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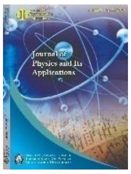

Radiation Dose Optimization in Adult Head CT: A Comprehensive Review from Phantom-Based Evaluation to Clinical Implementation

Inganatul Islamiyah[1,3], Yuyun Yueniwati[1], Chomsin S. Widodo[1], and Zainal Arifin[2]

[1]Department of Physics, Faculty of Mathematics and Natural Sciences, Brawijaya University, Malang, Indonesia
[2]Department of Physics, Faculty of Mathematics and Natural Sciences, Diponegoro University, Semarang, Indonesia
[3]Department of Radiology, Bhayangkara Hospital Bondowoso, Bondowoso, Indonesia

**Corresponding author:* ingefisika@student.ub.ac.id

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ABSTRACT

The widespread use of head computed tomography (CT) has led to a significant increase in patient radiation dose. Although modern CT systems include dose-saving technologies, further optimization is necessary to balance radiation dose and image quality. This study aims to review dose optimization strategies in head computed tomography (CT), focusing on the impact of acquisition parameter modifications across different phantom types and their translation into clinical applications. Variations in radiation dose and image quality are quantitatively assessed using multiple phantoms. PMMA phantoms validate dose measurements, image-quality phantoms enable comprehensive assessment of image metrics, and anthropomorphic phantoms ensure clinical relevance. In clinical applications, image quality is qualitatively evaluated by radiologists. Results show that tube voltage and tube current are the main strategies of dose optimization, supported by automatic exposure control, pitch adjustment, and reconstruction algorithms. Iterative reconstruction techniques effectively mitigate noise amplification due to the adjustments. Radiation dose reduction ranges from approximately 15% to 80%, depending on the applied parameter modifications. Since reductions often increase image noise and variability in image quality, this review identifies the optimal range of parameter adjustments to maintain diagnostically acceptable image quality. Combining quantitative assessments with phantoms and qualitative evaluations by radiologists enables a more comprehensive understanding of optimization results, which can greatly benefit clinical practice by providing a long-term guideline for safe and effective CT dose optimization.

1. Introduction

Use of Computed Tomography (CT) has increased steadily in recent years. Currently, CT has become one of the most reliable imaging modalities for diagnosing diseases and injuries [1]. CT provides detailed information about the body's structure and function within a short time, making it essential in modern diagnostic imaging [2]. Despite its clinical importance and widespread use, CT examinations deliver relatively high radiation doses to patients [3].

The UNSCEAR Global Survey reported that the distribution of radiological examinations consists of conventional radiography (59.8%), radiography and fluoroscopy (2%), dental radiography (25.2%), and CT examinations (13%). Nevertheless, CT accounts for approximately 70–80% of the collective effective dose among X-ray–based procedures [4]. Over the past 30 years, advancements in computed tomography (CT) technology have provided essential imaging for clinical use.

Although modern CT technologies include dose reduction features, the increasing number of CT examinations still raises the population's total exposure to medical exposure [5]. Ionizing radiation may cause harmful health effects on patients [6]. Epidemiological studies indicate that exposure to ionizing radiation is associated with an increased risk of cancer [7]. The risk is greater when radiosensitive organs are involved. Head CT examinations are among the most frequently performed CT procedures. During these exams, the brain, eye lenses, and thyroid gland are exposed to radiation [8].

Radiation dose in CT is commonly represented by the volume computed tomography dose index (CTDIvol) and the dose–length product (DLP). CTDIvol is a dose index derived from standardized measurements, whereas DLP represents the total radiation dose along the scanned length [9]. Both parameters are displayed as patient dose reports on the CT console.

According to ICRP recommendations, CTDIvol and DLP are fundamental values for establishing diagnostic reference levels (DRLs) [10]. DRLs is a valuable method that can be used to monitor radiation dose levels. If local DRLs exceed national DRLs, evaluation of scanning protocols and examination techniques is required [11].

Scanning techniques and protocols significantly influence radiation dose. Contributing factors include scan type, tube current, tube voltage, and other protocol parameters [12]. Protocol modifications affect not only dose but also image quality [13].

Although numerous studies and review articles have investigated dose optimization strategies in CT, most have focused on individual parameter adjustments or general optimization techniques without systematically comparing outcomes across different evaluation models. Limited attention has been paid to how optimization results vary across different phantom types and how these findings relate to clinical applications. Therefore, a clear understanding of the connection between dose evaluation, image quality assessment, and clinical relevance is lacking. This review aims to provide a structured analysis of dose optimization strategies in head CT by comparing parameter effects across multiple phantom models, mapping the dose–image quality trade-off, and assessing their relevance to clinical application.

2. Method

This study was conducted as a narrative review through stages of literature search, screening, analysis, and synthesis. Relevant studies published between 2011 and 2025 were identified from the following databases: ScienceDirect, PubMed, and Taylor & Francis Online. The literature search was performed using predefined keywords, including "Head CT Optimization," "Phantom Study," "Low-Dose CT," "Head CT Radiation Dose", and "Adult Head CT." These keywords were consistently applied across all databases.

The initial search yielded 387 articles. After removing duplicates, titles and abstracts were screened for relevance, resulting in 57 articles for full-text review. Studies were included if they investigated dose optimization in head CT using phantom models, clinical applications, and reported outcomes related to radiation dose and image quality. Studies were excluded if they did not focus on head CT, pediatric CT, or lacked sufficient methodological detail. A total of 25 studies were finally included in this review. Figure 1 illustrates the search flow of this study.

The selected studies were categorized by evaluation model type, including PMMA phantoms, image-quality phantoms, anthropomorphic phantoms, and patient-based clinical studies. Data related to acquisition parameters, radiation dose metrics, and image quality assessment (both quantitative and qualitative) were extracted and synthesized narratively.

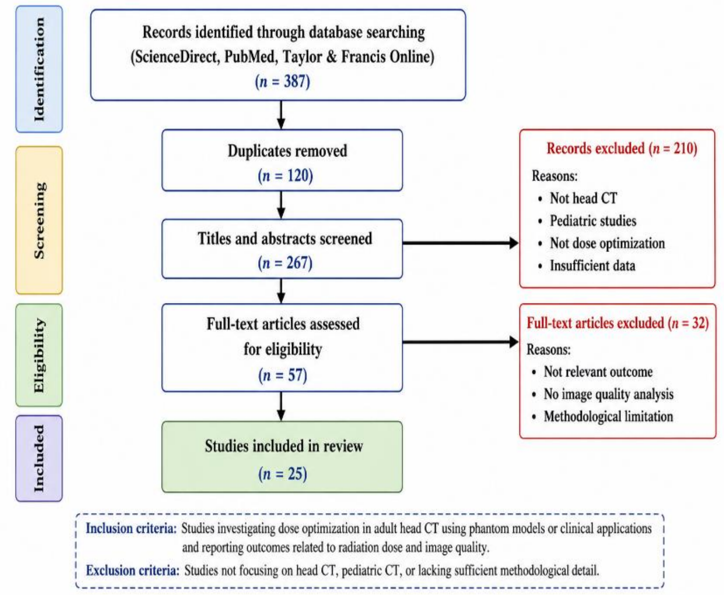

Fig. 1: Search flow diagram

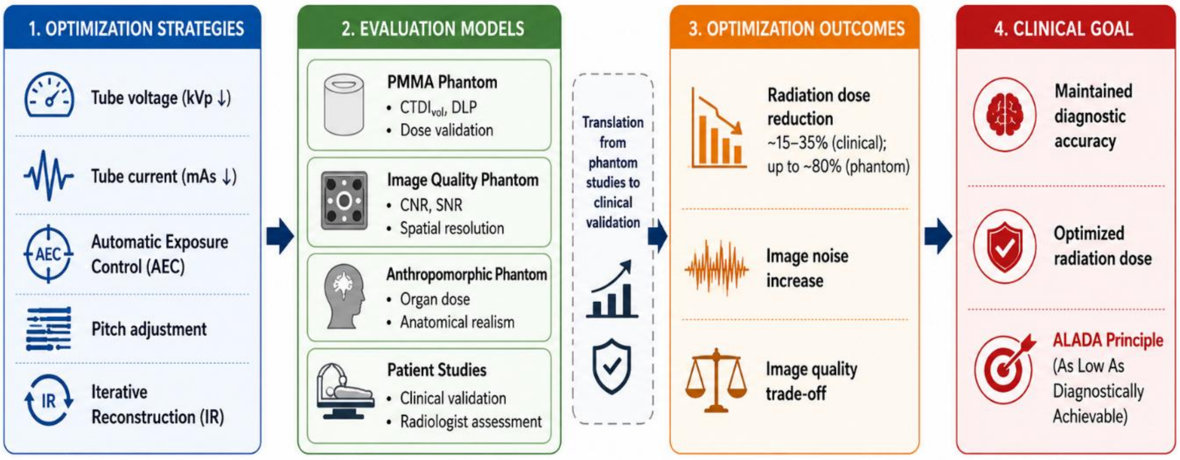

Fig. 2: Conceptual framework of head CT dose optimization

Table 1: PMMA Phantoms

Study	Year	CT System	Object	Unoptimized Protocol	Optimized Protocol	Unoptimized Dose	Optimized Dose
Gomez [21]	2019	NA	PMMA	120 kV, 200 mAs	80 kV, 450 mAs	23, 73 mGy	23,4 mGy
Santos [22]	2022	GE Lightspeed VCT Model 64 Slices	PMMA	120 kV, 200 mAs	80 kV, 420 mAs	39,92 mGy	28,87 mGy
Santos [23]	2023	Philips 16 Slices	PMMA	120 kV, 110,5 mAs	120 kV, 35 mAs	20,02 mGy	6,34 mGy
Fernandez [20]	2017	GE Discovery 64 Slices	PMMA	120 kV 200 mAs	80 kV, 100 kV, 120 kV, 160, 240, 420 mA	67,10 mGy	8,14 mGy
Mekonin [16]	2023	Philips Big Bore 16 Slice	PMMA	90 kV, 120 kV, 140 kV, 100 mAs, 200 mAs, 400 mAs,	NA	6,4 mGy, 13,6 mGy, 19,8 mGy, 15,5 mGy, 17 mGy,	NA

Table 2: Image Quality Phantoms

Study	Year	CT System	Object	Unoptimized Protocol	Optimized Protocol	Unoptimized Dose	Optimized Dose
Prabsattroo [25]	2023	NeuViz 128 Slices	Cathpan 700	120 kVp, 300 mAs,	80, 100, 140 kV 100, 200, 400 mA	NA	NA
Anam [13]	2025	GE Revolution 128 CT Scanner	ACR	120 kV, 160 mA, 1,25b mm, 235 mm	80 kV, 100 kV, 140 kV 80 mA, 100 mA, 120 mA, 140 mA, 200 mA, 1,2 mm, 5 mm, 3 mm, 5 mm , 6 mm, 7 mm, 9 mm	NA	NA
Chang [26]	2017	Philips Briliance iCT 128 Slices	ACR	120 kVp, 150 – 250 mAs	100 kVp, 150 – 250 mAs	NA	NA
Korn [27]	2015	GE Lightspeed VCT, Siemens Somatom Definition Flash Scanner	ACR	FBP	ASIR, SAFIRE	16 mGy	12 mGy, 8 mGy
Rapalino [28]	2012	GE Discovery CT750HD	ACR	FBP	ASIR	66,5 mGy	49,7 mGy

Figure 2 shows the conceptual framework of CT dose optimization strategies, integrating acquisition parameters, evaluation models, and resulting outcomes to achieve diagnostically acceptable image quality.

3. Result and Discussion

The main objective of CT optimization is to reduce radiation dose while maintaining diagnostically acceptable image quality [14]. However, reducing the radiation dose increases image noise and compromises diagnostic performance [15]. Therefore, protocol modifications for optimization purposes must be conducted carefully and accurately [13]. This study addresses CT optimization across various protocols and phantom models.

3.1 PMMA Phantom

The PMMA phantom is designed to evaluate CT dose index parameters, such as CTDIvol (volume CT dose index) and DLP (dose-length product). The phantom is made of polymethylmethacrylate (PMMA) solid acrylic material with a diameter of 16 cm for the head and 32 cm for the body phantom. The use of a PMMA phantom in CT optimization ensures consistent, reproducible evaluations of radiation dose before and after protocol changes, enabling accurate assessments of how parameter adjustments affect dose reduction [16].

Across the reviewed studies listed in Table 1, a consistent pattern is observed: radiation dose reduction is primarily achieved through modifications to tube voltage and tube current. Lowering tube voltage consistently reduces CTDIvol but increases noise due to higher quantum-noise contributions [17]. Consequently, most studies compensate for this by increasing the tube current to reduce the noise.

Comparative analysis across studies indicates that the effectiveness of tube voltage reduction is not uniform but depends on the balance between dose reduction and noise control [18].

Across the studies, reducing tube potential from 120 kVp to 100 kVp or 80 kVp correlates with notable radiation dose savings. However, this strategy also increases image noise [19]. Therefore, optimization strategies based solely on voltage reduction are often inadequate, and studies demonstrate improved outcomes when combined with tube current adjustment or modulation techniques.

Compared with fixed-parameter protocols, studies using automatic exposure control (AEC) demonstrate more efficient dose optimization by dynamically modulating tube current based on attenuation characteristics. This method lowers unnecessary radiation exposure while maintaining more stable image quality [20].

In addition, geometric parameters such as slice thickness also influence radiation dose. Thinner slices improve spatial resolution but increase image noise, often leading to higher radiation output and higher CTDIvol [16]. These findings collectively suggest that optimization outcomes are determined by the interaction of multiple acquisition parameters rather than a single dominant factor.

The percentage of dose reduction differs substantially across studies, ranging from around 1% to over 80%. This wide variation shows differences in scanner technology, parameter combinations, and optimization approaches. Notably, studies that use multiparametric strategies, particularly those that integrate AEC, tend to achieve more consistent and clinically relevant dose reductions than those relying solely on manual parameter adjustments. Across the reviewed studies, the primary advantage of the PMMA phantom is its ability to provide standard, reproducible, and comparable radiation dose measurements [16, 24].

Its homogeneous structure enables precise and consistent estimation of CTDIvol and DLP, making it the reference model for assessing the direct impact of modifications to acquisition parameters on radiation output [16]. In other words, PMMA-based studies consistently serve as the foundational step in optimization workflows before advancing to more complex phantom models and clinical validation.

Despite its strengths in initial dose validation, the PMMA phantom cannot assess comprehensive image quality parameters. These limitations highlight a significant gap in current optimization studies and underscore the need for additional models, such as image-quality and anthropomorphic phantoms, to enable more thorough evaluation and facilitate translation into clinical practice.

3.2 Image Quality Phantom

Collectively, studies using PMMA phantoms provide essential insights into dose validation; however, a comprehensive evaluation of CT imaging performance requires integrating image-quality phantoms [29]. Unlike PMMA phantoms, which primarily focus on dose assessment, image-quality phantoms contain structured inserts and variable-contrast objects that enable quantitative analysis of noise, spatial resolution, contrast-to-noise ratio (CNR), signal-to-noise ratio (SNR), and low-contrast detectability [25]. This supports a systematic evaluation of the trade-off between radiation dose and image quality. The image quality phantoms provide a strong framework for protocol optimization aimed at preserving diagnostic performance [30].

Across the reviewed studies in table 2, a consistent pattern emerges: aggressive reductions in tube voltage, especially to 80 kVp, effectively lower radiation dose but increase image noise and reduce CT number accuracy, thereby limiting their applicability.

In contrast, moderate tube voltage settings, especially around 100 kVp, combined with optimized tube current (150–250 mAs), consistently offer a better balance between dose reduction and image quality preservation. Higher tube voltage (120–140 kVp) improves photon penetration and reduces noise, but it also increases radiation dose and scatter. This indicates that optimal parameter selection requires balancing competing physical effects rather than maximizing a single variable [27].

Compared to only adjusting acquisition parameters, reconstruction-based optimization, particularly iterative reconstruction (IR), has shown better consistency in maintaining image quality while enabling significant radiation dose reduction [31]. Across studies, IR significantly reduces image noise and improves CNR, SNR, and low-contrast detectability when compared to conventional filtered back projection (FBP) [28,29]. However, its effectiveness depends strongly on the applied level. Moderate IR levels (approximately 20–40% blending) are consistently identified as optimal, enabling dose reductions of approximately 20–30% while preserving natural image texture and maintaining diagnostic confidence. Higher IR levels can reduce noise further but might create artificial image texture (unnatural image texture) and reduce subjective image acceptability, highlighting a critical limitation in reconstruction-based optimization [32].

The achievable extent of dose reduction also varies across studies. Moderate reductions of approximately 15–20% can be effectively compensated by IR without compromising diagnostic quality. However, more aggressive reductions (≥30%) are consistently associated with noticeable degradation in image quality. This indicates a limited margin for optimization in head CT, as it's important to preserve subtle differences between gray and white matter [33].

From a phantom-comparative perspective, image quality phantoms offer a significant advantage over PMMA phantoms. They enable direct, quantitative assessment of image quality metrics. This led to a more precise determination of acceptable dose reduction thresholds [26]. Their standard design also ensures reproducibility and comparability across studies and CT systems, making them highly suitable for protocol optimization and quality control [27].

Despite their utility for comprehensive image quality assessment, image quality phantoms have limitations. They lack anatomical realism and cannot adequately represent diverse tissue composition, organ-specific attenuation, and the complex structures seen in clinical imaging [34]. These limitations highlight an important gap between quantitative image evaluation and clinical applicability, emphasizing the need for anthropomorphic phantoms as the next level of validation [35]. To properly assess the impact of optimization on anatomically relevant image quality, anthropomorphic phantoms are necessary.

3.3 Anthropomorphic phantoms

To ensure clinical relevance, protocol optimization is evaluated using anthropomorphic phantoms. These phantoms are designed to replicate human anatomy and tissue variability. They provide a more realistic simulation of tissue–radiation interactions compared to simplified phantom models [36,37]. Anthropomorphic phantoms play a critical role in bridging experimental optimization and clinical implementation by enabling organ-specific dose assessment in realistic anatomical settings [38].

Compared with PMMA and conventional image-quality phantoms, anthropomorphic phantoms offer enhanced realism by incorporating anatomically accurate structures and heterogeneous attenuation characteristics [35]. PMMA phantoms enable standardized dose measurement, image-quality phantoms enable quantitative assessment of image metrics, and anthropomorphic phantoms uniquely integrate both aspects within a clinically relevant anatomical context [38].

Across the reviewed studies in Table 3, a consistent trend emerges: radiation dose reduction is primarily achieved by modifying tube voltage and tube current. As with simpler phantom models, lowering these parameters effectively reduces radiation dose but is consistently associated with increased image noise and potential loss of spatial resolution [32]. However, studies using anthropomorphic phantoms show a narrower range for optimization. Preserving anatomical detail and accurately representing organ dose become critical limiting factors [45].

The comparative analysis reveals that multiparametric strategies demonstrate more robust performance than single-parameter adjustments. Studies that combine tube current reduction with iterative reconstruction (IR) consistently report improved noise characteristics and maintain image quality compared to conventional filtered back projection (FBP) [39].

Moderate dose reductions of approximately 15–35% are commonly achieved without compromising diagnostically acceptable image quality. However, more significant reductions require careful balancing of reconstruction strength to prevent distortion of image texture [46]. In addition to acquisition parameters, strategies like pitch adjustment and automatic exposure control (AEC) further improve dose optimization [41,42]. Increasing pitch reduces longitudinal beam overlap, thereby reducing dose, while AEC dynamically modulates tube current based on anatomical attenuation, enhancing dose efficiency across various regions [42]. When combined with iterative reconstruction, these methods enable significant reductions in both overall and organ-specific radiation doses, especially in radiosensitive organs such as the eye lens, thyroid, and salivary glands. Reported organ dose reductions typically range from about 30% to over 60%, depending on the optimization strategy and the anatomical area assessed.

A key advantage of anthropomorphic phantoms is their ability to provide detailed spatial dose distributions using dosimetry tools such as thermoluminescent dosimeters (TLDs). This allows for direct evaluation of radiation exposure in specific organs [41,43]. This capability is not achievable with homogeneous or image quality phantoms and represents a critical step toward clinically meaningful dose assessment [44]. Studies involving anthropomorphic phantoms confirm that multiparametric optimization strategies can achieve substantial dose reduction and also demonstrate that the optimization limits are tighter than those in simpler phantom models.

3.4 Patient-based

The main goal of CT optimization is to implement it in clinical practice, ensuring radiation dose reduction while maintaining diagnostically acceptable image quality [49]. While phantom-based studies provide controlled environments for protocol development, patient-based studies are crucial. They validate whether these strategies work effectively in real clinical conditions, where anatomical variability and diagnostic requirements introduce additional complexity [34].

Across the reviewed clinical studies in Table 4, a consistent pattern emerged: dose reduction was primarily achieved by lowering tube current. This is done either alone or with advanced reconstruction techniques [54]. Moderate reductions in tube current consistently result in substantial decreases in CTDIvol and DLP, typically ranging from 10% to 45%, depending on the clinical application and optimization method. Compared with phantom-based studies, where dose reductions can exceed 80%, real clinical implementations show a more conservative range. This reflects the need to maintain diagnostic reliability [20,50].

In terms of image quality, most studies report that reduced tube current increases image noise. However, iterative reconstruction techniques often balance this effect, keeping it within diagnostically acceptable limits [29]. Quantitative assessments, including signal-to-noise ratio (SNR) and contrast-to-noise ratio (CNR), typically show minor or acceptable drops; qualitative evaluations by radiologists confirm that the visibility of anatomical structures and lesions remains intact. This pattern is consistently observed across various clinical scenarios, including acute neuroimaging, evaluation of intracranial hemorrhage, and radiotherapy planning. Radiologists assess image quality primarily through visual evaluation of image noise, sharpness of structures (GW/WM differentiation), presence of artifacts, and clarity of anatomical detail and lesions.

Across studies, the assessment is commonly conducted using Likert-type ordinal scales, with score ranges ranging from 1–4 to 1–5 depending on the parameters evaluated [50,51]. Although radiation-dose reductions often lead to higher noise levels and slight degradation in spatial detail, these changes do not necessarily compromise clinical usability. Instead, diagnostic acceptability remains the key factor, with many low-dose images still considered interpretable despite slight increases in noise or reduced sharpness [49].

Comparative analysis further shows that combining tube current reduction with iterative reconstruction results in more stable image quality than adjusting a single parameter [48]. Moderate dose reductions of about 20% to 35% can generally be achieved without compromising diagnostic performance. However, more significant reductions require careful consideration, particularly in regions such as the posterior fossa, where image noise can be more noticeable. These findings highlight that the acceptable level of dose reduction in clinical practice is more constrained than in phantom-based studies because of the need to maintain subtle Gray–white matter differentiation and diagnostic confidence.

Overall, patient-based studies confirm that optimization strategies derived from phantom models are clinically applicable. However, they also demonstrate that dose reduction must be carefully balanced with image quality requirements. This emphasizes the importance of combining phantom-based optimization with clinical validation to define the safe and effective limits of dose reduction in adult head CT.

4. Conclusion

In conclusion, optimizing dose in non-contrast head CT primarily involves adjusting tube voltage and tube current, along with iterative reconstruction, to consistently compensate for increased image noise. The reviewed evidence demonstrates that effective optimization requires a multiparametric approach rather than reliance on a single parameter.

A clear stepwise validation framework is observed, in which PMMA phantoms evaluate dose reduction, image-quality phantoms assess quantitative metrics, and anthropomorphic phantoms provide anatomically realistic, organ-specific dose assessment. Patient-based studies confirm clinical relevance, but the dose reductions achievable in practice are more limited than in controlled phantom conditions, which helps preserve diagnostic confidence. Overall, effective head CT optimization requires a systematic and stepwise approach that links experimental validation with clinical implementation, ensuring that radiation dose is reduced in accordance with the ALADA (As Low as Diagnostically Acceptable) principle while preserving diagnostic integrity

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