RESEARCH PAPER

"Quantitative Modeling and Optimization of Radiation Dose in Routine CT Imaging: Balancing Image Quality and Dose Reduction under the ALARA Principle Framework"

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Abstract

Background: Computed tomography is indispensable in modern diagnostic imaging, but it is also a major contributor to cumulative medical exposure from ionizing radiation. Under the ALARA framework, dose optimization is not simple dose minimization; it is the controlled reduction of exposure while preserving the level of image quality required for the clinical task. International guidance identifies CTDIvol and DLP as the operational dose quantities for CT optimization and recommends using diagnostic reference levels as audit tools rather than patient-specific dose limits.

Objective: To quantify the dose–image-quality trade off in routine CT imaging using the attached dataset and to identify which protocol pattern most closely satisfied an ALARA-consistent balance between dose reduction and preserved diagnostic quality.

Methods: A retrospective observational reanalysis was performed on the attached Excel dataset comprising 40 routine CT examinations from a tertiary-care radiodiagnosis department. The dataset contained 14 head, 14 chest, and 12 abdomen CT examinations, divided evenly into Group A and Group B protocols. Group A represented a standard fixed-parameter approach using 120 kVp, fixed mA, AEC off, pitch near 1.0, and filtered back projection. Group B represented an optimized approach using 80–100 kVp, AEC on, higher pitch, and iterative reconstruction. Outcomes included CTDIvol, DLP, effective dose, HU, noise, SNR, CNR, and an ordinal subjective image-quality score. Group comparisons used Welch's t test; exam-wise effects were explored with two-way ANOVA, Pearson correlation, and adjusted multivariable linear regression.

Results: Overall, Group B reduced mean DLP by 43.1% and mean effective dose by 45.4% relative to Group A, with no statistically significant overall difference in noise, SNR, or CNR, although subjective score was modestly lower. In the head CT subgroup, Group B reduced CTDIvol from 50.8 ± 2.2 to 32.2 ± 2.4 mGy and effective dose from 1.579 ± 0.078 to 0.958 ± 0.065 mSv, both $p < 0.001$, without significant changes in noise, SNR, CNR, or subjective score. Chest and abdomen CT also showed large dose reductions, but CNR fell modestly in both regions. In adjusted modeling, Group B remained independently associated with a 2.57 mSv lower effective dose (95% CI, 1.86 to 3.28 mSv lower; $p < 0.001$).

Conclusion: A lower-kVp, AEC-enabled, iterative-reconstruction protocol produced substantial dose savings across routine CT examinations. In this dataset, the optimized protocol was most clearly ALARA-concordant for head CT, where dose was reduced by about 39% without a statistically significant loss of objective or subjective image quality. For chest and abdomen CT, dose savings were still substantial, but additional tuning is needed to recover contrast performance while preserving the achieved reduction.

Keywords:computed tomography, radiation dose optimization, ALARA, CTDIvol, DLP, effective dose, automatic exposure control, iterative reconstruction, signal-to-noise ratio, contrast-to-noise ratio

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Introduction

CT remains one of the most clinically valuable cross-sectional imaging methods because it provides rapid volumetric information, strong soft-tissue contrast, and broad applicability in emergency and routine care. At the same time, CT is a major contributor to cumulative exposure from diagnostic radiology, which makes protocol optimization a central patient-safety issue rather than a purely technical preference. Population-level concern arises less from any single justified scan than from the combination of high utilization, repeated imaging, and large inter-protocol dose variation across practices.

Guidance from the National Cancer Institute and the U.S. Food and Drug Administration emphasizes that CT uses ionizing radiation at levels higher than conventional radiography, and that although the absolute risk from one appropriate scan is usually small, the risk is not zero and rises with radiation output and cumulative exposure. The International Commission on Radiological Protection has also made clear that effective dose is primarily a radiological protection quantity intended for comparison and planning, not a precise patient-specific predictor of stochastic risk.

The optimization principle is framed internationally by ICRP and IAEA as keeping exposures as low as reasonably achievable while still achieving the diagnostic purpose of the examination. In CT, diagnostic reference levels are intended to support this process; they are optimization tools and should not be applied to individual patients as dose limits. For CT specifically, the recommended dose quantities for monitoring and DRL work are CTDIvol and DLP.

The difficulty, however, is that dose cannot be reduced indiscriminately. The IAEA notes that lower tube output raises image noise, and increasing pitch may reduce dose only at the cost of image-quality changes. Technical guidance from AAPM further shows that tube current modulation, automatic exposure control, reconstruction algorithm, and task-based noise behavior all strongly influence whether a lower-dose dataset remains clinically acceptable. Large multi-institutional studies have shown that CT dose variation is driven predominantly by local technical choices rather than machine differences alone, which means optimization is achievable but must be protocol-specific and actively governed.

The present study was designed to answer a practical question: in the attached routine CT dataset, how much dose reduction can be achieved by moving from a conventional fixed-parameter protocol toward a lower-kVp, AEC-enabled, iterative-reconstruction protocol, and at what point does image quality begin to erode? The primary hypothesis was that the optimized protocol would substantially lower dose overall, but that the strength of the dose–quality tradeoff would differ by examination type, with head CT most likely to retain diagnostic adequacy under the optimized settings.

Methods

Study design and data source

This retrospective observational study was conducted in the Department of Radiodiagnosis at a tertiary-care hospital. A total of 40 CT examinations with complete dose and image-quality parameters were included for analysis, with no exclusions required due to missing primary endpoints. The study population comprised patients aged 24 to 74 years, with a balanced sex distribution across protocol groups.

Convenience sampling was applied to routine CT examinations meeting predefined eligibility criteria. Inclusion criteria consisted of CT scans with complete dose and imaging data, while studies with incomplete records or significant motion artifacts were excluded. All examinations were performed at Mahatma Gandhi Hospital and College using a 256-slice multidetector CT scanner (GE Healthcare). The study period spanned from January 2026 to April 2026.

The dataset included mixed examination types: 14 head CT scans, 14 chest CT scans, and 12 abdominal CT scans. These were evenly distributed between the two protocol groups, with Group A comprising 7 head, 7 chest, and 6 abdominal scans, and Group B having an identical distribution.

Protocol groups, variables, and operational definitions

Group A reflected a conventional protocol: 120 kVp throughout, fixed tube current with a mean of 234.5 ± 15.4 mA, AEC off, pitch 0.99 ± 0.02, and filtered back projection reconstruction. Group B reflected a lower-dose protocol: tube potential 80–100 kVp, AEC on, pitch 1.13 ± 0.04, and iterative reconstruction. For Group B, console-exported mA was not available because the

acquisition used AEC-driven modulation rather than a single fixed tube current.

The collected variables included age, sex, weight, examination type, kVp, mA where available, AEC status, pitch, reconstruction mode, scan length, CTDIvol, DLP, effective dose, mean ROI attenuation in HU, noise, SNR, CNR, and a subjective image-quality score. The ROI notes embedded in the worksheet indicated exam-specific objective assessment sites: frontal white matter with adjacent gray matter comparator for head CT, descending thoracic aorta with paraspinal muscle comparator for chest CT, and right hepatic lobe with erector spinae muscle comparator for abdomen CT.

CTDIvol and DLP were treated as the standard console-displayed CT dose quantities used to monitor CT practice. Current guidance describes DLP as the product of CTDIvol and the scanned length, which makes it sensitive both to scanner output and to anatomic coverage. AAPM Task Group 233 defines tube current modulation as automatic adaptation of tube current to patient attenuation to achieve a specified image-quality target, and defines AEC as the broader automatic adaptation of tube output to patient radiological properties. The same report defines image noise magnitude as the standard deviation of pixel values in a region of interest. Effective dose was used in this study only as a broad comparative index across protocols and body regions and not as an individualized risk measure.

Statistical analysis

Continuous variables were summarized as mean ± standard deviation, and categorical distributions were summarized descriptively. Between-group comparisons used Welch's independent-samples t test. To account for heterogeneity across body regions, examination-wise analyses were performed separately for head, chest, and abdomen CT. Two-way ANOVA was used to examine main effects of protocol group and examination type, and Pearson correlation was used within examination type to evaluate the dose–quality relationship between effective dose and objective image-quality indices. Multivariable linear regression was then used to assess whether protocol group remained associated with effective dose and image quality after accounting for age, weight, and examination type.

For practical optimization, an exploratory study-specific ALARA decision rule was also applied. Under this rule, a protocol was considered a practical optimization candidate if it achieved a lower mean effective dose while preserving a mean subjective score of at least 3 and showing no statistically significant decrease in SNR or CNR. This rule was not taken from an external guideline; it was used only to make the internal optimization decision transparent.

Results

The study included 40 routine CT examinations, divided evenly between Group A and Group B. Demographic balance was good: age and weight did not differ significantly between groups, and sex distribution was identical. The two groups were therefore broadly comparable at baseline, while acquisition parameters differed in the expected protocol-defined directions.

Table 1. Baseline demographic and protocol characteristics

Sample size, n	20	20	
Age, y	46.5 ± 13.9	48.3 ± 14.1	0.687
Weight, kg	71.3 ± 9.8	72.3 ± 9.8	0.768
Sex (M/F)	10/10	10/10	Balanced by design
Exam distribution (Head/Chest/Abdomen)	7/7/6	7/7/6	Balanced by design
Tube potential, kVp	120.0 ± 0.0	94.0 ± 9.4	Protocol-defined difference
Tube current, mA	234.5 ± 15.4	AEC-driven (console mA not exported)	Not comparable
AEC	Off	On	Protocol-defined difference
Pitch	0.99 ± 0.02	1.13 ± 0.04	<0.001
Reconstruction	FBP	IR	Protocol-defined difference

Across all examination types pooled together, Group B achieved large reductions in integrated dose metrics. Mean DLP fell from 601.9 ± 180.4 to 342.4 ± 116.3 mGy·cm, a 43.1% reduction, and mean effective dose fell from 5.494 ± 3.675 to 3.001 ± 1.958 mSv, a 45.4% reduction. Overall noise, SNR, and CNR did not differ significantly, although the mean subjective image-quality score was modestly lower in Group B. The pooled CTDIvol comparison approached significance but did not cross the 0.05 threshold, which reflected the large heterogeneity introduced by combining head, chest, and abdomen examinations in one global analysis.

Table 2. Overall radiation dose and image-quality outcomes

CTDIvol	26.27 ± 18.72	16.12 ± 12.27	-38.7	0.051
DLP	601.9 ± 180.4	342.4 ± 116.3	-43.1	<0.001
Eff Dose	5.494 ± 3.675	3.001 ± 1.958	-45.4	0.012
Noise	8.67 ± 3.77	8.86 ± 3.50	2.1	0.873
SNR	6.07 ± 2.22	5.64 ± 1.93	-7.1	0.517
CNR	2.73 ± 0.44	2.54 ± 0.39	-7.0	0.157
Score	3.35 ± 0.49	3.05 ± 0.39	-9.0	0.040

Examination-wise analysis produced a clearer picture. The head CT subgroup showed the most favorable balance between dose reduction and preserved quality. Group B reduced head CTDIvol from 50.8 ± 2.2 to 32.2 ± 2.4 mGy and effective dose from 1.579 ± 0.078 to 0.958 ± 0.065 mSv, both $p < 0.001$. Yet the corresponding differences in SNR, CNR, and subjective score did not reach statistical significance. This made head CT the strongest internal candidate for ALARA-concordant optimization. Chest and abdomen CT behaved differently: dose reductions were equally impressive, but CNR was significantly lower in the optimized group in both regions, suggesting that these body protocols still need technical refinement before routine unrestricted adoption.

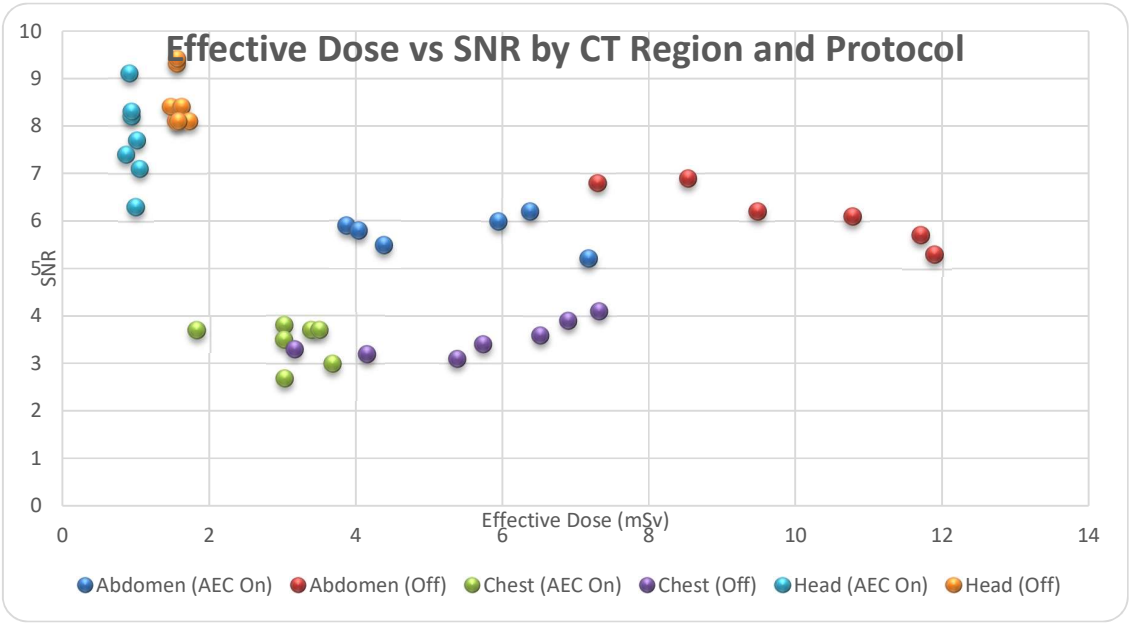

Figure 1. Effective Dose versus SNR Across CT Regions and Protocol Groups.

Table 3. Examination-wise comparison of key dose and quality outcomes

Exam	Outcome	Group A	Group B	P value
Head	Eff Dose	1.579 ± 0.078	0.958 ± 0.065	<0.001
Head	CTDIvol	50.8 ± 2.2	32.2 ± 2.4	<0.001
Head	SNR	8.54 ± 0.57	7.73 ± 0.91	0.072
Head	CNR	2.21 ± 0.18	2.13 ± 0.21	0.421
Head	Score	3.43 ± 0.53	3.14 ± 0.38	0.273
Chest	Eff Dose	5.594 ± 1.504	3.072 ± 0.608	0.003
Chest	CTDIvol	11.1 ± 3.0	6.5 ± 1.3	0.005
Chest	SNR	3.51 ± 0.37	3.44 ± 0.42	0.743
Chest	CNR	2.86 ± 0.15	2.61 ± 0.23	0.039

Chest	Score	3.29 ± 0.49	2.86 ± 0.38	0.093
Abdomen	Eff Dose	9.946 ± 1.831	5.301 ± 1.384	<0.001
Abdomen	CTDIvol	15.4 ± 2.8	8.6 ± 2.1	0.001
Abdomen	SNR	6.17 ± 0.62	5.77 ± 0.36	0.208
Abdomen	CNR	3.18 ± 0.19	2.93 ± 0.18	0.041
Abdomen	Score	3.33 ± 0.52	3.17 ± 0.41	0.550

An additional observation was that Group B had slightly shorter scan lengths within all examination types, by about 4% in head CT, 6% in chest CT, and 5% in abdomen CT. Because DLP depends on both CTDIvol and scan length, this tighter anatomic coverage contributed to dose reduction beyond the lower per-volume scanner output alone.

The adjusted modeling supported the unadjusted results. A multivariable model controlling for examination type, age, and weight showed that Group B remained associated with a 2.57 mSv lower effective dose than Group A (95% CI, 1.86 to 3.28 mSv lower; $p < 0.001$). When examination type, effective dose, age, and weight were considered together, Group B was associated with a modestly lower SNR and subjective score, but not with a statistically significant reduction in CNR. Two-way ANOVA also showed that the effect of protocol on effective dose depended on examination type, confirming that the optimization benefit was not uniform across body regions.

Within-examination dose–quality correlations were generally weak to moderate and mostly non-significant. The head CT subgroup is especially important here: effective dose correlated only moderately with SNR ($r = 0.421$, $p = 0.134$) and weakly with CNR ($r = 0.194$, $p = 0.507$). In practical terms, this means that higher radiation output in head CT did not translate into proportionate or statistically demonstrable image-quality gains in this sample.

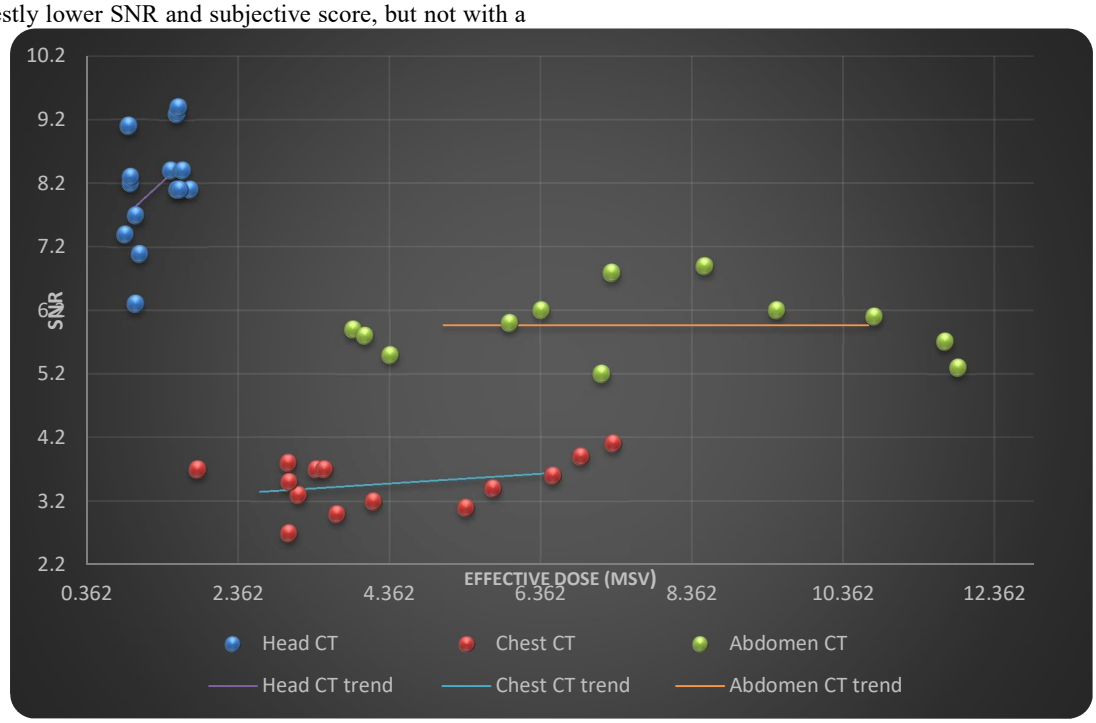

Figure 2. Effective Dose versus SNR Across CT Examination Types and Protocol Groups, Demonstrating Distinct Region-Specific Clustering.

For contextual benchmarking, current guidance recommends CTDIvol and DLP as the principal CT audit quantities, with local medians used as typical dose levels and higher percentiles used as optimization triggers. In the pooled dataset, the internal medians and 75th percentiles were 41.4 and 50.1 mGy for head CTDIvol with corresponding DLP values of 600.8 and 742.3 mGy·cm; 7.6 and 11.1 mGy for chest CTDIvol with DLP 256.6 and 403.2 mGy·cm; and 11.4 and 14.7 mGy for abdomen CTDIvol with DLP 482.6 and 653.5 mGy·cm. When these data were compared cautiously with current UK adult NDRLs, the optimized Group B medians remained below all contextual reference values, whereas Group A exceeded the chest and abdomen references and slightly exceeded the head CTDIvol reference. Because the UK benchmarks are indication-based and not identical to the clinical indications in this dataset, this comparison should be interpreted as contextual rather than definitive.

Table 4. Contextual comparison of protocol medians with published adult NDRLs

Exam	Group	Median CTDIvol	Median DLP	Contextual reference (CTDIvol / DLP)	Relative to reference
Head	A	50.1	743.6	47 / 790	CTDI above, DLP below
Head	B	32.7	445.2	47 / 790	Both below
Chest	A	11.1	409.6	8.5 / 290	Both above
Chest	B	6.5	217.1	8.5 / 290	Both below
Abdomen	A	15.6	675.0	10 / 530	Both above
Abdomen	B	8.4	344.4	10 / 530	Both below

Using the study-specific optimization rule defined a priori for this analysis, the optimized protocol qualified as the best ALARA candidate for head CT because it achieved a lower dose while preserving a mean score above 3 and showing no statistically significant degradation in SNR or CNR. By contrast, chest and abdomen CT under the optimized protocol still achieved very large dose savings, but they did not fully satisfy the same internal quality-preservation condition because CNR was significantly lower.

Discussion

The principal finding of this study is that protocol optimization worked, but not equally well for every examination type. A lower-kVp, AEC-enabled, higher-pitch, iterative-reconstruction approach achieved very large overall dose reductions, especially for DLP and effective dose. However, the best balance between dose saving and preserved image quality was observed in head CT, not uniformly across all routine CT examinations.

This head CT result is consistent with prior adult head CT literature. Published studies have reported that iterative reconstruction can permit meaningful dose reduction in routine head CT without major degradation of objective or subjective image quality, with reported ranges around 20% to 40% depending on scanner generation, reconstruction strength, and protocol design. The approximately 39% effective-dose reduction observed here for head CT, with no statistically significant loss of SNR, CNR, or subjective score, therefore sits squarely within the clinically plausible range described in prior work.

Chest and abdomen CT in the present dataset also showed impressive dose reductions, roughly 45% to 47%, but their image-quality behavior was more nuanced. This pattern is again consistent with the literature: adult chest CT studies have shown that iterative reconstruction can support substantial dose reduction, in some reports approaching 50%, while still preserving diagnostic confidence; abdominal low-kVp plus iterative-reconstruction studies have reported meaningful dose savings with acceptable image quality, although the exact balance depends heavily on target contrast, patient size, and the reconstruction implementation. Our chest and abdomen findings fit that broader evidence base, but they also show that practical optimization is task-specific: a protocol can be dose-efficient and still require further tuning if local contrast performance erodes.

The mechanistic explanation for these findings is also coherent. AAPM Task Group 233 describes AEC and tube current modulation as patient-attenuation-responsive control systems intended to maintain a target image-quality level, while also noting that CTDIvol is directly proportional to tube current. The IAEA likewise emphasizes that reducing tube output lowers dose but raises image noise, and that increasing pitch can reduce exposure at the cost of image-quality effects. In the current study, the optimized group used lower tube potential, higher pitch, and iterative reconstruction, and the adjusted dose model showed the expected positive association between patient weight and effective dose. At the same time, scan-length discipline contributed to DLP reduction, showing that careful control of anatomic coverage is part of optimization, not an incidental detail.

The broader clinical implication is that routine CT optimization should be region-specific and governed locally. Multi-center evidence shows that CT dose variation is driven largely by site-level protocol choices, not by scanner brand or patient factors alone. In the Indian regulatory context, the Atomic Energy Regulatory Board expects radiology practices to remain conscious of patient dose, align examinations with reference levels where possible, and customize protocols for optimum image quality. In practical terms, the present data support adoption of the optimized protocol as the default candidate for routine noncontrast head CT, while suggesting a second optimization cycle for chest and abdomen CT focused on improving low-contrast performance. Likely levers include revising the AEC target, iterative-reconstruction strength, reconstruction kernel, kVp selection by body habitus, and scan-range standardization.

Several limitations should be acknowledged. The study was retrospective, single-center, and small, with only 40 examinations. The dataset mixed head, chest, and abdomen CT rather than representing one uniform clinical indication set. The worksheet did not contain scan dates, scanner model, approval identifier, or AEC-resolved mA values for the optimized group. Objective image-quality metrics were recorded values rather than measurements redrawn for this reanalysis. No organ-dose modeling or size-specific dose estimate was available. Finally, effective dose was used here only as a comparative quantity for optimization and should not be

interpreted as an individualized risk estimate. These limitations do not negate the core finding, but they do mean that the proposed protocol decisions should be implemented as part of an iterative local audit cycle rather than as a final universal standard.

Conclusion

In this retrospective routine CT dataset, a lower-kVp, AEC-enabled, iterative-reconstruction protocol achieved substantial dose reduction across all body regions. The strongest ALARA-consistent balance was seen in head CT, where effective dose fell by about 39% without a statistically significant loss of objective or subjective image quality. Chest and abdomen CT also demonstrated major dose savings, but their modest loss of CNR indicates that these body protocols should undergo another optimization cycle before being adopted as unrestricted defaults. The evidence from this audit supports a practical institutional strategy built on protocol-specific tuning, local DRL surveillance, disciplined scan-length control, and repeated dose–quality review rather than one-size-fits-all dose reduction.

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Conflicts of interest

No conflicts of interest were declared.

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