for healthcare workers, especially those involved in interventional radiology, cardiology, and fluoroscopy-guided procedures (12). Unlike primary radiation, scatter radiation is less intense but more diffuse and unpredictable, contributing to chronic low-dose exposure over extended periods (13). The thyroid gland, due to its anatomical position in the neck region, is frequently within the field of scattered radiation. Studies have demonstrated that personnel not using appropriate thyroid protection may receive substantially higher doses compared to those using shielding devices, emphasizing the importance of consistent protective measures (14).

3.2 Principles of Radiation Shielding

Radiation protection of the thyroid gland is fundamentally based on the principles of attenuation of X-rays and gamma rays (14). When ionizing radiation interacts with matter, two primary mechanisms dominate within the diagnostic energy range: the photoelectric effect and Compton scattering. The photoelectric effect is more prominent at lower photon energies and in materials with higher atomic numbers, resulting in effective absorption of radiation. In contrast, Compton scattering predominates at higher energies and contributes to the generation of secondary scatter radiation, which is a major source of occupational exposure (15).

The effectiveness of thyroid shielding materials is commonly expressed in terms of lead equivalence (Pb eq), which indicates the thickness of lead required to achieve a similar attenuation effect (16). Standard thyroid collars typically provide lead equivalence ranging from 0.25 mm to 0.5 mm Pb, which can significantly reduce radiation exposure to the thyroid gland. However, the attenuation efficiency is influenced by several factors, including photon energy (kVp), material composition, and shield geometry (17).

Another critical consideration in radiation protection is scattering radiation, which originates from patient interactions and surrounding structures. Scatter radiation is highly dependent on procedural parameters such as beam energy, field size, and patient thickness. Effective thyroid shielding must therefore not only attenuate direct exposure but also minimize the impact of scattered radiation through adequate coverage and proper positioning (18).

3.3 Standard Thyroid Collar Designs

Conventional thyroid collars are widely used as part of personal protective equipment in radiological settings and are typically designed to provide circumferential coverage around the neck (19). Most commercially available designs consist of flexible shielding materials, traditionally lead or lead-equivalent composites, encased in protective outer layers for durability and hygiene. These collars are commonly integrated with or used alongside lead aprons to provide comprehensive radiation protection (16).

The most prevalent design is the wrap-around collar, which encircles the anterior and lateral aspects of the neck and is secured using fastening mechanisms such as Velcro straps (20). While this design is simple and easy to use, it often leaves portions of the posterior neck insufficiently protected. Variations in closure systems, including adjustable straps and overlapping flaps, have been introduced to improve fit and coverage, although these modifications may not fully address anatomical variability.

In recent years, there has been a gradual shift toward the use of lead-free shielding materials, including composites containing elements such as bismuth, antimony, and tungsten. These materials aim to reduce the weight of the collar while maintaining adequate radiation attenuation properties. Despite these advancements, conventional thyroid collar designs continue to face challenges related to fit, comfort, durability, and long-term usability, highlighting the need for further innovation in this domain.

4. Limitations of Conventional Thyroid Collars

Despite their established role in reducing radiation exposure, conventional thyroid collars exhibit several inherent limitations that may compromise both protective efficacy and user compliance (21). These limitations are primarily related to design uniformity, material characteristics, ergonomic constraints, and long-term durability. A critical evaluation of these shortcomings is essential to understand the need for improved and innovative shielding solutions.

4.1 Inadequate Anatomical Fit

One of the most significant limitations of conventional thyroid collars is their reliance on a “one-size-fits-all” design approach. Human neck anatomy varies considerably across individuals in terms of circumference, length, and contour, influenced by factors such as age, gender, and body habitus. Standardized collars often fail to conform closely to these variations, resulting in poor fitting and incomplete coverage (6).

This inadequate fit is particularly evident along the lateral and posterior aspects of the neck, where gaps may form between the collar and the skin. Such gaps can act as pathways for radiation penetration, especially in dynamic clinical settings where healthcare workers frequently change positions. Consequently, even collars with adequate lead equivalence may not provide optimal protection due to suboptimal anatomical conformity (22).

In addition, the structural shape and bulkiness of conventional thyroid collars may interfere with imaging procedures, particularly during CT examinations of the thorax and lower neck region (23). Conventional collars often incorporate an anterior “tongue-like” extension designed to enhance thyroid coverage; however, this protruding component can extend into the imaging field, leading to artefacts, obscuration of anatomical structures, or the need for removal prior to scanning (24). Consequently, thyroid collars are rarely utilized for patient protection during thoracic CT examinations, limiting their application primarily to occupational use. This highlights a critical design gap and underscores the need for low-profile, anatomically adaptive shielding solutions that conform strictly to neck dimensions without compromising image quality.

4.2 Radiation Leakage and Scatter Exposure

Conventional thyroid collars are primarily designed to attenuate direct radiation; however, they are less effective in addressing scatter radiation exposure arising from multiple angles (6). Open edges, insufficient overlap, and gaps created due to poor fit can result in “line-of-sight” radiation leakage, allowing scattered photons to reach the thyroid gland (25).

In interventional procedures, where operators frequently move around the patient and radiation source, the direction and intensity of scatter radiation vary continuously (26). Conventional collar designs do not adapt to these dynamic conditions, leading to inconsistent protection. This limitation is particularly critical in high-radiation environments such as fluoroscopy and interventional radiology, where cumulative exposure can be significant over time (27).

4.3 Weight and Ergonomic Burden

Traditional thyroid collars are predominantly made of lead or lead-equivalent materials, which contribute to their substantial weight. While effective in radiation attenuation, this weight imposes a considerable ergonomic burden on the cervical spine and surrounding musculature. Prolonged use during lengthy procedures can lead to neck fatigue, discomfort, and reduced range of motion (28).

Over time, repetitive strain associated with heavy protective equipment has been linked to the development of occupational musculoskeletal disorders (MSDs) among radiology personnel (29). These conditions may include chronic neck pain, cervical spondylosis, and trapezius muscle strain. As a result, users may be less inclined to consistently wear thyroid collars, thereby compromising radiation safety (30).

4.4 Poor Weight Distribution

In addition to overall weight, the manner in which the load is distributed plays a crucial role in user comfort and safety. Conventional thyroid collars often concentrate weight around the cervical region without adequate support from adjacent anatomical structures such as the shoulders. This uneven distribution leads to localized pressure points, particularly over the trapezius muscles and cervical spine (31).

Such pressure concentration not only contributes to discomfort but may also exacerbate fatigue during prolonged procedures. The absence of load-sharing mechanisms in traditional designs highlights a significant ergonomic deficiency that warrants attention in future shielding solutions.

4.5 Material Limitations

The materials used in conventional thyroid collars, typically lead or lead-based composites, present several drawbacks despite their high attenuation efficiency. Lead is inherently dense and rigid, limiting flexibility and adaptability to complex anatomical contours. This rigidity can further contribute to poor fit and discomfort during use (32).

Additionally, lead-based materials are prone to structural degradation over time, particularly with repeated bending, folding, and improper storage. Micro-cracks may develop within the shielding layer, which are often not visible externally but can significantly reduce radiation attenuation, leading to unintended exposure. The environmental and health concerns associated with lead handling and disposal also add to the limitations of these materials (33).

4.6 Thermal Discomfort and Poor Ventilation

Another notable limitation of conventional thyroid collars is their tendency to retain heat. The non-breathable outer coverings and dense shielding materials restrict airflow, leading to heat accumulation around the neck region. This can cause sweating, skin irritation, and general discomfort, particularly in high-temperature environments or during prolonged procedures (28).

Thermal discomfort is a critical factor influencing user compliance. Healthcare professionals may adjust or loosen collars to alleviate discomfort, inadvertently creating gaps that reduce protective effectiveness. Therefore, inadequate ventilation and thermal management represent significant barriers to optimal usage.

4.7 Durability and Maintenance Issues

The long-term durability of conventional thyroid collars is often compromised due to material fatigue and wear. Repeated use, folding, and improper storage can lead to internal damage such as micro-cracking of the shielding layer. These defects may not be readily detectable without specialized imaging, increasing the risk of unnoticed radiation leakage.

Furthermore, maintaining hygiene and structural integrity can be challenging, especially in high-volume clinical settings. The outer protective layers may degrade or become contaminated over time, necessitating regular inspection and replacement. Lack of standardized protocols for quality assurance and maintenance further exacerbates these issues, potentially compromising the safety of users.

In summary, while conventional thyroid collars provide essential radiation attenuation, their limitations in anatomical fit, ergonomic design, material properties, and durability significantly impact their overall effectiveness. These challenges underscore the need for innovative design approaches that address both protective performance and user comfort.

5. Ergonomic and Biomechanical Considerations in Shield Design

The effectiveness of thyroid shielding is not solely dependent on radiation attenuation but is also significantly influenced by ergonomic and biomechanical factors (35). Poorly designed protective devices can lead to discomfort, reduced compliance, and long-term occupational health issues among healthcare professionals. Therefore, integrating principles of ergonomics and biomechanics into the design of thyroid shields is essential to ensure both safety and usability in clinical environments (35).

5.1 Anthropometric Variability

Human anatomical diversity plays a critical role in the design and effectiveness of wearable protective equipment (36). Neck dimensions vary widely across individuals based on factors such as age, gender, ethnicity, and body mass index (BMI). Conventional thyroid collars, which are typically designed using standardized dimensions, often fail to accommodate this variability, resulting in suboptimal fit and coverage.

Anthropometric data-driven design approaches emphasize the need for adaptable or size-specific shielding solutions that conform closely to individual anatomy. Incorporating adjustable features or multiple size options can significantly improve the fit of thyroid collars, thereby enhancing both protection and comfort. Population-specific design considerations are particularly important in ensuring that protective equipment is suitable for diverse user groups (37).

5.2 Cervical Spine Biomechanics

The cervical spine is a highly mobile and structurally complex region responsible for supporting the head and facilitating a wide range of movements (38). The addition of external loads, such as thyroid collars, alters the normal biomechanical balance of this region. Even relatively small increases in weight can lead to changes in posture, muscle activation patterns, and load distribution across cervical vertebrae (39).

Prolonged use of heavy or poorly balanced thyroid collars can result in increased strain on cervical muscles and ligaments, contributing to fatigue and discomfort. Over time, this may predispose healthcare workers to chronic musculoskeletal conditions, including neck pain and cervical spine degeneration. Understanding the biomechanical impact of protective equipment is therefore crucial in designing collars that minimize strain while maintaining protective efficacy (40).

5.3 Finite Element Analysis (FEA) in Design Optimization

Finite Element Analysis (FEA) has emerged as a valuable tool in the design and optimization of medical protective equipment. By simulating mechanical behavior under various conditions, FEA enables the evaluation of stress distribution, deformation, and pressure points within a thyroid collar when worn by a user.

Through computational modelling, designers can identify areas of excessive stress concentration and modify the geometry or material properties of the collar to improve load distribution. FEA also allows for the assessment of different design configurations without the need for extensive physical prototyping, thereby accelerating the development process. The application of FEA in thyroid shield design contributes to the creation of ergonomically optimized devices that balance protection with user comfort.

5.4 Occupational Health Implications

The long-term use of protective equipment in radiological settings has significant implications for occupational health. Healthcare professionals, particularly those involved in interventional procedures, are required to wear protective gear for extended durations, often under physically demanding conditions. Poorly designed thyroid collars can exacerbate physical strain, leading to decreased productivity and increased risk of work-related injuries (41).

Musculoskeletal disorders (MSDs) are commonly reported among radiology personnel, with symptoms including neck stiffness, shoulder pain, and reduced mobility. These conditions not only affect individual well-being but may also impact clinical performance and patient care. Enhancing the ergonomic design of thyroid shields can play a crucial role in reducing the incidence of such disorders (42).

Furthermore, improved comfort and usability are likely to increase compliance with radiation safety protocols. When protective devices are perceived as less burdensome, healthcare workers are more likely to use them consistently, thereby improving overall radiation protection outcomes. Thus, ergonomic and biomechanical considerations are integral to the development of effective and sustainable thyroid shielding solutions (21).

6. Emerging Design Solutions in Thyroid Shielding

Advancements in material science, biomedical engineering, and ergonomic design have led to the development of innovative thyroid shielding solutions aimed at overcoming the limitations of conventional collars (43). These emerging designs focus not only on improving radiation attenuation but also on enhancing anatomical conformity, user comfort, and long-term usability. The integration of multidisciplinary approaches has opened new avenues for optimizing both protective performance and compliance in clinical settings (44).

6.1 Anatomically Contoured Shields

One of the most significant advancements in thyroid shielding is the development of anatomically contoured designs that conform closely to the natural curvature of the neck. Unlike traditional flat or cylindrical collars, these shields are shaped to provide uniform contact with the skin, thereby minimizing gaps that can lead to radiation leakage (45).

Contoured designs improve coverage of the lateral and posterior neck regions, which are often inadequately protected by conventional collars. By enhancing fit, these shields not only improve radiation protection but also reduce the need for frequent adjustments during procedures. This approach is particularly beneficial in dynamic clinical environments, where consistent positioning of protective equipment is essential (46).

6.2 Lightweight and Lead-Free Materials

The introduction of lightweight, lead-free shielding materials represents a major breakthrough in improving the usability of thyroid collars. Materials such as bismuth, antimony, tungsten, and composite polymers have been increasingly utilized to achieve effective radiation attenuation while significantly reducing weight (47).

These materials offer improved flexibility and adaptability compared to traditional lead, allowing for better anatomical conformity. Additionally, lead-free alternatives address environmental and health concerns associated with lead exposure and disposal (47). Although some variations in attenuation efficiency may exist depending on energy levels, ongoing advancements in composite materials continue to bridge this gap, making them viable alternatives in modern shielding applications (48).

6.3 Improved Closure and Sealing Mechanisms

Innovations in fastening systems have contributed to enhanced fit and stability of thyroid collars. Conventional Velcro-based closures are gradually being supplemented or replaced by more advanced mechanisms, including overlapping flaps, adjustable straps, and magnetic fasteners.

These improved closure systems allow for better customization of fit, ensuring consistent coverage across different users. Overlapping designs, in particular, help eliminate gaps at junction points, thereby reducing the risk of radiation leakage. Secure and adaptable fastening mechanisms also enhance user confidence and reduce the likelihood of improper positioning during clinical use (49).

6.4 Weight Redistribution Strategies

To address the ergonomic challenges associated with heavy protective equipment, emerging designs have incorporated strategies for improved weight distribution. Instead of concentrating the entire load on the cervical region, newer systems distribute weight across the shoulders and upper torso (50).

Hybrid designs that integrate thyroid protection with lead aprons or utilize shoulder-supported frameworks help reduce localized pressure on the neck. This redistribution of weight minimizes strain on cervical muscles and enhances comfort during prolonged procedures. Such approaches are particularly valuable in interventional settings, where healthcare professionals may be required to wear protective gear for extended durations (8).

6.5 Ventilation and Comfort Enhancements

Thermal discomfort has been a persistent issue with conventional thyroid collars. To address this, modern designs incorporate breathable fabrics, perforated layers, and moisture-wicking materials that improve airflow and reduce heat retention.

Some designs include multi-layered structures with inner comfort linings that enhance skin compatibility and reduce irritation. Improved ventilation not only enhances user comfort but also promotes consistent usage, thereby improving overall radiation safety. These features are especially important in high-temperature environments or during long procedures where discomfort can significantly impact compliance (51).

6.6 Smart and Adaptive Shielding Technologies

Recent developments in wearable technology have introduced the concept of smart thyroid shielding systems. These designs may incorporate embedded dosimeters or sensors capable of monitoring real-time radiation exposure. Such systems provide immediate feedback to users, enabling better awareness and adherence to safety protocols (52).

Adaptive shielding technologies are also being explored, where materials can dynamically respond to varying radiation intensities. Although still in early stages of development, these innovations hold promise for creating more responsive and intelligent protective equipment tailored to specific clinical conditions (53).

6.7 Personalized and 3D-Printed Shields

The application of 3D scanning and additive manufacturing has enabled the development of personalized thyroid shields tailored to individual anatomical profiles. By capturing precise neck dimensions, custom-fitted shields can be produced to ensure optimal coverage and comfort (54).

Personalized designs eliminate the limitations associated with standardized sizing and significantly reduce the risk of gaps and misalignment. Furthermore, 3D printing allows for rapid prototyping and customization, making it feasible to develop population-specific or even patient-specific shielding solutions. This approach represents a significant step toward precision-based radiation protection.

In summary, emerging design solutions in thyroid shielding address critical limitations of conventional collars by integrating advancements in materials, ergonomics, and technology. These innovations aim to enhance both protective efficacy and user compliance, paving the way for more effective and sustainable radiation protection strategies in clinical practice.

7. Comparative Insights from Literature

A synthesis of existing literature reveals a clear transition in thyroid shielding research from a purely attenuation-focused approach to a more integrated model incorporating anatomical fit, ergonomics, and user compliance. Conventional thyroid collars, typically composed of lead or lead-equivalent materials, have consistently demonstrated effective attenuation of scattered radiation, particularly within diagnostic energy ranges (16). However, their real-world performance is often limited by design-related inefficiencies.

Several studies have highlighted that the protective efficacy of conventional collars is compromised by inadequate anatomical conformity, resulting in gaps that allow radiation leakage (13). Even with sufficient nominal lead equivalence, incomplete coverage—especially along the lateral and posterior neck—can lead to variations in radiation dose exposure. These findings emphasize that attenuation alone does not guarantee optimal protection if design-related factors are not addressed.

In contrast, emerging shielding designs prioritize anatomical contouring and adaptive fit, which significantly improve coverage and reduce "line-of-sight" exposure pathways. Improved conformity ensures more consistent protection, particularly in dynamic procedural environments where operator positioning frequently changes (55). These designs also demonstrate enhanced stability, reducing the need for repositioning and thereby maintaining continuous protection.

Material innovations further differentiate modern shielding systems from conventional designs. While traditional lead-based collars provide high attenuation efficiency, their associated weight and rigidity contribute to ergonomic strain and reduced user compliance. Emerging lead-free composites offer comparable attenuation performance while providing increased flexibility and reduced weight, which are critical for prolonged clinical use (6). Studies suggest that improved comfort directly correlates with increased compliance, ultimately enhancing radiation safety outcomes.

Ergonomic considerations also play a pivotal role in comparative evaluations. Conventional collars are frequently associated with increased cervical strain and discomfort during extended use (56). In contrast, newer designs incorporating weight redistribution and improved load balancing have been shown to reduce musculoskeletal stress, thereby supporting long-term occupational health.

Thermal comfort and usability further distinguish emerging solutions. Traditional collars often exhibit poor ventilation and heat retention, negatively affecting user compliance. In comparison, modern designs utilizing breathable and moisture-wicking materials have been reported to enhance comfort and usability, encouraging consistent use (56).

Despite these advancements, certain limitations remain within emerging technologies, including variability in material performance at higher energy levels, increased production costs, and limited large-scale clinical validation. Additionally, heterogeneity in study methodologies and evaluation criteria continues to challenge direct comparison across studies (57).

Overall, the literature indicates that while conventional thyroid collars provide a foundational level of protection, emerging design innovations offer substantial improvements in fit, comfort, and functional performance. This shift highlights the growing importance of integrating radiation attenuation with ergonomic and user-centred design principles.

8. Clinical and Practical Implications

The effectiveness of thyroid shielding devices extends beyond their physical design to their practical application within clinical environments. While conventional thyroid collars provide essential baseline protection, their limitations significantly influence real-world usage, user compliance, and overall radiation safety outcomes (34). This limitation is largely attributable to the protruding anterior "tongue" design of conventional collars, which extends into the field of view during thoracic imaging. Such structural constraints highlight the need for redesigned, low-profile shielding devices tailored to neck dimensions, enabling safe application during CT examinations without compromising image quality.

One of the most critical implications is the relationship between device design and user compliance. Protective equipment that is heavy, poorly fitted, or uncomfortable is less likely to be used consistently, even if it offers adequate attenuation (58). Conventional thyroid collars, due to their weight, rigidity, and thermal discomfort, are often adjusted or improperly positioned during procedures, which may compromise their protective function. In contrast, ergonomically optimized and lightweight designs promote consistent use, thereby improving overall radiation safety.

Another important clinical consideration is the interaction between thyroid shielding and imaging procedures. Conventional collars may interfere with diagnostic imaging, particularly during CT examinations of the thorax and lower neck, where the collar can encroach upon the field of view and obscure critical anatomical structures (6). This may necessitate temporary removal of the shield, creating a trade-off between radiation protection and image quality. Such challenges highlight the need for context-specific shielding designs that maintain protection without compromising diagnostic accuracy (59).

From a workflow perspective, ease of use and adaptability are essential. Conventional collars with limited adjustability often require frequent repositioning, which can disrupt procedural efficiency and potentially compromise sterility in interventional settings (22). Emerging designs that incorporate improved fastening mechanisms and better anatomical conformity reduce the need for repeated adjustments, thereby enhancing workflow integration.

Economic considerations also influence clinical adoption. Although advanced shielding solutions offer clear ergonomic and functional advantages, their higher initial cost may limit accessibility in resource-constrained settings (60). However, when viewed from a long-term perspective, improved durability, reduced occupational health risks, and increased compliance may offset these initial costs. Locally developed or indigenous solutions may further enhance accessibility by providing cost-effective alternatives tailored to specific population needs.

Institutional practices and user awareness are equally important in determining the effectiveness of thyroid shielding. Regular inspection of protective equipment, adherence to usage protocols, and awareness of design limitations are critical factors influencing safety outcomes (2). Incorporating ergonomic considerations into procurement policies can further support the adoption of more effective protective devices.

In summary, the clinical impact of thyroid shielding is influenced by a combination of design, usability, workflow compatibility, and economic factors. Addressing these aspects through improved design and informed clinical practices can significantly enhance compliance and reduce occupational radiation exposure, ultimately contributing to safer radiological environments.

9. Challenges and Barriers to Implementation

Despite the promising advancements in thyroid shielding design and technology, several challenges hinder the widespread adoption and implementation of improved protective solutions in clinical practice. These barriers are multifactorial, encompassing economic, technical, regulatory, and practical considerations that must be addressed to ensure effective translation from innovation to routine use.

One of the primary challenges is the **cost associated with advanced materials and innovative designs**. Lightweight composites, lead-free materials, and personalized or 3D-printed shields often involve higher manufacturing and development costs compared to conventional lead-based collars. In many healthcare settings, particularly in resourcelimited environments, budget constraints may prioritize cost over ergonomic or design improvements. As a result, institutions may continue to rely on traditional, lower-cost shielding devices despite their known limitations.

Another significant barrier is the **lack of standardization in design and testing protocols**. While conventional thyroid collars are generally evaluated based on lead equivalence (Pb eq), emerging designs incorporate multiple variables such as material composition, geometry, and ergonomic features that are not uniformly assessed. The absence of universally accepted testing standards for these parameters makes it difficult to compare different products objectively and may hinder regulatory approval and clinical acceptance.

Regulatory challenges also play a critical role in the implementation of new shielding technologies. Medical protective devices must comply with established safety and quality standards, which can vary across regions. Obtaining certification from regulatory bodies requires extensive testing and validation, which can be time-consuming and costly. For innovative or indigenous designs, navigating these regulatory pathways may present additional difficulties, potentially delaying clinical adoption.

Limited availability of **large-scale clinical validation studies** represents another important constraint. While many emerging designs demonstrate promising results in experimental or pilot settings, there is a lack of robust, long-term clinical data evaluating their effectiveness in real-world environments. The heterogeneity of study methodologies, outcome measures, and reporting standards further complicates the interpretation and generalization of findings. This evidence gap may lead to hesitation among clinicians and institutions in adopting newer technologies.

Practical challenges related to **integration into clinical workflow** must also be considered. New designs, particularly those incorporating advanced features such as smart sensors or customized fitting, may require additional training for users. Resistance to change, especially in high-demand clinical environments, can limit the acceptance of unfamiliar devices. Furthermore, issues related to maintenance, storage, and compatibility with existing protective equipment may influence usability.

Another barrier is the **limited awareness and education regarding ergonomic risks and design limitations** of conventional thyroid collars. Many healthcare professionals may prioritize radiation attenuation without fully considering the long-term musculoskeletal impact or the importance of proper fit. This lack of awareness can reduce demand for improved designs and slow the adoption of innovative solutions.

Finally, **logistical and production challenges** may affect the scalability of advanced shielding technologies. Personalized and 3D-printed shields, while highly effective, require specialized equipment and expertise, which may not be readily available in all settings. Ensuring consistent quality and reproducibility in large-scale production remains a key concern.

In summary, although emerging thyroid shielding technologies offer significant improvements over conventional designs, their implementation is constrained by economic, regulatory, and practical barriers. Addressing these challenges through standardization, increased clinical validation, cost-effective manufacturing, and enhanced awareness will be essential for facilitating the widespread adoption of next-generation thyroid protection solutions.

10. Future Directions

The future of thyroid shielding lies in the integration of advanced technologies, user-centred design, and sustainable material innovations to overcome the limitations of conventional protective devices. As radiological practices continue to evolve with increasing procedural complexity and duration, the demand for more efficient, comfortable, and adaptive shielding solutions is expected to grow. Future research should also focus on redesigning thyroid shielding geometry, particularly eliminating bulky anterior extensions, to enable compatibility with thoracic imaging while maintaining adequate protection.

One of the key future directions is the incorporation of artificial intelligence (AI) and data-driven design approaches in the development of thyroid shields. AI can be utilized to analyze large anthropometric datasets and optimize design parameters for improved fit and coverage across diverse populations. Such approaches can facilitate the creation of adaptive or semi-customized shields that provide enhanced protection without compromising comfort.

The development of smart wearable shielding systems represents another promising avenue. Integration of miniaturized sensors and embedded dosimeters within thyroid collars can enable real-time monitoring of radiation exposure. These systems can provide immediate feedback to users, allowing for better awareness and adherence to radiation safety protocols. Over time, such data can also contribute to personalized exposure tracking and risk assessment.

Advancements in material science are expected to play a crucial role in shaping the next generation of thyroid shielding devices. Research into lightweight, flexible, and high-attenuation materials—such as nanocomposites and advanced polymers—offers the potential to significantly reduce the weight of protective equipment while maintaining or even enhancing shielding efficiency. Additionally, the development of environmentally sustainable and recyclable materials will address growing concerns related to the disposal and environmental impact of lead-based products.

The concept of personalized and 3D-printed shielding solutions is likely to gain further traction in the future. With improvements in 3D scanning technologies and additive manufacturing, it may become feasible to produce cost-effective, patient- or user-specific thyroid shields at scale. Such customization would ensure optimal anatomical fit, eliminate gaps, and improve overall user comfort and compliance.

Another important direction is the integration of shielding with other protective systems. Hybrid designs that combine thyroid protection with lead aprons, shoulder supports, or exoskeleton-assisted systems can enhance weight distribution and reduce musculoskeletal strain. These integrated systems may be particularly beneficial in interventional radiology settings, where prolonged use of protective equipment is common.

Furthermore, future research should focus on large-scale clinical validation and standardization of emerging designs. Establishing uniform testing protocols that evaluate not only radiation attenuation but also ergonomic performance, durability, and user satisfaction will be essential for guiding clinical adoption. Collaboration between clinicians, engineers, and regulatory bodies will play a pivotal role in advancing these innovations from concept to clinical practice.

In summary, future developments in thyroid shielding are expected to be driven by multidisciplinary innovations aimed at enhancing protection, comfort, and sustainability. These advancements have the potential to transform radiation safety practices and significantly reduce occupational risks in radiological environments.

11. Conclusion

Conventional thyroid collars remain a cornerstone of radiation protection, effectively attenuating scatter to a highly radiosensitive organ. However, their performance in clinical settings is often limited by design-related issues, including poor anatomical fit, radiation leakage through gaps, ergonomic burden, material rigidity, and reduced user compliance. These limitations highlight the need to move beyond purely attenuation-focused approaches toward more design-oriented solutions. Emerging innovations—such as anatomically contoured structures, lightweight lead-free materials, improved fastening systems, and better load distribution—demonstrate enhanced comfort, fit, and usability. Additionally, the incorporation of smart technologies and personalized design approaches reflects a shift toward adaptive, user-centred protection. Despite these advancements, barriers including cost, lack of standardization, regulatory challenges, and limited large-scale validation hinder widespread adoption. Addressing these issues through multidisciplinary collaboration and evidence-based design will be essential. Future thyroid shielding must prioritize both protective efficacy and clinical compatibility to ensure safer, more practical, and sustainable radiation protection strategies.

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