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REVIEW ARTICLE

Radiation safety in high-resolution computed tomography imaging: a detailed review of thyroid dose measurement techniques and protective strategies

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Abstract

High-resolution computed tomography (HRCT) provides exceptional diagnostic precision but raises significant concerns about thyroid radiation exposure, given the gland's high radiosensitivity and the increasing global burden of thyroid cancer. Approximately 560,000 new cases of thyroid cancer are diagnosed worldwide each year, with a female-to-male incidence ratio of roughly 3:1 and the highest age-standardized rates in high-income regions. Ionizing radiation is a well-established risk factor, particularly in children and adolescents, where even low doses (<0.2 Gy) can increase lifetime cancer risk. This review critically evaluates methods for quantifying thyroid dose during HRCT, including direct approaches such as thermoluminescent dosimeters (TLDs) and optically stimulated luminescent dosimeters (OSLDs), as well as indirect metrics like the computed tomography dose index (CTDI), dose– length product (DLP), and Monte Carlo simulations. Protective strategies are examined in detail, encompassing hardware-based measures (thyroid collars, bismuth shields), software and algorithmic solutions (automatic exposure control, iterative reconstruction), and imaging protocol optimization tailored to patient size, anatomy, and clinical need. Technological innovations, such as ultra-high-resolution CT and photon-counting detector CT, are discussed for their potential to reduce exposure without compromising diagnostic quality. The review also explores the influence of patient-specific factors, operator expertise, and cost–benefit considerations in implementing protective measures. Emphasis is placed on adhering to the "As Low as Reasonably Achievable" (ALARA) principle, ensuring that diagnostic accuracy is maintained while minimizing avoidable thyroid dose. Adoption of evidence-based protocols, accurate dosimetry, and continuous professional education is essential to enhance radiation safety in HRCT and reduce long-term thyroid health risks.

Keywords: High-resolution computed tomography. Radiation. Thyroid. Thermoluminescent dosimeters. Protection.

Introduction

Thyroid cancer is a growing global public health concern, with an estimated 560,000 new cases diagnosed annually and a marked female-to-male incidence ratio of approximately 3:1 **[1]**. Age-standardized rates are highest in North America and other high-income regions, while sub-Saharan Africa reports the lowest rates **[2]**. Over the past two decades, the incidence of thyroid cancer, particularly papillary thyroid carcinoma (PTC), has risen sharply, driven partly by increased detection through advanced imaging modalities such as high-resolution neck ultrasound **[3,4]**. These epidemiological trends highlight the combined impact of improved diagnostic capacity, demographic factors, and modifiable risk factors such as obesity and radiation exposure on the global burden of disease.

High-resolution computed tomography (HRCT) is indispensable in assessing lung conditions due to its ability to produce precise images, facilitating the diagnosis and management of various pulmonary diseases. It is particularly valuable in detecting interstitial lung diseases (ILD) by identifying distinctive patterns such as ground-glass opacities, reticular patterns, and honeycombing, which are essential for differential diagnosis and therapy planning **[5]**. These imaging capabilities often reduce the need for invasive procedures like surgical lung biopsies. Technological advancements such as ultra-high-resolution CT (U-HRCT) have further improved spatial resolution, enabling detection of minute structures and subtle disease manifestations that conventional HRCT may miss **[6]**. U-HRCT has proven effective in evaluating conditions like pulmonary hypertension and emphysema by detecting small airway and pulmonary vascular abnormalities **[7]**. It is also beneficial in complex cases where standard imaging is insufficient, such as ILD associated with systemic sclerosis **[8]**.

The thyroid gland is particularly sensitive to ionizing radiation due to its anatomical, physiological, and hormonal functions. This sensitivity is heightened in children and adolescents, where radiation can cause thyroid cancer, hypothyroidism, and structural changes **[9]**. Thyroid cancer, especially papillary thyroid carcinoma, has been linked to radiation exposure in survivors of the Japanese atomic bombings and the Chernobyl accident **[10]**. Even low doses (<0.2 Gy) increase thyroid cancer risk **[11]**. Radiation-induced thyroid cell DNA damage can lead to chromosomal rearrangements and mutations such as RET/PTC, frequently found in radiation-associated thyroid cancers **[12]**. The gland's genetic profile, metabolic activity, and iodine uptake contribute to its vulnerability **[13]**.

Beyond cancer, radiation exposure can cause hypothyroidism and autoimmune thyroiditis **[14-16]**. Children treated with radiation for other cancers often experience long-term endocrine problems affecting growth and development **[15]**. Radiation dose and protection are critical, especially in sensitive populations. Studies after Chernobyl documented a dose-response relationship between radioactive iodine exposure and thyroid cancer risk, with high rates in children **[17]**. Even low doses increase risk, with a threshold around 0.05–0.1 Gy, beyond which risk rises sharply **[18,19]**.

For hypothyroidism, doses as low as 3–5 Gy are significant in children. Preventive measures are essential, as cumulative doses as low as 0.065 mGy per procedure have been linked to increased risk in pediatric interventional cardiology. Effective protection includes using lead aprons and thyroid shields, which significantly reduce exposure **[20]**. Improvements in radiological procedures, such as pulsed fluoroscopy, can cut exposure to patients and staff by up to 70% **[21]**.

Scope of the Review

Thyroid Dose Measurement – The review examines methods for accurately quantifying thyroid doses in HRCT, including phantom applications, dosimetry techniques, and advancements in imaging technology. Particular emphasis is placed on U-HRCT, which improves image quality but may influence the dose received by the thyroid. The clinical applicability and accuracy of these techniques will be critically evaluated.

Protective Measures – Various precautions to protect the thyroid from ionizing radiation during imaging will be reviewed, including thyroid shields, lead aprons, and optimized imaging protocols. The effectiveness of these strategies will be assessed based on current evidence, such as studies confirming that proper shielding significantly lowers thyroid dosage.

Health Impacts – The review will address the health effects of radiation exposure to the thyroid, particularly the elevated risks of hypothyroidism and thyroid cancer. Emphasis will be given to the dose–response relationship and long-term impacts, especially in vulnerable groups like children and patients undergoing frequent imaging.

Technological Advances – Recent HRCT innovations affecting thyroid dose measurement and protection will be explored. This includes the development of U-HRCT,

its role in enhancing diagnostic accuracy and spatial resolution, and its potential for reducing radiation exposure.

Objectives of the Review

1. Evaluate techniques for determining thyroid dose in HRCT and identify gaps in current practice.
2. Assess the effectiveness of protective measures to minimize thyroid radiation exposure.
3. Highlight health risks from thyroid radiation and promote awareness among medical professionals.
4. Provide evidence-based recommendations for safe imaging and thyroid dose control in HRCT.

Understanding Radiation Exposure in HRCT

Radiation Basics in CT Imaging

Computed tomography (CT) is based on X-ray attenuation, where beams from a rotating X-ray source pass through the body, capturing projections from multiple angles. These are reconstructed into cross-sectional images using algorithms such as iterative reconstruction or filtered back projection, enabling detailed visualization of internal structures for diagnosing conditions like bleeding, fractures, and tumors **[21]**. CT offers high-contrast imaging of soft tissues, further enhanced by multislice CT (MSCT), which captures images faster with higher spatial resolution, facilitating advanced applications such as vascular imaging and blood flow assessment **[22]**.

HRCT employs ≤1 mm slice thickness to improve detail, crucial for diagnosing subtle pathologies like interstitial lung diseases and ground-glass opacities **[23]**. Innovations such as photon-counting detector (PCD) CT improve spatial resolution, reduce noise, and enable energy-resolved imaging, aiding in the detection of minute structures **[24,25]**. Advanced reconstruction methods, including compressed sensing and iterative reconstruction, enhance image quality, reduce noise, and allow lower radiation doses, especially valuable in pediatric imaging due to higher sensitivity to ionizing radiation **[26-28]**.

These technological improvements enable earlier and more accurate diagnosis of conditions like lung cancer and heart disease, supporting precise evaluations and personalized treatment plans. Despite these benefits, CT delivers significantly higher doses of ionizing radiation than standard radiography. Understanding radiation sources and their clinical implications is critical to optimizing protocols and ensuring patient safety.

Sources of Radiation in CT Imaging

In CT imaging, the X-ray tube is the primary radiation source, emitting ionizing radiation as it rotates around the body. Exposure levels depend on scanner type, imaging protocol, and body region. For example, coronary CT angiography delivers doses ranging from 1.2 to 4.3 mSv, depending on parameters **[29]**. Low-dose CT protocols can reduce exposure with minimal compromise to diagnostic quality, but balancing dose and image clarity remains essential, as poor images risk missed diagnoses **[30]**.

Technological advancements, such as iterative reconstruction, enable reduced doses while improving image quality. Ultra-low-dose CT can approach the radiation levels of conventional chest radiographs, significantly lowering exposure **[31]**. Patient factors, including age and body mass index, also influence dose, with higher BMI often requiring more radiation.**[32]** Pediatric imaging warrants special caution due to increased sensitivity and longer lifespans for potential adverse effects **[33,34]**.

Radiation-induced cancer remains a major concern; exposure above 10 mGy has been linked to increased tumor risk **[33]**. Growing awareness of these risks has driven calls for optimized imaging practices using CT only when necessary and employing low-dose protocols. Patient education is vital, as many are unaware of radiation risks. Informed consent ensures they understand both benefits and drawbacks **[27,35]**. Regulatory agencies have established diagnostic reference levels (DRLs) to guide safe radiation use while maintaining diagnostic quality. Facilities exceeding these levels are advised to investigate causes and implement corrective actions to enhance safety **[36]**.

Thyroid as a Sensitive Organ

The thyroid gland is highly sensitive to ionizing radiation, with risks including cancer and hypothyroidism. Sensitivity varies by age, radiation type, and biological traits, with children and teenagers particularly vulnerable due to active cell division **[37,38]**. Following the Chernobyl accident, infant exposure to radioactive iodine led to a marked increase in thyroid cancers **[38]**. Cellular radiosensitivity is linked to variations in DNA repair mechanisms, such as DNA-PKcs expression **[39,40]**. High metabolic activity also increases vulnerability **[41]**. Doses as low as 10 cGy raise cancer and nodule risk, and hypothyroidism risk increases with dose **[42]**. Gender differences exist, with women showing greater susceptibility **[43]**.

Protective measures like thyroid shields and bismuth shielding can significantly reduce exposure during imaging **[44,45]**. Monitoring thyroid function after radiation, particularly in head and neck tumor patients, is essential due to the high incidence of post-radiation hypothyroidism in children **[46]**. Public health

education is vital to encourage judicious imaging use.

Techniques for Thyroid Dose Measurement

Direct Dosimetry Methods

Measuring thyroid doses from radiation exposure is essential for assessing ionizing radiation hazards in medical imaging and therapy. Thermoluminescent dosimeters (TLDs) are widely used in radiology and radiation therapy to measure exposure by absorbing energy in a crystalline material and emitting light upon heating, with light intensity proportional to dose received. Their high sensitivity and broad measurement range make them suitable for thyroid dose assessment. Regular calibration, such as annual checks at personal monitoring centres in a Korean study, ensures accuracy **[47]**.

Other devices include optically stimulated luminescent dosimeters (OSLDs) and electronic personal dosimeters (EPDs). OSLDs operate similarly to TLDs but use different materials and stimulation methods, offering reusability and real-time readings. EPDs provide immediate exposure feedback, useful in high-radiation environments **[18]**. Accuracy is often evaluated via phantom tests using anthropomorphic models to replicate anatomy and assess device performance **[46]**.

Accurate thyroid dose measurement is crucial for estimating risks such as thyroid cancer and hypothyroidism, particularly for children exposed to higher doses **[48]**. Direct dosimetry data informs protective guidelines from organizations such as the American Thyroid Association, which advocate dose-reduction strategies including thyroid shields. Understanding dose–response relationships help clinicians decide on imaging necessity and protection use. Continuous monitoring of high-exposure individuals supports early detection of thyroid disease through imaging and functional assessments. TLDs and similar devices enable reliable historical dose tracking, aiding in both clinical decision-making and long-term health protection.

Indirect Dosimetry Methods

When direct measurement is not possible, indirect dosimetry techniques help determine thyroid doses from radiation exposure. Computed tomography dose index (CTDI) and dose-length product (DLP) are commonly used metrics. DLP, calculated by multiplying CTDI with scan length (cm), offers a normalized measure of radiation exposure, useful for comparing imaging protocols. In pediatric patients more sensitive to radiation DLP aids in estimating potential thyroid exposure during CT scans **[49]**.

CTDI, measured in milli-gray, quantifies the dose to a specified tissue volume. CTDIvol accounts for scan pitch, while CTDIw represents the weighted average dose. Both are vital in tailoring imaging procedures to minimize thyroid exposure **[50]**. Monte Carlo simulations also estimate organ doses by modeling radiation matter interactions, considering variables such as radiation type, energy, and geometry. This is valuable in complex cases where direct measurement is unfeasible **[51]**.

Accurate thyroid dose assessment is critical for evaluating risks of radiation-induced diseases such as thyroid cancer and hypothyroidism. Studies show higher risk in children and individuals exposed to higher doses **[52,53]**. Applying DLP, CTDI, and TLDs improves understanding of these risks and informs protective strategies. Professional bodies, including the American Thyroid Association, recommend methods to minimize thyroid exposure in imaging and treatment **[54]**. Knowledge of the dose–response relationship supports decisions on scan necessity and protective measures like thyroid shields. For those with significant exposure, ongoing monitoring, through thyroid imaging, function testing, and historical dose data from TLDs or other sensors, is essential to detect early disease and guide intervention **[55,56]**.

Factors Influencing Thyroid Radiation Dose

Patient-Specific Factors

Understanding the variables affecting thyroid radiation dose is essential in clinical settings involving therapeutic interventions and diagnostic imaging. Age significantly influences thyroid sensitivity to radiation. Children and teenagers are more prone to radiation-induced thyroid disorders, including cancer and hypothyroidism, due to higher gland activity and longer life expectancy, increasing cancer risk **[57]**. A pooled analysis showed higher thyroid cancer prevalence in survivors of childhood cancer exposed to radiation therapy, with risk decreasing as exposure age increased. Gender also affects vulnerability; epidemiological studies reveal higher post-radiation thyroid cancer rates in women than men, potentially due to hormonal and physiological differences **[57,58]**. For example, female patients receiving head and neck radiation therapy exhibited a significantly higher relative risk of thyroid cancer **[59]**.

Thyroid gland size and anatomical location also influence absorbed dose. Research indicates that greater gland exposure, especially to doses exceeding 30 Gy, increases hypothyroidism risk **[60,61]**. The height of the radiation field, treatment method, and gland size are major dose determinants **[62]**. Larger glands may absorb more radiation, elevating disease risk. Gland mass is a key factor in radioiodine therapy

planning for hyperthyroidism or thyroid cancer, with optimized parameters improving treatment effectiveness while minimizing side effects **[63]**.

Radiation therapy technique also matters. For example, IMRT can target tumors more accurately, sparing the thyroid and nearby healthy tissues **[64,65]**. However, thyroid dysfunction may still occur if the volume treated exceeds certain limits. Identifying patientspecific factors allows clinicians to tailor imaging and treatment plans, guiding dose measurement and identifying high-risk individuals **[66]**.

Insights from such research inform guidelines for thyroid radiation protection, as recommended by organizations like the American Thyroid Association **[67]**. Understanding dose–response relationships help clinicians decide on imaging necessity and preventive measures, such as thyroid shields. Long-term monitoring is critical for patients exposed to high radiation doses, involving regular thyroid imaging and function tests. Recognizing how age, gender, and anatomy influence dose enables more effective monitoring and protection strategies **[68]**.

Imaging Protocols

Factors influencing thyroid radiation exposure are vital for patient safety and diagnostic success during HRCT. Key parameters include scan range, tube voltage, and tube current. Tube voltage (kV) significantly impacts thyroid dose, with reductions to 80 kV lowering exposure by 32–60% without affecting diagnostic quality **[69]**. Because radiation exposure has an exponential relationship with voltage, even small reductions yield substantial dose decreases **[70]**. This is especially important for children, who are more sensitive to radiation. Tube current (mA) is directly proportional to absorbed dose; thus, lowering mA can reduce exposure while maintaining quality, particularly with adaptive modulation techniques tailored to patient size and imaging needs **[70,71]**.

Scan range also affects thyroid dose, as larger areas increase scatter radiation. Limiting coverage to necessary anatomical regions can reduce exposure **[72]**. Dose reduction can be further enhanced by iterative reconstruction, which maintains quality at lower doses **[73]**. Slice thickness and reconstruction method influence exposure. Thin slices increase dose but may improve resolution, whereas thicker slices reduce dose at the risk of diagnostic loss **[74]**. Reconstruction options, such as iterative algorithms and filtered back projection, can alter dose–quality balance, with iterative methods generally enabling lower doses.

Patient age, gender, and anatomy also influence thyroid dose. Children receive higher relative doses due to smaller gland volumes, and anatomical differences may affect distribution patterns **[75]**. Understanding these factors aids in assessing risks such as radiation-induced thyroid cancer or hypothyroidism, guiding clinical choices for imaging modality and protective strategies **[76]**. Professional bodies, including the American Thyroid Association, recommend minimizing thyroid exposure during diagnostic and therapeutic procedures **[77]**. Awareness of dose–response relationships helps determine imaging necessity and the use of preventive measures like thyroid shields. For those with high exposure, long-term monitoring is crucial, involving early disease detection imaging and regular thyroid function tests. Knowledge of parameter–dose relationships also support improved monitoring techniques **[78]**.

Operator Expertise

Operator skill significantly influences radiation exposure during imaging procedures, particularly in thyroid dose measurement. In operations like cardiac catheterization and interventional radiology, inexperienced operators often deliver higher doses due to less effective protective techniques and longer fluoroscopy times **[79]**. For instance, the REVERE study showed that novice operators had higher diagnostic angiography rates and prolonged fluoroscopy, leading to increased exposure **[80]**.

Operator behaviour, such as imaging technique selection and protective equipment use, affects dose levels. Skilled operators apply strategies like optimizing tube current/voltage, adjusting scan ranges, and efficient shielding **[81]**. Less-informed operators may inadvertently increase exposure through suboptimal practices. Protective gear, including thyroid shields, lead aprons, and protective curtains, can substantially reduce operator dose **[82]**. Proper operator placement and maintaining distance from X-ray beams are also critical **[83]**. Real-time dosimetry allows operators to monitor exposure and adapt techniques accordingly **[84]**. Awareness of received dose encourages optimization of imaging methods and protective measures. Continuous education and training are key. Studies confirm that recurrent training in radiation protection and dosimetry improves dose-reduction practices **[85]**.

Understanding how operator expertise influences radiation dose is vital for assessing risks such as thyroid cancer and hypothyroidism. Accurate dose quantification supports clinical decision-making, guiding imaging method selection and identifying high-risk individuals **[86]**. Follow-up for those with significant exposure should include periodic thyroid function assessment and early detection imaging. Professional

guidelines, such as those from the American Thyroid Association, recommend strategies to minimize thyroid dose during diagnostic and therapeutic procedures **[87]**. A clear understanding of dose-response relationships enables clinicians to balance diagnostic benefit with radiation risk **[88]**.

Protective Strategies for Reducing Thyroid Dose

Hardware-Based Approaches

Reducing radiation dose in imaging procedures such as high-resolution computed tomography (HRCT) is critical to prevent risks like thyroid cancer and hypothyroidism. Thyroid shields and collars, typically made of lead or other high-attenuation materials, are the most effective in limiting thyroid exposure. Studies show thyroid collars can significantly reduce radiation from modalities like CBCT and panoramic imaging **[89]**. For example, Hafezi et al. reported a 50% reduction during panoramic imaging **[90]**.

Recent innovations include elastic X-ray shields with bismuth oxide (BiO_3) in porous polyurethane, providing comfort and flexibility for chest CT exams **[91]**. Extended protectors now shield the neck and head, drastically lowering exposure to the thyroid and surrounding tissues **[92]**. Marshall et al. found that a lead acrylic face mask reduced brain dose by up to 80% while protecting the thyroid **[92]**. Bismuth shielding has also been tested in dental and medical imaging, effectively reducing thyroid doses, though efficacy varies with modality and placement **[93]**. Additional protective gear lead aprons, gloves, and eyewear further lowers operator exposure. Combining multiple protective devices enhances both patient and staff safety **[94]**.

Advances in CT technology also reduce radiation. Iterative reconstruction algorithms enable lower doses without image degradation, improving signal-to-noise ratio for sensitive organs like the thyroid **[95]**. Organ-based dose modulation adjusts radiation according to anatomy, minimizing exposure to radiosensitive organs, especially in children **[96]**. Beam shaping and collimation further limit dose by focusing the X-ray beam on the target area and reducing scatter, which also improves image quality **[97]**. Real-time dose monitoring systems provide immediate feedback, prompting operators to adjust techniques and adopt preventive measures.

Software and Algorithmic Solutions

Accurate thyroid dose estimation during high-resolution CT is essential to maximize patient safety and minimize exposure. Automatic Exposure Control (AEC) systems adjust tube current and voltage based on patient size and imaging needs, using real-time scout data to optimize exposure while preserving image quality, even for sensitive organs like the thyroid **[98]**. Generalized detectability indices now enable precise control of exposure for specific imaging tasks **[99]**. By integrating AEC with existing imaging protocols, unnecessary thyroid exposure can be significantly reduced without compromising diagnostic quality **[91,100]**.

Iterative reconstruction (IR) techniques further lower doses while maintaining image quality. Unlike filtered back projection, IR uses statistical modeling to iteratively refine images, reducing noise at low doses **[101]**. Studies show IR can cut pediatric radiation exposure by up to 60% while preserving diagnostic utility **[102]**, making it especially valuable for sensitive populations. Combining IR with AEC enhances thyroid safety by optimizing parameters and reducing total exposure **[103]**.

Software tools such as CT-Expo and ImPACT estimate organ doses based on CT parameters, offering superior thyroid exposure assessments **[104]**. Integrated with AEC, these programs provide immediate feedback during scanning. Understanding how AEC and IR affect thyroid dose informs risk assessment for radiation-induced conditions like thyroid cancer and hypothyroidism **[105]**. Professional bodies, including the American Thyroid Association, recommend dose-minimization strategies in diagnostic imaging **[106]**. Accurate dose quantification supports clinical decision making, identifying high-risk patients and guiding protective measures. Continuous monitoring of individuals receiving higher exposures through functional tests and targeted imaging helps detect early signs of thyroid disease. Knowledge of AEC and IR dose impacts enables more efficient monitoring and better long-term thyroid protection strategies **[107]**.

Protocol Optimization

Optimizing imaging protocols is key to reducing thyroid radiation during HRCT scans. Factors such as scan range, tube voltage, current, and preventive measures directly influence exposure. Limiting the scan range to essential anatomy can reduce unnecessary radiation, particularly in young patients with higher thyroid sensitivity **[108,109]**. Adjusting tube voltage and current is effective for dose minimization. Lowering tube voltage, e.g., from 120 kV to 80 kV, can reduce exposure by up to 50% without compromising image quality **[110]**. Tube current should be tailored to patient size and imaging needs **[111]**. Age, gender, and anatomy should guide protocol selection, with children requiring lower-dose settings **[112]**. Patient-specific phantoms help determine optimal parameters

to achieve ALARA-compliant imaging **[113]**.

Iterative reconstruction (IR) techniques allow dose reductions of 30-65% while maintaining quality, benefiting sensitive groups like children **[114,115]**. Automated exposure control (AEC) further optimizes doses by adjusting tube settings to patient size and study requirements, proving especially valuable in paediatric imaging **[116]**. Physical protection remains important. Lead or bismuth thyroid shields can substantially cut radiation, with collars reducing exposure by up to 50% in panoramic imaging **[117,118]**. Technological advances, such as improved collimation and photon-counting detectors, enhance targeting accuracy and reduce scatter, lowering thyroid dose **[119]**. Continuous operator education on radiation safety significantly improves the success of dose-reduction strategies **[120]**.

Clinical and Practical Implications

Radiation safety in HRCT imaging carries significant clinical and practical implications, particularly regarding prevention and monitoring of thyroid doses.

Balancing Diagnostic Accuracy with Safety

The primary aim of imaging is to minimize radiation exposure while ensuring diagnostic accuracy. HRCT is valuable in thyroid assessment but involves high ionizing radiation, which can raise thyroid cancer risk, especially in younger patients **[121]**. Adhering to ALARA, newer techniques like iterative reconstruction enable 30-60% dose reductions without loss of accuracy **[122,123]**. Automated exposure control can further optimize parameters based on patient size and anatomy **[124]**.

Impact of Dose Reduction on Outcomes

Reducing thyroid exposure lowers cancer risk. Shields can cut thyroid dose by up to 89%, significantly decreasing cancer induction risk **[125]**. Bismuth shields and lead aprons reduce exposure for both patients and operators, an important consideration in interventional radiology where cumulative exposure is a concern **[126]**.

Cost–Benefit of Protective Measures

Economic evaluation supports protective devices. Though shields require initial investment, preventing one thyroid cancer, costly to treat and detrimental to quality of life, justifies the expense **[119, 124]**. Advanced software, dose monitoring systems, and Monte Carlo simulations can further optimize protocols **[127]**. Demonstrating measurable exposure reduction helps institutions validate expenditures and promote a safety culture.

Current Challenges and Future Directions

Thyroid dose measurement during HRCT imaging is an evolving field, with ongoing research addressing technical limitations and exploring future improvements.

Dosimetry Limitations

Common dosimetry tools such as thermoluminescent dosimeters (TLDs) and computed tomography dose index (CTDI) metrics may yield inaccuracies due to calibration issues, varying measurement techniques, and patient-specific anatomical differences **[128]**. The choice of imaging protocols and dosimeter placement can significantly influence accuracy, and size or shape variations particularly in paediatric patients further affect dose estimation **[129]**. Despite their utility, TLDs and similar devices are not always available in clinical settings, with routine calibration and maintenance posing challenges, especially in low-resource environments **[130]**. Equipment type, environmental factors, and lack of standardized protocols also impact result validity **[131,132]**. Integration into routine practice remains limited, with many clinicians not consistently verifying radiation doses, leading to data gaps in risk assessment and prevention strategies **[133]**.

Gaps in Long-Term Risk Data

Data on the late effects of radiation on the thyroid are limited, despite known acute effects such as thyroid cancer and hypothyroidism **[134]**. Further research is needed into the molecular mechanisms of radiation-induced thyroid disorders and cumulative risks from repeated exposures. Current models often overlook patient-specific factors such as age, sex, and anatomy. Developing personalized risk assessment models could improve dose estimation accuracy and protective strategies **[135]**. While protective measures like thyroid shields are known to reduce exposure, guidelines for their optimal use, including best design and material, are lacking, necessitating further investigation **[136]**.

Role of AI and Advanced Modelling

Machine learning and AI offer potential for real-time, patient-specific dose optimization by analysing large datasets and adjusting imaging protocols accordingly **[137,138]**. Advances in hybrid computational phantoms and Monte Carlo simulations enable individualized thyroid dose and risk assessments based on patient anatomy and imaging parameters **[139]**. Integrating dosimetry estimates with imaging

data, such as quantitative SPECT/CT for analysing radioiodine biodistribution, can refine dose calculations and improve treatment personalization **[140]**. Such approaches could enhance patient safety, optimize protection, and improve therapeutic outcomes.

Conclusion

The thyroid gland's heightened radiosensitivity demands rigorous attention to radiation safety during high-resolution computed tomography imaging, especially in children and patients requiring repeated scans. This review underscores that accurate dose quantification whether through computed tomography dose index, dose-length product, thermoluminescent dosimeters, or computational modelling is fundamental to informed risk assessment and protective strategy design. Effective dose reduction can be achieved through a combination of physical shielding, optimized imaging protocols, iterative reconstruction, and automated exposure control, all integrated into routine workflows. Equally vital is ongoing operator training to ensure consistent application of best practices. Emerging technologies, including AI-driven dose optimization, advanced reconstruction algorithms, and novel shielding materials, hold promise for further reducing thyroid exposure while maintaining diagnostic precision. A shift toward personalized, evidence-based radiation protection will be key to enhancing patient safety and improving long-term outcomes in high-resolution computed tomography imaging.

CRediT

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Conflict of Interest

The authors declare no conflict of interest.

Similarity Check

It was applied by Ithenticate@.

Application of Artificial Intelligence (AI)

Not applicable.

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