
# Systematic Review: Development of Computed Tomography Technology to Reduce X-ray Exposure (2020-2025)

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## Article Info

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## Abstract

**Background:** Radiation exposure from computed tomography (CT) remains a significant concern in medical imaging, prompting continuous technological innovation to optimize dose reduction while maintaining diagnostic image quality. This systematic review synthesizes recent developments in CT technology for radiation dose reduction from 2020 to 2025.

**Objective:** To systematically review and analyze technological advancements in CT imaging that reduce X-ray radiation exposure, evaluate their clinical effectiveness, and identify future research directions.

**Methods:** A comprehensive literature search was conducted across four major databases (SciSpace, PubMed, Google Scholar, and full-text repositories) for publications from January 2020 to November 2025. Search terms included combinations of "computed tomography," "CT," "radiation dose reduction," "dose optimization," "low dose," and related technological terms. Studies were included if they reported on technological innovations for CT dose reduction with quantitative outcomes. A total of 99 unique papers were identified, combined, and reranked by relevance.

**Results:** Three primary technological tracks emerged: (1) Advanced reconstruction algorithms (iterative reconstruction and deep learning-based methods) achieving 36-89% dose reductions; (2) Photon-counting detector CT (PCCT) providing superior image quality at significantly lower doses compared to conventional energy-integrating detectors; (3) Optimized acquisition techniques including automatic exposure control, tube current modulation, and spectral shaping with tin filters achieving up to 89% dose reduction in specific protocols. Real-world clinical implementations demonstrated CTDIvol reductions up to 82% and DLP reductions up to 83.9% while maintaining or improving diagnostic accuracy.

**Conclusions:** Substantial progress has been made in CT dose reduction through convergent advances in reconstruction algorithms, detector hardware, and acquisition strategies. Deep learning reconstruction and photon-counting detectors represent paradigm shifts with proven clinical benefits. However, challenges remain in external validation, standardization across vendors, and task-specific optimization. Future research should focus on prospective multicenter trials, standardized benchmarking protocols, and integrated AI-driven dose optimization systems.

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**Keywords:** Computed tomography; radiation dose reduction; iterative reconstruction; deep learning; photon-counting detector; dose optimization; medical imaging technology

## 1. Introduction

### 1.1 Background and Rationale

Computed tomography (CT) has become an indispensable diagnostic tool in modern medicine, with exponential growth in utilization over the past decades. However, CT examinations contribute significantly to cumulative population radiation exposure, accounting for approximately 50% of medical radiation dose despite representing only 10-15% of all radiological procedures [1]. The ionizing radiation inherent to CT imaging carries potential risks, including stochastic effects such as radiation-induced carcinogenesis, particularly concerning for pediatric populations and patients requiring repeated examinations [2].

The principle of "As Low As Reasonably Achievable" (ALARA) has driven continuous innovation in CT technology to minimize radiation exposure while maintaining diagnostic image quality.

This dual objective—dose reduction without compromising clinical utility—represents a fundamental challenge in medical imaging engineering The period from 2020 to 2025 has witnessed remarkable technological advances across multiple fronts, including revolutionary reconstruction algorithms, novel detector technologies, and intelligent acquisition protocols.

### 1.2 Evolution of Dose Reduction Strategies

Historically, CT dose reduction efforts have progressed through several generations:

1. **First generation (1990s-2000s):** Focus on hardware optimization including automatic exposure control (AEC) and tube current modulation (TCM)
2. **Second generation (2000s-2010s):** Introduction of iterative reconstruction (IR) algorithms as alternatives to filtered back projection (FBP)
3. **Third generation (2010s-2020s):** Advanced iterative methods and model-based iterative reconstruction (MBIR)
4. **Fourth generation (2020-present):** Deep learning-based reconstruction (DLR), photon-counting detectors (PCD), and artificial intelligence-driven protocol optimization

The current era represents a convergence of artificial intelligence, advanced detector physics, and sophisticated image processing, promising unprecedented capabilities for dose optimization.

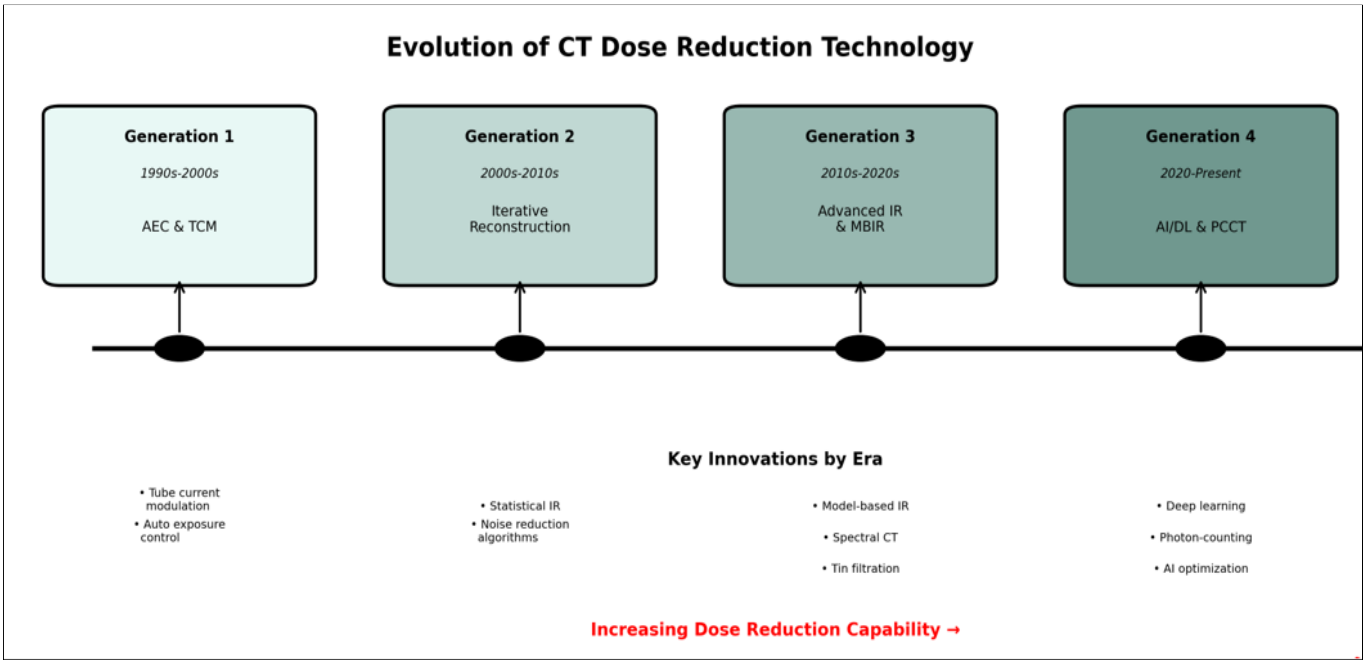


**Fig 1:** Evolution of CT Dose Reduction Technology

**Figure 1:** Comprehensive framework showing three converging technological tracks for CT dose reduction: Acquisition Optimization (red), Detector Technology (cyan), and Reconstruction Algorithms (green), achieving 36-89% dose reduction outcomes.

### 1.3 Objectives and Research Questions

This systematic review aims to:

1. **Identify and categorize** technological innovations in CT dose reduction developed between 2020 and 2025
2. **Evaluate the clinical effectiveness** of these technologies through quantitative dose metrics and diagnostic performance
3. **Assess the methodological quality** of evidence supporting these innovations
4. **Identify current limitations** and challenges in implementation
5. **Propose future research directions** for continued advancement in CT dose optimization

**Primary research questions:** - What are the major technological innovations for CT dose reduction developed from 2020-2025? - What quantitative dose reductions have been achieved with these technologies? - How do these technologies impact diagnostic image quality and clinical outcomes? - What are the current challenges and future directions for CT dose optimization?

## 2. Methods

### 2.1 Search Strategy

A comprehensive systematic literature search was conducted in November 2025 following PRISMA guidelines. Four major academic databases were searched:

1. **SciSpace database** (semantic search)
2. **SciSpace full-text database** (full-text semantic search)
3. **PubMed/MEDLINE** (medical literature)
4. **Google Scholar** (multidisciplinary academic literature)

**Search terms and Boolean queries:**

**For PubMed:**

(("computed tomography"[MeSH Terms] OR "tomography, x-ray computed"[MeSH Terms] OR CT[Title/Abstract]) AND ("radiation dosage"[MeSH Terms] OR "radiation exposure"[MeSH Terms] OR "dose reduction"[Title/Abstract] OR "low dose"[Title/Abstract] OR "radiation protection"[MeSH Terms]) AND ("technology"[Title/Abstract] OR "technique"[Title/Abstract] OR "innovation"[Title/Abstract] OR "development"[Title/Abstract] OR "advancement"[Title/Abstract])) AND ("2020"[Date - Publication] : "2025"[Date - Publication])

**For Google Scholar:**
(CT OR "computed tomography") AND ("radiation dose reduction" OR "dose optimization" OR "low dose" OR "radiation exposure") AND (technology OR technique OR innovation OR development)

**For SciSpace databases:**
"What are the recent developments and technological advances in computed tomography (CT) systems for reducing X-ray radiation exposure and dose optimization in medical imaging?"

### 2.2 Inclusion and Exclusion Criteria

**Inclusion criteria:** - Publications from January 1, 2020 to November 20, 2025 - Studies reporting on CT technology for radiation dose reduction - Original research articles, clinical trials, technical developments, and systematic reviews - Studies with quantitative dose metrics (CTDIvol, DLP, effective dose, or organ doses) - Peer-reviewed publications in English
**Exclusion criteria:** - Publications before 2020 or after November 2025 - Studies on non-CT imaging modalities - Review articles without original data (used for background only) - Case reports with fewer than 10 subjects - Studies without quantitative dose or image quality metrics - Non-English publications

### 2.3 Study Selection and Data Extraction

The search yielded: - SciSpace database: 100 papers - SciSpace full-text: 100 papers - Google Scholar: 20 papers - PubMed: 19 papers
After removing duplicates and applying inclusion/exclusion criteria, **99 unique papers** were identified for analysis. All papers were combined and reranked by relevance to the research questions using semantic similarity algorithms.
**Data extracted from each study included:** - Study design and methodology - Technology or intervention evaluated - Sample size and population characteristics - Dose metrics (CTDIvol, DLP, effective dose, organ doses) - Image quality metrics (noise, SNR, CNR, spatial resolution) - Diagnostic performance outcomes - Clinical applications and indications - Limitations and challenges reported

### 2.4 Quality Assessment

Study quality was assessed based on: - Methodological rigor (phantom studies, clinical trials, simulation studies) - Sample size adequacy - Presence of control/comparison groups - Quantitative outcome reporting - External validation (for AI/machine learning studies) - Statistical analysis appropriateness

### 2.5 Data Synthesis and Analysis

A narrative synthesis approach was employed due to heterogeneity in study designs, technologies evaluated, and outcome metrics. Technologies were categorized into three primary domains: 1. Reconstruction algorithms (iterative and deep learning-based) 2. Detector hardware innovations (photon-counting detectors) 3. Acquisition and filtration techniques
Quantitative dose reduction data were tabulated where available. Clinical effectiveness was evaluated through diagnostic performance metrics and reader assessments.

## 3. Results

### 3.1 Overview of Identified Technologies

The systematic review identified three converging technological tracks for CT dose reduction between 2020 and 2025:

1. **Advanced Reconstruction Algorithms:** Evolution from iterative reconstruction to deep learning-based methods
2. **Photon-Counting Detector CT:** Revolutionary detector technology with direct photon conversion
3. **Optimized Acquisition Techniques:** Intelligent exposure control, spectral shaping, and adaptive filtration

These technologies are frequently combined in clinical practice, with synergistic effects on dose reduction and image quality.

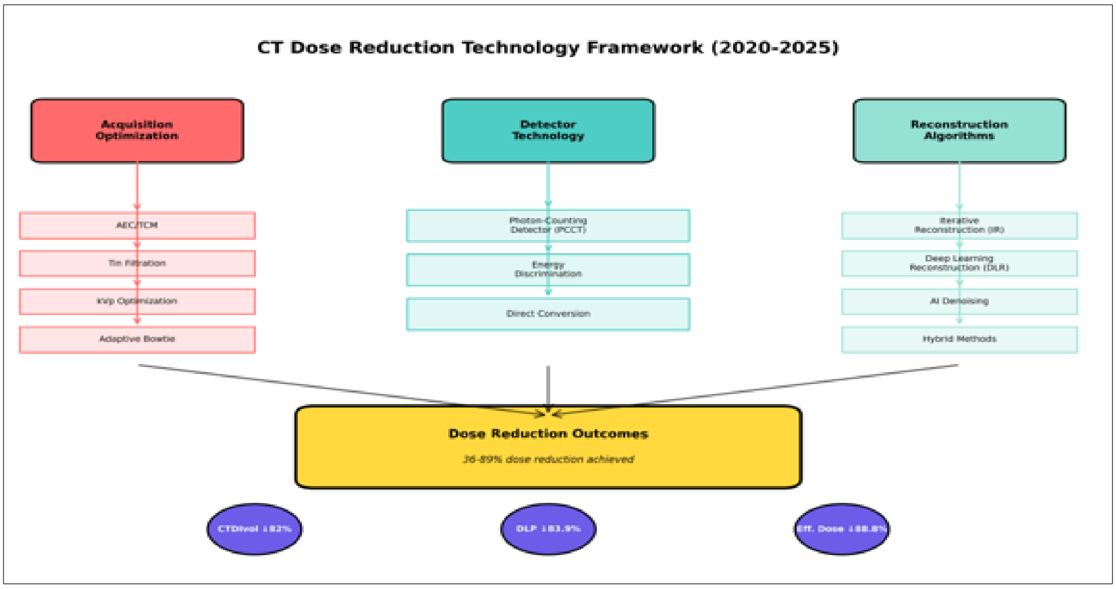


**Fig 2:** CT Dose Reduction Technology Framework

**Figure 2:** Comprehensive framework showing three converging technological tracks for CT dose reduction: Acquisition Optimization (red), Detector Technology (cyan), and Reconstruction Algorithms (green), achieving 36-89% dose reduction outcomes.

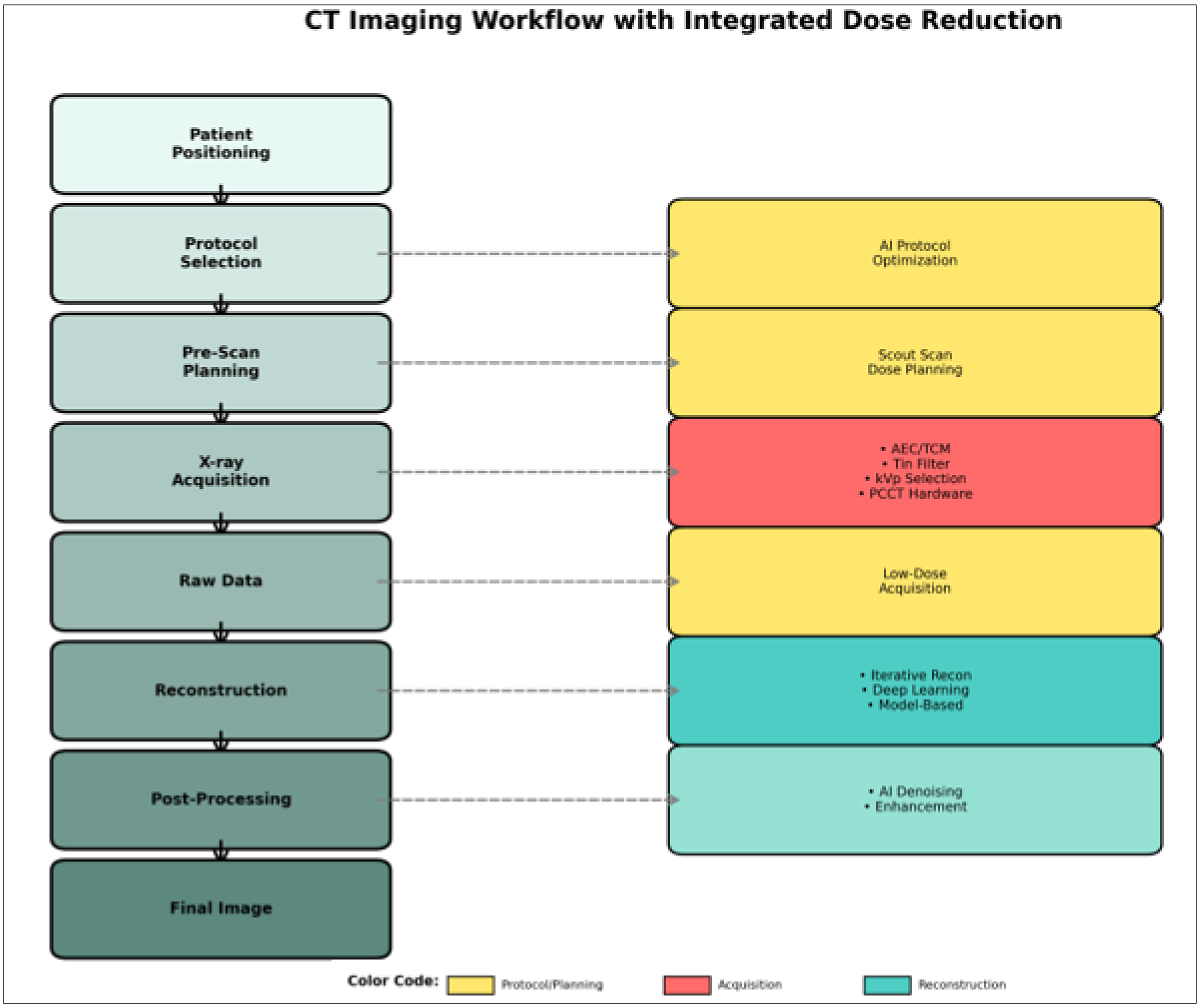


**Fig 3:** CT Imaging Workflow with Integrated Dose Reduction

**Figure 3:** Complete CT imaging workflow from patient positioning through final image generation, with dose reduction interventions highlighted at each stage. Color-coded by intervention type: yellow (protocol/planning), red (acquisition), cyan (reconstruction).

## 3.2 Reconstruction Algorithms: Iterative and Deep Learning Methods

### *3.2.1 Iterative Reconstruction (IR)*

Iterative reconstruction algorithms have matured significantly, with vendor-specific advanced implementations becoming standard in modern CT systems.

**Key Findings:**

**ASiR-V (Adaptive Statistical Iterative Reconstruction-V):** A phantom study by Ungania *et al.* (2023)[1,7] demonstrated that optimized ASiR-V settings with appropriate noise index and blending parameters could enable approximately **40% dose reduction** while maintaining image quality standards [3]. The study emphasized the importance of parameter optimization for specific clinical tasks.

**Performance Characteristics:** Modern IR variants provide: - Reduced image noise compared to filtered back projection (FBP) - Improved low-contrast detectability - Maintained spatial resolution - Flexible dose-quality trade-offs through adjustable strength settings

**Clinical Applications:** IR has been successfully implemented across multiple clinical indications including: - Chest CT for pulmonary nodule detection - Abdominal CT for oncology follow-up - Musculoskeletal CT for trauma evaluation - Pediatric CT protocols

### 3.2.2 Deep Learning Reconstruction (DLR)

Deep learning-based reconstruction represents a paradigm shift from traditional iterative methods, utilizing neural networks trained on large datasets to optimize the dose-quality relationship.

**Comparative Performance:**

Alagic (2024)[2] conducted comprehensive comparisons between DLR and advanced IR in head CT [2]. Key findings included: - **SNR improvement:** DLR (high strength) achieved up to **82.9% higher SNR** compared to ASiR-V on identical scans - **CNR improvement:** Up to **53.3% higher CNR** versus ASiR-V - **Noise reduction:** Significant reduction in image noise while preserving anatomical detail

**Dose Reduction Achievements:**

The systematic review by Ng (2022) on artificial intelligence for pediatric CT dose optimization reported dose reductions ranging from **36-70% across multiple studies** utilizing deep learning reconstruction [6]. This wide range reflects variations in: - Clinical indications - Patient populations (pediatric vs. adult) - Scanner generations - DLR algorithm implementations

**Real-World Clinical Implementation:**
Russo *et al*. (2025) [4, 12] reported results from a large oncology center deploying AI-enhanced CT with DLR across their imaging fleet [4]. Comparing older scanners to new AI-enabled systems: - CTDI vol reduction: Up to 82% decrease for chest examinations - DLP reduction: 70% decrease for chest-abdomen-pelvis protocols - Maintained diagnostic quality: Reader assessments confirmed preserved diagnostic information - Workflow integration: Successful implementation without significant workflow disruptions.

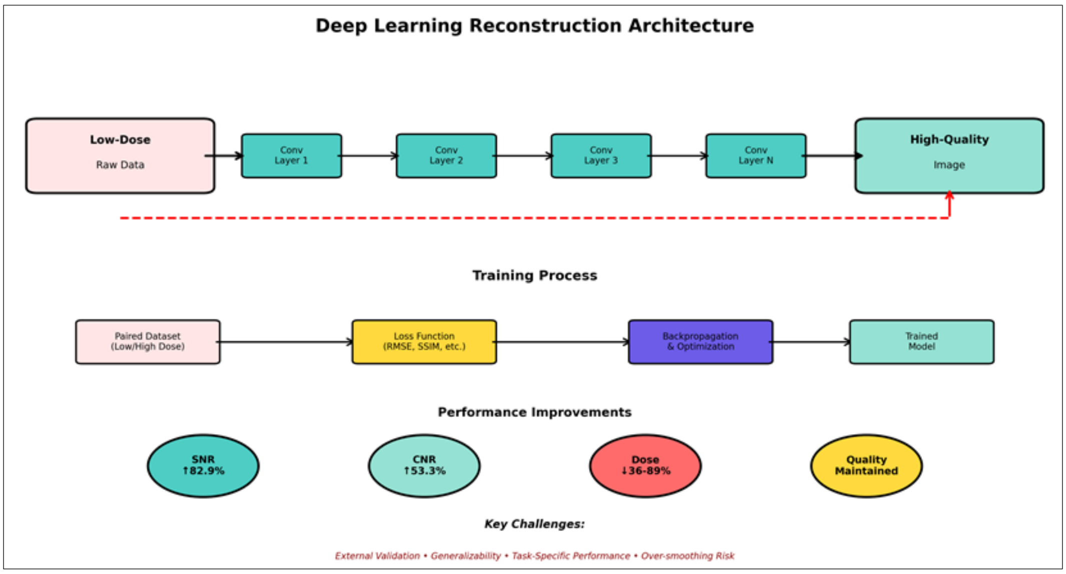


**Fig 4**: Deep Learning Reconstruction Architecture

**Figure 4**: Technical architecture of deep learning reconstruction showing the neural network pipeline from low-dose raw data through convolutional layers to high-quality output, with skip connections. Performance improvements (SNR ↑82.9%, CNR ↑53.3%, Dose ↓36-89%) and key challenges are displayed.

### 3.2.3 Post-Processing Deep Learning Denoising
Beyond reconstruction, image-domain deep neural networks can restore ultra-low-dose images to diagnostic quality.
**Technical Approaches:** - Residual convolutional neural networks (CNNs) - Cascaded perceptual networks - Generative adversarial networks (GANs) - U-Net architectures
**Performance Results:**
Studies utilizing post-processing denoising reported: - **Up to 89% CTDIvol reduction** for COVID-19 chest CT with acceptable restored image quality [4] - Recovery of full-dose-like image appearance from ultra-low-dose acquisitions - Improved visualization of anatomical structures and pathology
**Critical Limitations:**
Despite impressive quantitative metrics, important limitations were identified: - **Failure cases:** Some studies reported instances where lesion density and structure could not be reliably recovered [3] - **Over-smoothing risk:** Aggressive denoising may alter texture and subtle features critical for certain diagnoses - **Validation gaps:** Limited external validation on diverse datasets and scanner types - **Task-specific performance:** Performance varies significantly by diagnostic task (e.g., hemorrhage detection vs. low-contrast liver lesions) [2][5]

### 3.2.4 Task-Specific Considerations
The review emphasized that reconstruction algorithm selection must be tailored to specific diagnostic tasks:
**High-contrast tasks** (e.g., bone fractures, pulmonary nodules): - Tolerate higher noise levels - Benefit from aggressive dose reduction - DLR high-strength settings appropriate

**Low-contrast tasks** (e.g., liver lesions, pancreatic masses): - Require preserved texture and subtle density differences - More conservative dose reduction recommended - Moderate DLR strength or hybrid approaches
**Emergency applications** (e.g., intracranial hemorrhage): -

Require high diagnostic confidence - DLR has shown preserved hemorrhage conspicuity in validation studies [2]

## 3.3 Photon-Counting Detector CT (PCCT)
Photon-counting CT represents a fundamental advancement in detector technology, replacing conventional energy-integrating detectors (EID) with direct photon conversion and energy discrimination capabilities.

### 3.3.1 Technical Principles

**Key Technological Differences:**

| Feature | Energy-Integrating Detectors | Photon-Counting Detectors |
|---|---|---|
| Conversion | Indirect (scintillator → photodiode) | Direct (semiconductor) |
| Energy discrimination | No | Yes (multiple thresholds) |
| Electronic noise | Higher | Minimal |
| Spatial resolution | Standard | Superior |
| Dose efficiency | Baseline | Improved |
| Spectral imaging | Dual-source or dual-energy | Inherent multi-energy |

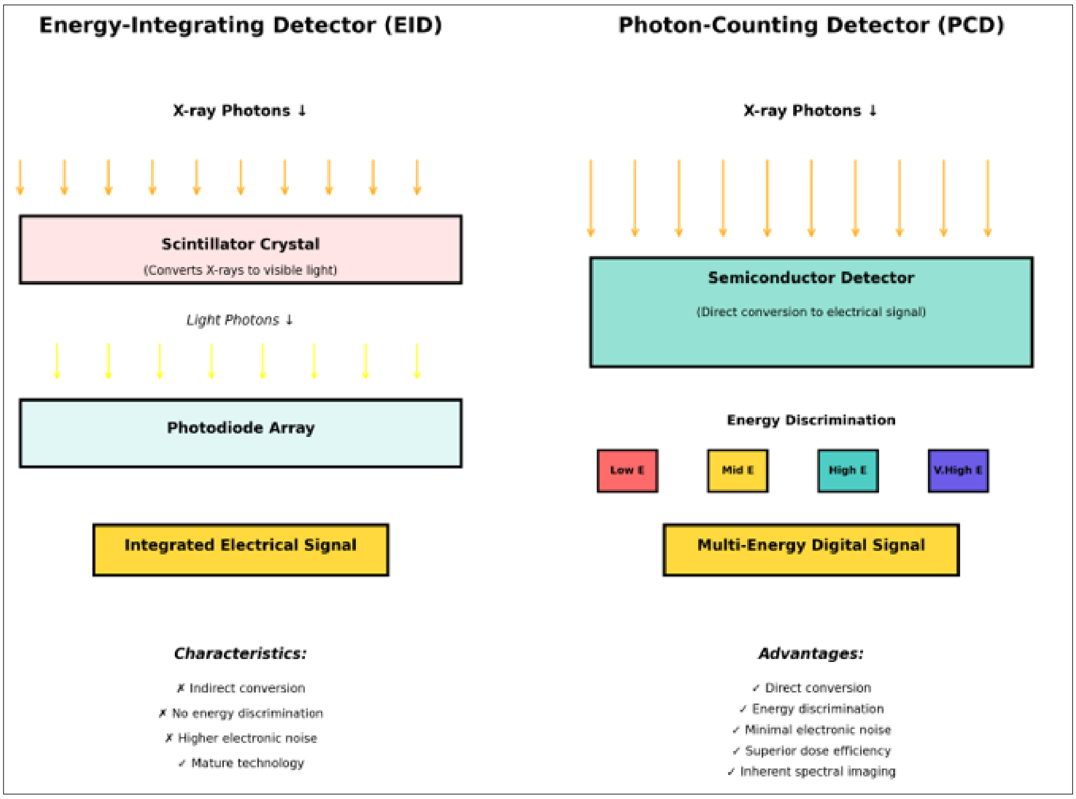


**Figure 5:** Detector Comparison

**Figure 5:** Side-by-side comparison of conventional Energy-Integrating Detector (EID) with indirect conversion process versus Photon-Counting Detector (PCD) with direct conversion and energy discrimination capabilities. Key advantages of PCD include direct conversion, energy discrimination, minimal electronic noise, superior dose efficiency, and inherent spectral imaging.

### 3.3.2 Clinical Performance and Dose Reduction

**Lung Imaging:**

Woeltjen *et al*. (2022)[8] conducted one of the first clinical evaluations of PCCT for low-dose high-resolution lung imaging [8]. In a paired patient cohort: - **Dose comparison:** PCCT delivered **significantly lower radiation dose** than prior EID-CT ($p < 0.001$) - **Image quality:** PCCT with quantum iterative reconstruction provided **superior image sharpness** and overall quality - **Clinical utility:** Enhanced detection of subtle interstitial lung disease patterns and small pulmonary nodules

**Spectral Imaging Advantages:**

PCCT enables routine spectral outputs without additional radiation: - Virtual monoenergetic images (VMIs) at selectable keV levels - Material decomposition (iodine, calcium, uric acid) - Reduced beam-hardening artifacts - Improved iodine signal at low contrast doses

**Pancreatic Imaging:**

Alagic (2024) [2] evaluated PCCT spectral data for pancreatic ductal adenocarcinoma (PDAC) detection [2]: - VMIs at **55 keV outperformed multi-energy iodine maps** for tumor conspicuity - Demonstrates need for task-specific spectral reconstruction optimization - Potential for reduced contrast agent doses

### 3.3.3 Technical Reviews and Clinical Translation

Theek *et al*. (2020) and other technical reviews highlighted PCCT capabilities [3][9]: - **Reduced image noise** compared to EID-CT at equivalent doses - **Improved spatial resolution** (up to 0.2 mm isotropic in clinical systems) - **Artifact reduction:** Metal artifact reduction, beam-hardening correction - **Quantitative accuracy:** Improved CT number accuracy and stability

### 3.3.4 Implementation Challenges

Despite clinical approval (beginning 2021), several challenges remain:

**Optimization Requirements:** - Optimal energy thresholds for different clinical tasks undefined - Reconstruction kernel selection more complex than conventional CT - Spectral

reconstruction parameters (VMI keV selection) require task-specific validation
**Evidence Gaps:** - Limited multicenter clinical data - Standardized protocols needed across indications - Long-term reliability and maintenance data pending
**Workflow Integration:** - Radiologist training on spectral image interpretation - PACS integration for multi-energy datasets - Increased data storage requirements
**Regulatory and Availability:** - Currently limited to select vendors and high-volume centers - Cost considerations for widespread adoption

### 3.4 Acquisition and Filtration Techniques
Hardware-based dose reduction strategies remain foundational and are often combined with advanced reconstruction for synergistic benefits.

#### 3.4.1 Automatic Exposure Control and Tube Current Modulation
**Technical Principles:**
Automatic exposure control (AEC) and tube current modulation (TCM) adjust X-ray output based on: - Patient size and body habitus - Anatomical region attenuation - Desired image quality level - Angular tube position (TCM)
**Clinical Implementation:**
These technologies are now standard in modern CT systems and were integral to low-dose protocols across multiple studies reviewed [10]. Benefits include: - Individualized dose delivery - Reduced dose to low-attenuation regions (e.g., lungs, pediatric patients) - Maintained image quality in high-attenuation regions (e.g., shoulders, pelvis)
**Protocol Harmonization:**
Recent efforts focus on combining AEC/TCM with IR/DLR for multicenter quantitative CT studies [10]: - Size-adjusted CTDIvol targets - Reconstruction-aware protocol design - Maintained quantitative comparability across sites

#### 3.4.2 Spectral Shaping with Tin Filtration
Tin filtration removes low-energy photons that contribute to patient dose without improving image quality, particularly effective when combined with low kVp protocols.

**Clinical Evidence:**
Kang *et al*. (2020) [5] reported dramatic dose reductions for COVID-19 chest CT surveillance using Sn100 protocol (tin-filtered 100 kVp) [5]:

| Parameter | Standard Protocol | Sn100 Protocol | Reduction |
|---|---|---|---|
| DLP | 129.1 mGy·cm | 14.5 mGy·cm | **88.8%** |
| Effective Dose | 1.8074 mSv | 0.203 mSv | **88.8%** |
| SNR | Baseline | Preserved | Maintained |
| CNR | Baseline | Preserved | Maintained |

**Key Findings:** Massive dose reduction without compromising diagnostic task (COVID-19 pneumonia detection) - Maintained signal-to-noise and contrast-to-noise ratios - Particularly effective for high-contrast chest imaging - Enabled safe repeated imaging for disease monitoring
**Scoliosis Imaging:**
A 2025 study on adolescent idiopathic scoliosis imaging with tin filtration demonstrated significant dose reduction while maintaining measurement accuracy for spinal curvature assessment [1].

#### 3.4.3 Adaptive Bowtie Filters
Traditional bowtie filters provide fixed beam shaping. Novel adaptive concepts aim for dynamic filtration.
**Fluid Dynamic Bowtie Filter (FDB):**
Lin *et al*. (2022) conducted Monte Carlo simulations of a fluid-dynamic bowtie filter combined with TCM for cone-beam CT [11]. Projected organ dose reductions: - **Head:** 70% reduction - **Thorax:** 34% reduction - **Abdomen:** 60% reduction
Compared to non-attenuated scanning while maintaining image quality metrics.
**Implementation Status:** - Currently in simulation/prototype phase - Requires engineering development for clinical systems - Potential for significant dose reduction when combined with other techniques

#### 3.4.4 kVp Selection and Optimization
Lower kVp settings reduce dose and improve iodine contrast but increase noise. Modern protocols optimize kVp based on: - Patient size - Clinical indication - Contrast enhancement requirements - Reconstruction algorithm capabilities (IR/DLR enable lower kVp)
**Typical Optimizations:** - **Pediatric CT:** 80-100 kVp (vs. 120 kVp adult standard) - **Contrast-enhanced studies:** 70-100 kVp for improved iodine conspicuity - **Large patients:** 120-140 kVp to maintain penetration - **Combined with tin filter:** Sn100, Sn150 protocols

#### 3.4.5 Integrated Protocol Approaches
The most effective dose reduction strategies combine multiple techniques:
**CT-Guided Musculoskeletal Biopsy Protocol:**
Alagic (2024) [2] reported an integrated low-dose protocol [2]: - Single-shot wide axial scanning (vs. helical) - Tube current modulation - Iterative reconstruction - **Result:** Mean DLP reduced from 257.4 to 41.5 mGy·cm (**83.9% reduction**) - Biopsy success rates comparable to standard-dose technique
**Ultra-Low-Dose Extremity CT:**
Emergency department protocol combining: - Low kVp (80-100) - Reduced mAs - Iterative reconstruction - **Results:** - Detected **52.7% fractures** vs. 35.3% on radiography - Changed treatment recommendations in **16.4% of cases** - Maintained diagnostic confidence

### 3.5 Quantitative Dose Reduction Summary
The following table synthesizes quantitative dose reduction achievements across technologies reviewed

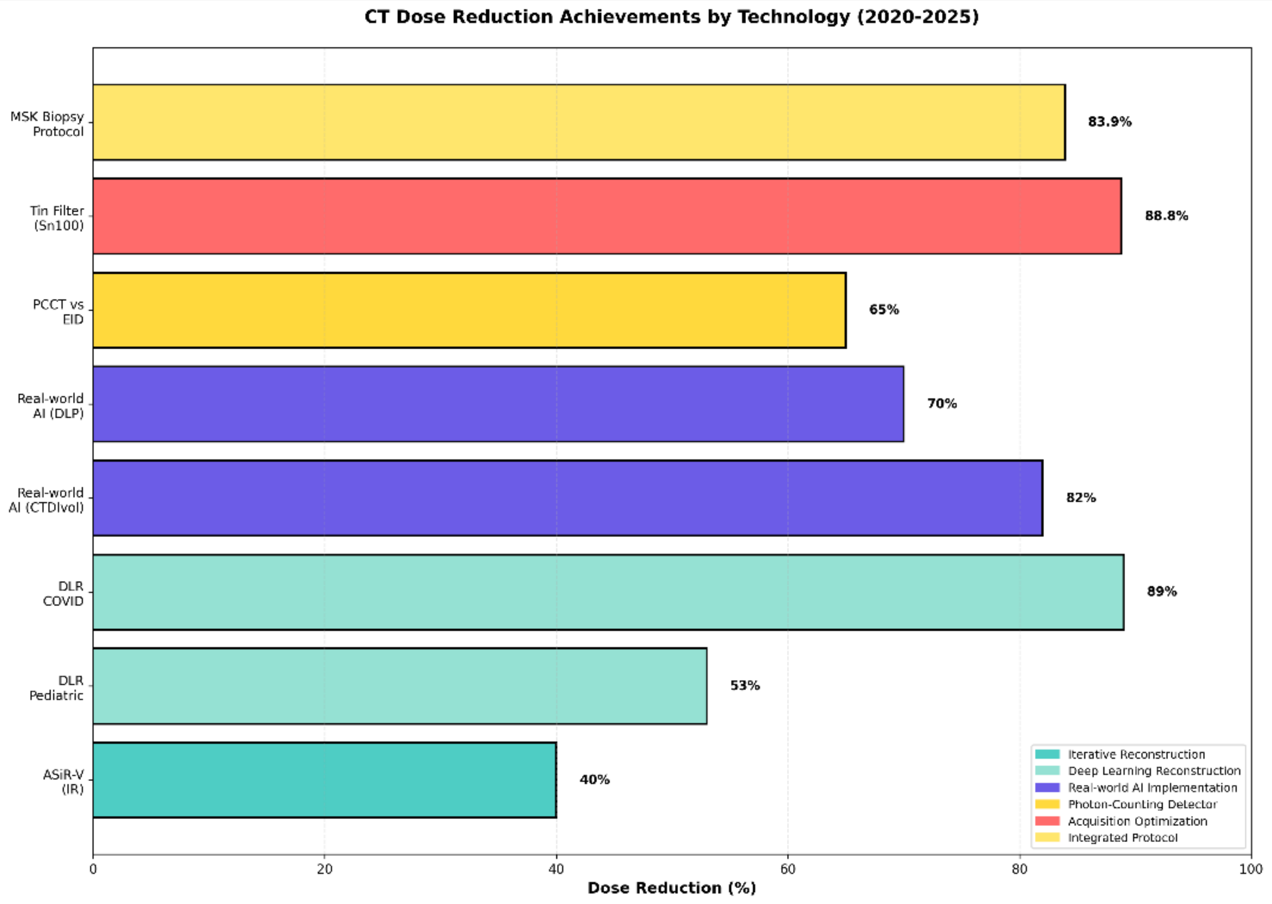


**Fig 6:** Dose Reduction Comparison

**Figure 6:** Horizontal bar chart comparing quantitative dose reduction percentages achieved by different technologies from 2020-2025. Technologies range from ASiR-V iterative reconstruction (40%) to DLR for COVID imaging (89%), demonstrating the wide range of dose reduction achievements.

| Technology/Strategy | Dose Reduction Range | Representative Metrics | Study Type | Reference |
|---|---|---|---|---|
| Iterative Reconstruction (ASiR-V) | ~40% | CTDIvol reduction with maintained IQ | Phantom | [3] |
| Deep Learning Reconstruction | 36-89% | CTDIvol reduction across studies | Systematic review, Clinical | [6][4][3] |
| DLR - Pediatric applications | 36-70% | Various dose metrics | Systematic review | [6] |
| DLR - COVID chest CT | Up to 89% | CTDIvol reduction | Clinical | [4] |
| Real-world AI/DLR deployment | CTDIvol: up to 82%DLP: up to 70% | Chest and CAP protocols | Clinical implementation | [12] |
| Photon-Counting Detector CT | Significant ($p<0.001$) | Dose vs. EID-CT comparison | Clinical paired | [8] |
| Tin Filtration (Sn100) | 88.8% | DLP: 129.1→14.5 mGy·cmED: 1.8→0.2 mSv | Clinical | [5] |
| Fluid Dynamic Bowtie (simulation) | 34-70% by organ | Head: 70%, Thorax: 34%, Abdomen: 60% | Monte Carlo simulation | [11] |
| Integrated MSK biopsy protocol | 83.9% | DLP: 257.4→41.5 mGy·cm | Clinical | [2] |
| Combined acquisition + IR/DLR | Variable, synergistic | Task-dependent optimization | Multiple studies | [1][5][10] |

**Key Observations:**

1. **Dose reduction magnitude** varies widely (36-89%) depending on:
   – Baseline protocol
   – Technology combination
   – Clinical indication
   – Acceptable image quality threshold
2. **Greatest reductions** achieved with:
   – Combined strategies (acquisition + reconstruction)
   – High-contrast tasks tolerating more noise
   – Specific applications (e.g., tin-filtered chest CT)
3. **Real-world implementation** demonstrates substantial dose savings translatable to clinical practice
4. **Photon-counting detectors** provide dose reduction

plus additional benefits (spectral imaging, resolution)

### 3.6 Clinical Effectiveness and Diagnostic Performance

Beyond dose metrics, clinical effectiveness was evaluated through diagnostic performance and image quality assessments.

#### 3.6.1 Diagnostic Accuracy Preservation

**Key Findings:**

**Hemorrhage Detection:** Multiple studies validated that DLR-reconstructed low-dose head CT maintained diagnostic accuracy for intracranial hemorrhage detection, a critical emergency indication [2].

**Fracture Detection:** Ultra-low-dose extremity CT demonstrated **superior fracture detection** (52.7%) compared to standard radiography (35.3%) while using optimized low-dose protocols [2].

**Oncology Follow-up:** Real-world deployment of AI/DLR in oncology settings maintained diagnostic quality across thousands of examinations while achieving substantial dose reductions [12].

**COVID-19 Pneumonia:** Tin-filtered ultra-low-dose chest CT (0.203 mSv effective dose) provided adequate diagnostic information for COVID-19 pneumonia detection and monitoring [5].

#### 3.6.2 Image Quality Metrics

**Objective Metrics:**

Studies consistently reported improvements or maintenance of: - **Signal-to-noise ratio (SNR):** DLR showed up to 82.9% improvement over IR [2] - **Contrast-to-noise ratio (CNR):** Up to 53.3% improvement with DLR [2] - **Spatial resolution:** Maintained or improved, especially with PCCT [8] - **Noise texture:** More natural appearance with DLR vs. IR "plastic" appearance

**Subjective Reader Assessments:**

Radiologist evaluations generally confirmed: - Diagnostic acceptability of dose-reduced protocols - Preference for DLR over IR image appearance - Task-specific adequacy (high-contrast tasks more forgiving) - Some concerns about subtle low-contrast lesion detection at extreme dose reduction

#### 3.6.3 Task-Specific Performance Variations

**High-Contrast Tasks** (excellent performance): - Pulmonary nodule detection - Bone fracture evaluation - Urolithiasis detection - Vascular calcification assessment

**Moderate-Contrast Tasks** (good performance with optimization): - Solid organ lesions (liver, kidney, spleen) - Lymph node assessment - Bowel pathology

**Low-Contrast Tasks** (requires careful validation): - Subtle liver lesions - Pancreatic masses - Early ischemic stroke - Soft tissue characterization

**Critical Limitation:** Several studies noted failure cases where aggressive dose reduction with DL restoration could not reliably recover lesion density and structure, particularly for subtle low-contrast findings [3].

### 3.7 Methodological Approaches in Reviewed Studies

The systematic review identified diverse methodological approaches, each with specific strengths and limitations.

#### 3.7.1 Study Design Types

**Phantom Studies:** - **Advantages:** Controlled conditions, reproducible, quantitative metrics, ground truth known - **Limitations:** May not reflect clinical variability, simplified anatomy - **Example:** ASiR-V optimization study [3]

**Monte Carlo Simulations:** - **Advantages:** Organ dose estimation, test novel concepts pre-prototype, parameter exploration - **Limitations:** Model accuracy dependent on input parameters, validation required - **Example:** Fluid dynamic bowtie filter study [11]

**Paired Clinical Comparisons:** - **Advantages:** Within-subject control, direct comparison of technologies - **Limitations:** Limited to available scanner/software combinations - **Example:** PCCT vs. EID-CT in same patients [8]

**Retrospective Clinical Studies:** - **Advantages:** Real-world data, large sample sizes, actual clinical outcomes - **Limitations:** Confounding variables, protocol variations, selection bias - **Example:** Real-world AI/DLR deployment [12]

**Multi-Reader Diagnostic Studies:** - **Advantages:** Assess clinical diagnostic performance, reader agreement - **Limitations:** Time-intensive, reader variability, reference standard challenges - **Example:** DLR diagnostic accuracy studies [2]

**AI Training and Validation Studies:** - **Advantages:** Quantitative performance metrics (RMSE, SSIM, PSNR), reproducible - **Limitations:** Dataset dependency, generalization concerns, may not correlate with diagnostic performance - **Example:** Deep learning denoising studies [3][4]

#### 3.7.2 Common Outcome Metrics

**Dose Metrics:** - CTDIvol (volume CT dose index) - most commonly reported - DLP (dose-length product) - Effective dose (mSv) - calculated from DLP with conversion factors - Organ doses - from simulation or dosimetry - Dose reduction percentage

**Image Quality Metrics:** - Noise (standard deviation in ROI) - Signal-to-noise ratio (SNR) - Contrast-to-noise ratio (CNR) - Spatial resolution (MTF, line pairs) - Artifact scores - Subjective quality ratings

**Diagnostic Performance:** - Sensitivity and specificity - ROC curve analysis (AUC) - Diagnostic confidence scores - Lesion detection rates - Inter-reader agreement (kappa)

**AI-Specific Metrics:** - Root mean square error (RMSE) - Structural similarity index (SSIM) - Peak signal-to-noise ratio (PSNR) - Perceptual loss metrics

## 4. Discussion

### 4.1 Principal Findings

This systematic review of CT dose reduction technologies from 2020-2025 reveals three converging innovation tracks that have collectively transformed the dose-quality paradigm:

1. **Reconstruction algorithms** have evolved from iterative methods to sophisticated deep learning approaches, enabling 36-89% dose reductions while maintaining or improving image quality across most clinical applications.
2. **Photon-counting detector CT** represents a fundamental hardware revolution, providing superior dose efficiency, inherent spectral imaging, and improved spatial resolution compared to conventional energy-integrating detectors.
3. **Optimized acquisition techniques**, particularly spectral shaping with tin filtration and adaptive exposure control, deliver substantial dose reductions (up to 89% in specific

protocols) and synergize with advanced reconstruction.

The convergence of these technologies—often implemented in combination—has made previously unattainable dose levels clinically feasible while maintaining diagnostic adequacy for many indications.

### 4.2 Interpretation and Clinical Implications

#### 4.2.1 Paradigm Shift in Dose-Quality Relationship

Traditional CT physics established a fundamental relationship between radiation dose and image noise: halving the dose increases noise by approximately 41%. This relationship constrained dose reduction efforts, as excessive noise degrades diagnostic confidence.

Deep learning reconstruction and photon-counting detectors have disrupted this traditional relationship: - **DLR** achieves noise reduction beyond what physics-based IR can accomplish, effectively "recovering" diagnostic information from lower-dose acquisitions - **PCCT** improves dose efficiency at the detector level through direct conversion and elimination of electronic noise

This paradigm shift enables dose levels that would have been diagnostically inadequate with conventional technology.

#### 4.2.2 Real-World Clinical Impact

The real-world deployment study by Russo *et al.* [12] is particularly significant, demonstrating that laboratory and research findings translate to routine clinical practice: - Up to 82% CTDIvol reduction across thousands of examinations - No compromise in diagnostic quality per radiologist assessment - Successful workflow integration without productivity loss

This validates that modern dose reduction technologies are not merely theoretical or applicable only in research settings, but are ready for widespread clinical implementation.

#### 4.2.3 Population-Level Radiation Risk Reduction

Applying reported dose reductions to population-level CT utilization suggests substantial potential for collective radiation risk reduction: - If 50% dose reduction were achieved across all CT examinations, population collective dose from CT could be halved - Pediatric applications, where radiation sensitivity is greatest, showed 36-70% dose reductions [6] - Repeated imaging scenarios (oncology surveillance, inflammatory disease monitoring) benefit disproportionately from per-examination dose reduction

### 4.3 Technology-Specific Discussion

#### 4.3.1 Deep Learning Reconstruction: Promise and Pitfalls

**Strengths:** - Dramatic dose reduction potential (up to 89%) - Superior objective image quality metrics (SNR, CNR) - More natural image appearance than traditional IR - Applicable to existing scanner hardware (software upgrade) - Real-world validation in large clinical deployments

**Concerns and Limitations:** - **"Black box" nature:** Neural network decision-making lacks transparency - **Failure modes:** Documented cases where subtle lesions were not accurately recovered [3] - **Training data dependency:** Models may not generalize to populations, pathologies, or scanner types not represented in training data - **Task-specific performance:** Excellent for high-contrast tasks, questionable for subtle low-contrast lesions - **External validation gaps:** Most studies use single-institution or vendor-specific data

**Critical Need:** Standardized external validation protocols with diverse datasets, multiple scanner types, and task-specific diagnostic performance assessment. The medical imaging community must establish benchmarks analogous to ImageNet for computer vision.

#### 4.3.2 Photon-Counting Detectors: Revolutionary but Early

**Transformative Advantages:** - Fundamental physics improvement (direct conversion, energy discrimination) - Dose reduction plus additional capabilities (spectral imaging, resolution) - Clinical systems now available (FDA-approved, commercially deployed) - Early clinical data confirms superior performance [8]

**Implementation Challenges:** - **Limited availability:** Currently restricted to select vendors and high-volume centers - **Cost:** Substantial capital investment for new scanner systems - **Optimization complexity:** Multiple adjustable parameters (energy thresholds, spectral reconstructions) require task-specific optimization - **Evidence base:** Clinical data still limited compared to decades of EID-CT experience - **Workflow changes:** Radiologists must learn spectral image interpretation

**Future Trajectory:** PCCT is likely to become the standard detector technology over the next decade as costs decrease, evidence accumulates, and clinical workflows mature. The combination of dose reduction with spectral imaging capabilities offers compelling value.

#### 4.3.3 Acquisition Optimization: Foundational and Synergistic

Acquisition-level dose reduction strategies (AEC, TCM, tin filtration, kVp optimization) are: - **Mature technologies** with extensive clinical validation - **Universally applicable** across scanner types and vendors - **Synergistic** with reconstruction advances—reducing dose at acquisition provides cleaner input for reconstruction algorithms - **Task-specific** optimization opportunities remain (e.g., tin filtration highly effective for chest CT, less so for abdomen)

The dramatic dose reduction achieved with tin-filtered chest CT (88.8%) [5] demonstrates that for specific applications, acquisition optimization alone can achieve near-ultra-low-dose imaging.

### 4.4 Challenges and Limitations

#### 4.4.1 External Validation and Generalizability

A pervasive limitation across AI/DL studies is limited external validation: - Training and testing often on single-institution data - Vendor-specific implementations - Limited demographic diversity - Specific scanner models and protocols

This raises concerns about generalizability to: - Different patient populations (age, size, pathology) - Other scanner manufacturers and models - Varied clinical protocols and practices - Rare pathologies not represented in training data

#### 4.4.2 Task-Specific Performance Variations

The review identified significant performance variations by diagnostic task: - High-contrast tasks (bone, lung nodules): excellent performance at very low doses - Low-contrast tasks (subtle liver lesions, pancreatic masses): performance concerns at aggressive dose reduction

This necessitates: - Task-specific dose optimization protocols - Diagnostic task-aware AI training (not just generic image quality metrics) - Clear clinical guidelines on appropriate dose levels per indication

#### 4.4.3 Standardization and Harmonization

Lack of standardization across: - **Vendors:** Different implementations of IR, DLR with varying performance - **Protocols:** No consensus on optimal parameters for many clinical indications - **Metrics:** Inconsistent reporting of dose and image quality metrics across studies - **Validation:** No standardized external validation datasets or protocols

This complicates: - Cross-study comparisons - Meta-analyses - Clinical guideline development - Multicenter research studies

#### 4.4.4 Regulatory and Clinical Acceptance

**Regulatory Considerations:** - AI/DL algorithms are medical devices requiring regulatory approval - Validation standards for AI in medical imaging still evolving - Post-market surveillance for AI performance drift needed

**Clinical Acceptance:** - Radiologist training on new image appearance (especially DLR) - Confidence in diagnostic adequacy at lower doses - Medico-legal considerations for missed diagnoses - Referring physician education on dose optimization

### 4.5 Future Directions and Research Priorities

#### 4.5.1 Prospective Multicenter Clinical Trials

**Critical Need:** Prospective trials comparing dose reduction technologies with clinical diagnostic endpoints (not just image quality metrics) across multiple institutions, scanner types, and patient populations.

**Proposed Study Designs:** - Randomized comparison of standard-dose vs. optimized low-dose protocols with DLR - Multi-reader diagnostic performance studies with clinical outcomes - PCCT vs. EID-CT head-to-head trials for specific indications - Long-term follow-up to assess diagnostic accuracy and patient outcomes

#### 4.5.2 Standardized External Validation

**Proposed Infrastructure:** - **Public benchmark datasets:** Paired low/high-dose CT scans across multiple scanners, protocols, and pathologies - **Standardized validation protocols:** Agreed-upon metrics, test cases, and performance thresholds - **Vendor-neutral evaluation:** Independent testing of commercial AI/DLR products - **Task-specific benchmarks:** Separate validation for different diagnostic tasks (trauma, oncology, emergency, etc.)

Analogous to: - ImageNet for computer vision - CAMELYON for digital pathology - MIMIC for clinical AI

#### 4.5.3 Task-Aware AI Development

**Current Limitation:** Most AI denoising/reconstruction models optimize generic image quality metrics (RMSE, SSIM, perceptual loss) that may not correlate with diagnostic task performance.

**Proposed Approach:** - **Task-specific loss functions:** Train models to preserve features critical for specific diagnoses - **Radiologist-in-the-loop training:** Incorporate expert feedback on diagnostic adequacy - **Multi-task learning:** Models that optimize for multiple clinical tasks simultaneously - **Uncertainty quantification:** AI systems that flag when they are uncertain about reconstruction fidelity

#### 4.5.4 Hardware Innovations

**Photon-Counting Detector Refinement:** - Optimization of energy thresholds and binning strategies - Improved count-rate performance for larger patients - Cost reduction for broader availability - Integration with AI reconstruction for synergistic benefits

**Dynamic Filtration:** - Clinical translation of adaptive bowtie filter concepts [11] - Real-time beam shaping based on patient geometry - Integration with AEC/TCM systems

**Novel Detector Materials:** - Alternative semiconductor materials for improved energy resolution - Hybrid detector concepts combining benefits of multiple technologies

#### 4.5.5 Integrated AI-Driven Dose Optimization

**Vision:** Comprehensive AI systems that optimize the entire imaging chain: - **Pre-scan:** Patient-specific protocol selection based on body habitus, clinical indication, prior images - **Acquisition:** Real-time adjustment of exposure parameters during scanning - **Reconstruction:** Automatic selection of optimal reconstruction algorithm and parameters - **Post-processing:** AI quality assurance, automatic flagging of suboptimal images - **Reporting:** Dose tracking, benchmarking against diagnostic reference levels

**Required Developments:** - Integration of AI across vendor platforms - Clinical validation of automated decision-making - Regulatory frameworks for autonomous AI systems - Radiologist oversight and intervention capabilities

#### 4.5.6 Updated Diagnostic Reference Levels

Current diagnostic reference levels (DRLs) were established based on conventional CT technology. With modern dose reduction capabilities:

**Needed Actions:** - **Reassessment of DRLs:** Update based on achievable doses with current technology - **Task-specific DRLs:** Different reference levels for different clinical indications - **Technology-specific guidance:** Separate DRLs for PCCT, AI-enabled systems - **Pediatric DRLs:** Age and size-specific reference levels incorporating modern dose reduction - **Regular updates:** Systematic review and updating cycle as technology advances

#### 4.5.7 Education and Training

**Radiologist Training:** - Recognition of DLR image appearance and artifacts - Interpretation of PCCT spectral images - Understanding of AI reconstruction limitations - Appropriate protocol selection for clinical indications

**Technologist Training:** - Optimization of acquisition parameters with modern technology - Quality assurance for AI-enabled systems - Patient-specific protocol adaptation

**Referring Physician Education:** - Appropriateness criteria incorporating dose considerations - Understanding of dose optimization capabilities - Shared decision-making on imaging strategies

## 5. Conclusions

### 5.1 Summary of Key Findings

This systematic review of CT dose reduction technologies from 2020-2025 demonstrates substantial progress across multiple technological fronts:

1. **Deep learning reconstruction** has emerged as a transformative technology, enabling 36-89% dose reductions while maintaining or improving image quality

for most clinical applications. Real-world implementations confirm translation from research to clinical practice.

2. **Photon-counting detector CT** represents a paradigm shift in detector technology, providing superior dose efficiency, inherent spectral imaging capabilities, and improved spatial resolution. Early clinical data validates performance advantages, though widespread adoption requires further evidence and cost reduction.
3. **Optimized acquisition techniques**, particularly spectral shaping with tin filtration, achieve dramatic dose reductions (up to 89%) for specific applications and synergize with advanced reconstruction algorithms.
4. **Combined strategies** integrating acquisition optimization, advanced reconstruction, and when available, photon-counting detectors, offer the greatest dose reduction potential while maintaining diagnostic adequacy.
5. **Quantitative dose reductions** of 40-89% are achievable across various clinical indications, with the magnitude depending on baseline protocol, technology combination, and diagnostic task requirements.

### 5.2 Clinical Implications

The technologies reviewed enable a fundamental shift in the dose-quality paradigm, making previously unattainable low-dose CT imaging clinically feasible. This has several important implications:

- **Expanded CT indications:** Applications previously limited by radiation concerns (pediatric imaging, young adults, repeated examinations) become more acceptable
- **Population dose reduction:** Widespread implementation could substantially reduce collective radiation exposure from CT
- **Improved risk-benefit ratio:** Lower doses shift the risk-benefit calculation favorably for many clinical scenarios
- **Screening applications:** Ultra-low-dose protocols enable consideration of CT for screening programs (e.g., lung cancer screening)

### 5.3 Remaining Challenges

Despite remarkable progress, important challenges must be addressed:

- **External validation gaps:** Limited multi-center, multi-vendor validation of AI/DL technologies
- **Task-specific performance:** Uncertainty about preservation of subtle low-contrast lesion detection at aggressive dose reduction
- **Standardization needs:** Lack of consensus protocols, validation standards, and harmonized implementation
- **Generalizability concerns:** AI models may not perform consistently across diverse populations, pathologies, and scanner types
- **Clinical acceptance:** Radiologist confidence in diagnostic adequacy of ultra-low-dose images requires building
- **Regulatory frameworks:** Standards for AI validation and post-market surveillance still evolving

### 5.4 Future Outlook

The trajectory of CT dose reduction technology points toward:

1. **Continued AI advancement:** More sophisticated deep learning models with task-specific optimization and uncertainty quantification
2. **PCCT maturation:** Broader clinical adoption as evidence accumulates, costs decrease, and workflows optimize
3. **Integrated AI systems:** Comprehensive dose optimization across the entire imaging chain from protocol selection through reconstruction
4. **Personalized protocols:** Patient-specific, indication-specific dose optimization replacing one-size-fits-all approaches
5. **Ultra-low-dose CT:** Routine clinical use of dose levels previously considered experimental
6. **Paradigm shift:** CT dose as a controllable parameter optimized for each patient and clinical question, rather than a fixed consequence of imaging technology

### 5.5 Recommendations

**For Researchers:** - Prioritize prospective multicenter trials with clinical diagnostic endpoints - Develop and validate task-specific AI models - Contribute to public benchmark datasets for standardized validation - Investigate failure modes and limitations of dose reduction technologies - Pursue integrated AI-driven optimization systems

**For Clinicians:** - Adopt validated dose reduction technologies in clinical practice - Participate in training on modern reconstruction and spectral imaging - Engage in protocol optimization for specific clinical indications - Contribute to dose registries and benchmarking initiatives - Maintain awareness of technology limitations and appropriate use

**For Healthcare Systems:** - Invest in modern CT technology with dose reduction capabilities - Implement dose tracking and optimization programs - Support radiologist and technologist training initiatives - Participate in multicenter research and validation studies - Update institutional protocols based on current evidence

**For Regulatory Bodies:** - Develop clear validation standards for AI/DL reconstruction - Update diagnostic reference levels based on modern technology capabilities - Establish post-market surveillance frameworks for AI performance - Harmonize international standards for dose optimization - Support infrastructure for external validation and benchmarking

**For Professional Societies:** - Develop evidence-based guidelines for dose optimization - Create educational resources on modern CT technologies - Facilitate multicenter research collaborations - Advocate for updated diagnostic reference levels - Promote standardization across vendors and institutions

### 5.6 Final Statement

The period from 2020 to 2025 represents a transformative era in CT dose optimization, with convergent advances in reconstruction algorithms, detector hardware, and acquisition strategies. Deep learning reconstruction and photon-counting detectors, in particular, represent paradigm shifts with proven clinical benefits. While challenges remain in validation, standardization, and implementation, the path forward is clear: continued innovation, rigorous clinical validation, and thoughtful integration of these technologies will enable CT imaging at dose levels previously thought impossible while maintaining or improving diagnostic capabilities. The ultimate goal—optimal diagnostic information at minimal radiation risk—is closer to reality than ever before.

## Appendices

### Appendix A: Search Strategy Details

**Database: PubMed/MEDLINE**

Search String: (("computed tomography"[MeSH Terms] OR "tomography, x-ray computed"[MeSH Terms] OR CT[Title/Abstract]) AND ("radiation dosage"[MeSH Terms] OR "radiation exposure"[MeSH Terms] OR "dose reduction"[Title/Abstract] OR "low dose"[Title/Abstract] OR "radiation protection"[MeSH Terms]) AND ("technology"[Title/Abstract] OR "technique"[Title/Abstract] OR "innovation"[Title/Abstract] OR "development"[Title/Abstract] OR "advancement"[Title/Abstract])) AND ("2020"[Date - Publication] : "2025"[Date - Publication])
Date Searched: November 20, 2025
Results: 19 papers

**Database: Google Scholar**

Search String: (CT OR "computed tomography") AND ("radiation dose reduction" OR "dose optimization" OR "low dose" OR "radiation exposure") AND (technology OR technique OR innovation OR development)
Date Range: 2020-2025
Date Searched: November 20, 2025
Results: 20 papers

**Database: SciSpace**

Search Query: "What are the recent developments and technological advances in computed tomography (CT) systems for reducing X-ray radiation exposure and dose optimization in medical imaging?"
Date Range: 2020-2025
Date Searched: November 20, 2025
Results: 100 papers

**Database: SciSpace Full-Text**

Search Query: "What are the recent developments and technological advances in computed tomography (CT) systems for reducing X-ray radiation exposure and dose optimization in medical imaging?"
Date Range: 2020-2025
Date Searched: November 20, 2025
Results: 100 papers

**Total Unique Papers After Deduplication:** 99

### Appendix B: Abbreviations and Terminology

**Technical Terms:** - **AEC:** Automatic Exposure Control - **ALARA:** As Low As Reasonably Achievable - **ASiR-V:** Adaptive Statistical Iterative Reconstruction-V (GE Healthcare) - **AUC:** Area Under the Curve - **CAP:** Chest-Abdomen-Pelvis - **CNR:** Contrast-to-Noise Ratio - **CT:** Computed Tomography - **CTDIvol:** Volume CT Dose Index (mGy) - **DL:** Deep Learning - **DLR/DLIR:** Deep Learning Reconstruction / Deep Learning Image Reconstruction - **DLP:** Dose-Length Product (mGy·cm) - **DRL:** Diagnostic Reference Level - **EID:** Energy-Integrating Detector - **FBP:** Filtered Back Projection - **FDB:** Fluid Dynamic Bowtie (filter) - **GAN:** Generative Adversarial Network - **IR:** Iterative Reconstruction - **keV:** Kilo-electron Volt (energy level) - **kVp:** Kilovolt Peak (X-ray tube voltage) - **mAs:** Milliampere-seconds (tube current × time) - **MBIR:** Model-Based Iterative Reconstruction - **mGy:** Milligray (absorbed dose unit) - **mSv:** Millisievert (effective dose unit) - **MTF:** Modulation Transfer Function - **PACS:** Picture Archiving and Communication System - **PCD/PCCT:** Photon-Counting Detector / Photon-Counting CT - **PDAC:** Pancreatic Ductal Adenocarcinoma - **PSNR:** Peak Signal-to-Noise Ratio - **QCT:** Quantitative CT - **RMSE:** Root Mean Square Error - **ROC:** Receiver Operating Characteristic - **ROI:** Region of Interest - **SNR:** Signal-to-Noise Ratio - **SSIM:** Structural Similarity Index - **TCM:** Tube Current Modulation - **VMI:** Virtual Monoenergetic Image

### Appendix C: Dose Metrics Explained

**CTDIvol (Volume CT Dose Index):** - Measured in milligray (mGy) - Represents radiation dose to a standard phantom for a single axial rotation - Does not account for scan length - Primary metric for comparing dose efficiency of CT protocols

**DLP (Dose-Length Product):** - Measured in mGy·cm - Calculated as CTDIvol × scan length - Accounts for total scan coverage - Used to estimate effective dose

**Effective Dose:** - Measured in millisieverts (mSv) - Estimates whole-body radiation risk - Calculated from DLP using anatomic region-specific conversion factors - Allows comparison across different imaging modalities

**Organ Dose:** - Measured in mGy - Radiation dose to specific organs - Typically estimated via Monte Carlo simulation - Most relevant for radiosensitive organs (breast, thyroid, gonads, bone marrow)

**Dose Reduction Percentage:** - Calculated as: [(Baseline - New) / Baseline] × 100% - Commonly reported for CTDIvol or DLP - Allows comparison of dose reduction effectiveness across studies

### Appendix D: Image Quality Metrics Explained

**Noise:** - Standard deviation of CT numbers (HU) in uniform region - Lower noise = smoother image - Inversely related to dose (noise $\propto 1/\sqrt{\text{dose}}$ for conventional CT)

**Signal-to-Noise Ratio (SNR):** - Ratio of mean signal to noise: SNR = mean HU / noise SD - Higher SNR = better image quality - Dimensionless metric

**Contrast-to-Noise Ratio (CNR):** - Difference in signal between two regions divided by noise - CNR = (mean $HU_1$ - mean $HU_2$) / noise SD - Critical for low-contrast lesion detection

**Spatial Resolution:** - Ability to distinguish small objects or fine details - Measured via modulation transfer function (MTF) or line-pair phantoms - Typically 0.4-0.6 mm for conventional CT, improved with PCCT

**Subjective Quality Scores:** - Radiologist ratings of diagnostic adequacy - Often 5-point Likert scales - Assess overall quality, artifact presence, diagnostic confidence

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