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Reducing Unnecessary Repeat CT Examinations Through Imaging Protocol Optimization: A Retrospective Quality Improvement Study

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ABSTRACT:

Background. Repeat computed tomography (CT) due to failure of the ordering process, technique or specific protocol, rather than in response to a change in the clinical question adds to the levels of radiation and healthcare costs, and increases time delays without further diagnostics, and is sparsely collected as a quality measure.

Objectives. To explore if a multicomponent CT protocol optimization bundle decreased the rate of unnecessary repeated CT examinations at a tertiary teaching hospital.
Methods. Retrospective analysis of quality improvement with interrupted time series using three CT scanners (12-month pre-implementation, 1-month transition, 12-month post-implementation; 38,719 CT examinations). The bundle of protocol standardization, indication-based protocol assignment, technologist pre-scan check list, standardized bolus-tracking criteria, duplicate-order alert, and monthly audit-and-feedback. Two radiologists established re-examinations (k = 0.84). The primary outcome was unnecessary repeat CT per 1,000 examinations and was analyzed with quasi-Poisson segmented regression and a statistical process control chart. Secondary outcomes were cause-specific rates, dose, image quality, workflow, and costs; all clinically indicated re-examinations were a negative-control outcome.

Results. Unnecessary repeat CT decreased from 35.4 to 23.5 per 1,000 examinations (rate ratio 0.66 (0.59-0.75)). Segmented regression detected an immediate change in level of 0.74 (0.57-0.95) (p =.021) and a decreasing trend; an estimated 326 fewer repeat examinations (41.3% of the counterfactual) and 2,310 person-mSv were avoided. Largest reductions occurred in duplicate orders, protocol selection, and contrast-timing errors; contrast-absent examination results was unchanged. Median effective dose per examination declined from 5.8 to 5.1 mSv; image-quality scores did not decline; repeat examinations with a clinical indication (a negative control) was unaffected. **Conclusions.** A simple, process-focused protocol optimization bundle was associated with a sustained, clinically significant reduction of unwarranted repeat CTs without a loss of image quality or throughput. Protocol optimization for motion repeats requires a different approach. A prospective multicentre trial is indicated.

1. INTRODUCTION

While CT is essential to current diagnostic processes, it is also the largest cause of medical radiation exposure, with CT alone accounting for 49-66% of a patient's total radiation dose in imaging for cancer (Granata et al., 2021). There is now more cohort evidence regarding the safety of low-dose exposure, which was previously uncertain, and it remains in focus (Granata et al., 2021). In a multi-national cohort of 948,174 persons imaged before 22 years, cumulative marrow dose was correlated with risk of hematological malignancy (excess relative risk 1.96/100 mGy), and a projection was made that a hematological malignancy would develop within 12 years in 1-2/10,000 children scanned today at a mean dose of 8 mGy (Bosch de Basea et al., 2023). A parallel analysis revealed a significant linear dose-response relationship for brain cancer (Hauptmann et al., 2023). A recent meta-analysis in adults similarly showed higher risk with increasing dose, but the estimates depended too much on lifetime risk modelling, whereas the estimates in the pooled adult cohorts were not precise (Cao et al., 2022). Whatever the figure, the concept remains: each test must be justified, and each dose must be optimized.

Much of the avoidable CT literature focuses on ordering – were the examination indicated to start with? Decision rules and appropriateness criteria are designed to address this, identifying very-low risk children who can avoid head CT (Ryan et al., 2020) or improve clinical decision rules by adding blood biomarkers (Maas et al., 2022), as 90-95% of people scanned after mild traumatic brain injury show no intracranial pathology. Parallels have been made with re-imaging asymptomatic individuals with no new clinical triggers: in blunt liver and spleen trauma, only 4% of routine repeat scans revealed new findings and led to management change in contrast to 47% of on-demand scans (Malloum Boukar et al., 2021); routine reimaging of asymptomatic children with high-grade renal injury was not associated with improved outcomes (Schmidt et al., 2022); early surveillance imaging may not be justified in grade 1 blunt thoracic aortic injury (Jinadasa et al., 2022); and management benefits of repeat head CT after mild traumatic brain injury are inconsistent and practice varies (Taddei et al., 2025). Redundancy also exists at the step of order entry: 13% of sinus CTs at an academic centre followed previous head imaging of the sinuses (Xu & Lee, 2021).

Perhaps less well known and less studied is avoidable CT that occurs within the radiology department-incorrect protocol, mistimed contrast phase, limited coverage, patient motion or positioning, or data transfer error. Dose monitoring data suggest the problem is significant: wrong study label or wrong protocol selection accounted for 29-40% of high-dose alerts in one tertiary centre (Fusco et al., 2022). Protocol standardisation can reduce doses profoundly: one tertiary centre eliminated 86/222 apparently redundant protocols, reducing dose by 23-58% (Rajiah et al., 2020), and systematic optimisation of acquisition parameters using automatic exposure control, iterative reconstruction, and custom kV can deliver large dose reductions without compromising image quality (Jubran et al., 2022; Stojadinović et al., 2024; Tulik et al., 2020). Objective metrics such as automated image-quality indicators also allow monitoring of such improvements (Chun et al., 2022). But all of these studies are based on dose per examination; they rarely examine whether optimised protocols also reduce the number of examinations required.

Tools developed for low-value care have had mixed success at reducing excess imaging, showing limited impact in individual trials and widely varying results (Lange et al., 2023; Moore et al., 2022; Soltana et al., 2021). Direct feedback on quality issues, clinical decisions support and more consultation between providers and specialists could reduce imaging that is generally thought to be avoidable (Moore, 2022). Providing care in a more coordinated fashion can also help reduce imaging, as seen with re-imaging due to the timing of vaccination relative to cancer imaging (McIntosh et al., 2021).

So we developed and tested a multicomponent protocol optimization bundle targeted at technique- and process-driven repeat CT. The goal of this retrospective quality improvement study was to measure its impact on unnecessary repeat CT, to determine which causes it would resolve and to establish that we could still go up (radiation dose), go down (costs) and maintain (image quality, throughput).

2. METHODS

2.1 Design, setting and reporting

This was a retrospective quality-improvement intervention study with an ITS design, performed in a radiology department of a tertiary-hospital academic medical centre, with about 19,000-20,000 CT exams annually, performed on three multidetector CT scanners (Scanner A, 64-slice; Scanner B, 128-slice; Scanner C, dual-source), with emergency department-, inpatient- and outpatient-based services to adults and children. The 25-month observation period consisted of a 12-month pre-

implementation baseline (January-December 2023), a onemonth roll-out (January 2024) from which no data was collected, and a 12-month post-implementation period (February 2024-January 2025). The quality-improvement research report follows the relevant framework, namely: context, intervention, study of the intervention, measures, analysis and ethical considerations.

2.2 Ethical considerations

The study was approved by [institutional review board/ethics committee name, approval number and date] as a service improvement study involving analysis of operational data that was routinely collected, with the intention of improving quality. Consent from individuals to participate was therefore not needed. Data were extracted from the radiology information system (RIS) and the picture archiving and communication system (PACS) and analysed on an aggregate basis.

2.3 Baseline problem analysis

A multidisciplinary team (2 radiologists, lead technologist, medical physicist, emergency physician, RIS/PACS analyst and a quality officer) reviewed all false positive (ie unnecessary repeat imaging) in the baseline year. They assigned each to one of the 7 following root causes in mutually exclusive categories (Table 4). The Pareto analysis of the baseline year revealed that protocol choice, contrast phase/timing and incomplete coverage comprised close to 2/3rds of unnecessary repeats, and these identified as main intervention areas. This stage reiterates the advice that protocol standardization be implemented as a managed operational program with dose registry, written standard operating procedures and technologist training (Rajiah et al., 2020).

2.4 Intervention: the protocol optimization bundle

The bundle was adopted in January 2024 and consisted of six components (Table 1), each targeting one or more root causes. Components were intentionally low technology, delivered by current staff via the department's existing quality governance structure.

Table 1 : Components of the CT protocol optimization bundle and the root causes they target

Component	Description	Target cause(s)	Owner
1. Protocol consolidation	Review of all active protocols; redundant and legacy protocols retired (148 → 62); one named protocol per indication, harmonized across the three scanners with locked default kV/mAs/reconstruction settings.	Protocol selection; coverage	Radiologist lead; physicist
2. Indication-driven protocol assignment	Mandatory structured indication at order entry mapped to a protocol; radiologist vetting of non-standard requests before the patient is scanned.	Protocol selection; duplicate orders	Radiology; referring services
3. Technologist pre-scan checklist	Five-item checklist (correct protocol, coverage and FOV, contrast volume/rate/access, positioning and metal removal, breath-hold and motion coaching) confirmed on the console before acquisition.	Coverage; motion; positioning	Lead technologist
4. Standardized contrast timing	Bolus-tracking ROI placement and trigger thresholds specified per protocol; test-bolus rule for abnormal cardiac output; saline-chaser standard.	Contrast phase/timing	Technologist; radiologist
5. Duplicate-order alert	RIS alert when a CT of the same body region has been performed or ordered in the preceding 30 days, prompting review of prior imaging and the report before proceeding.	Duplicate orders	RIS/PACS analyst

Component	Description	Target cause(s)	Owner
6. Audit-and-feedback	Monthly dashboard of repeat rate by cause, scanner and shift shared in a 20-minute huddle; individual feedback only for systems learning, not performance management.	All causes	Quality officer

ROI = region of interest; FOV = field of view; RIS = radiology information system.

2.5 Study population and definitions

All CT scans performed on the three scanners in the study window were eligible. These scans were CT acquired for PET/CT or SPECT/CT attenuation correction, CT guidance procedures, radiotherapy-planning CT and roll-out month were excluded. A potential repeat was identified if it was either (a) a same-session rescan of the same anatomical region following completion of the initial acquisition, or (b) an additional same-body-region scan within 30 days of an index scan. Two radiologists independently reviewed all potential repeats, using the hospital RIS, report and computer record, and categorised each as "needed", requiring it to be (a) a new clinical symptom or event, (b) in preparation for planned follow-up or surveillance, (c) as a treatment response, (d) to assess a complication or (e) as trauma re-evaluation, or as "not needed", attributable to incorrect protocol, technical, or clinical ordering process, with no new clinical features. A third radiologist moderated disagreements, which resulted in a $\varkappa = 0.84$ in a study sample of 400 flagged instances. "Not needed" repeats were then individually allocated to one root cause, body area, clinical application and scanner.

2.6 Outcomes

The main outcome measure was the monthly number of unnecessary repeat CT examinations per 1,000 CT examinations. Secondary outcome measures included cause, region, setting and scanner specific rates; dose metrics (volume CT dose index, dose-length product [DLP] and effective dose (computed with region-specific conversion coefficients)); and collective dose saved; cost; balancing measures were diagnostic image quality (assessed by radiologists on a 5-point Likert scale during a random sample of 600 CT examinations per period); non-diagnostic examination rate; report turnaround time; time spent in the scanner room per examination; contrast volume; and the rate of radiologists' recommending additional CT. Process measures were number of active protocols, compliance with the daily checklist (through monthly console audit) and performance of the duplicate-order alert. Repeat CT for clinically indicated reasons was used as a negative-control outcome: because the bundle should not change actual clinical need, a stable rate would suggest no secular trend in case-mix or in behavior (re-scanning as a proxy for overuse).

2.7 Data sources

Examination counts, protocol name, scanner, setting and region were retrieved from the RIS. Dose indices were acquired from an automatic dose-index monitoring system; this type of system allows granular analysis by protocol and acquisition throughout time and generates alert signals for protocol-selection errors (Fusco et al., 2022). Image-quality ratings were acquired during a structured audit conducted by the radiologists blinded to period.

2.8 Statistical analysis

Baseline characteristics were compared with χ^2 tests, Welch t tests, and Mann-Whitney U tests. Crude pre-post rate ratios (RR) with 95% CIs used the log-rate-ratio standard error (1/e1 + 1/e0). The primary analysis was a segmented (interrupted time series) regression of monthly counts, fitted using a Poisson general linear model with a log link, an offset term (by a measure of the log monthly CT volume), time (linear pre-intervention trend), a post-implementation indicator (level change), and time since implementation (change in slope); standard errors were scaled by the Pearson χ^2 dispersion (quasi-Poisson). This approach mirrors the design used to evaluate national low-value-imaging campaigns (Lange et al., 2023). Residual autocorrelation was evaluated with the Durbin-Watson statistic. A counterfactual forecast was generated by extending the pre-implementation trend, and avoided examinations was estimated as the difference between the counterfactual and observed counts in the post-implementation period. The number of avoided examinations was multiplied by the mean effective dose of the baseline repeat examinations, using the recommended dose by body region, to estimate collective dose avoided. Sensitivity analyses included fitting a negative binomial model, adjusting for annual seasonality with harmonic terms, removing the first two months of the

post-implementation period, using alternative repeat windows (same session, 7, 14, and 60 days), and using the negative-control outcome. As a concurrent approach, a p-chart (statistical process control) was constructed with 3 σ control limits and a centerline re-computed for the post-implementation phase; a run of eight or more points on one side of the baseline centerline was interpreted as evidence of special-cause variation. Two-sided $p<.05$ was considered statistically significant. Analyses were performed in Python with stats models and SciPy.

2.9 Economic estimate

The direct cost of a repeat examination (scanner, contrast and consumables, radiologist and technologist time) was obtained from departmental cost accounting at US$168, while program costs (workshops for redesign of protocol, build of informatics system, training, audit) were US$41,500. Savings due to reduction in downstream clinical impact of scans were not monetized.

3. RESULTS

3.1 Study population

The department performed 40,314 CTs over the 25 months; 1,595 were excluded from the roll-out month and 19,019 and 19,700 for the pre- and post-implementation periods, respectively (Figure 1). The adjudication of 1,247 and 1,079 identified potential repeats flagged 673 and 463 unnecessary repeat studies, respectively. The two time periods were similar in sex, contrast administration, clinical location, body regions and scanner distribution (Table 2); the statistically significant but clinically irrelevant difference in mean age (52.5 versus 53.1 years, p =.006) was due to the large sample size.

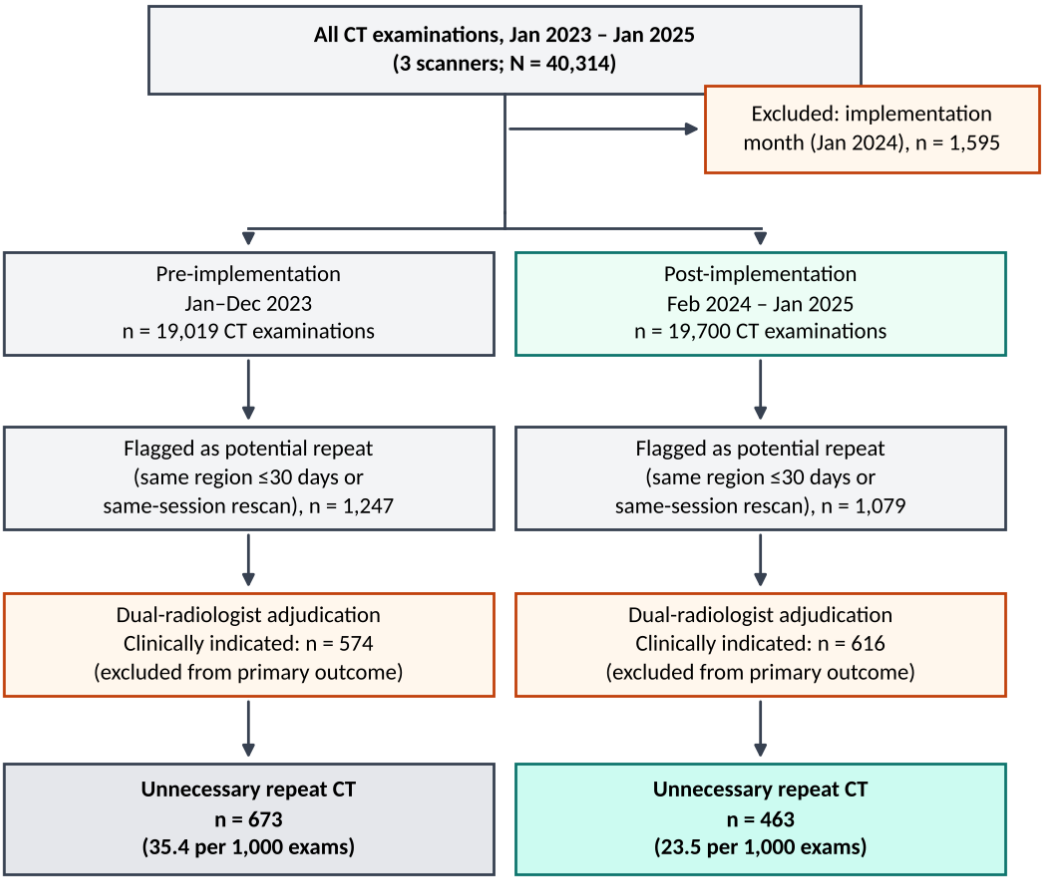


Figure 1. Flow of CT examinations through the study. Potential repeats were adjudicated by two radiologists; clinically indicated repeats were excluded from the primary outcome and analysed as a negative-control outcome.

Table 2. Characteristics of CT examinations before and after implementation

Characteristic	Pre-implementation (Jan–Dec 2023)	Post-implementation (Feb 2024–Jan 2025)	p
CT examinations, n	19,019	19,700	
Age, years, mean (SD)	52.5 (19.6)	53.1 (19.5)	.006
Female sex, n (%)	9,238 (48.6)	9,665 (49.1)	.342
Contrast-enhanced, n (%)	10,378 (54.6)	10,686 (54.2)	.530
Clinical setting, n (%)			**.010**
Emergency	7,240 (38.1)	7,659 (38.9)	
Inpatient	6,389 (33.6)	6,728 (34.2)	
Outpatient	5,390 (28.3)	5,313 (27.0)	
Body region, n (%)			**.345**
Head	4,144 (21.8)	4,308 (21.9)	
Neck/sinus	1,137 (6.0)	1,252 (6.4)	
Chest	3,966 (20.9)	4,152 (21.1)	
Abdomen/pelvis	5,700 (30.0)	5,884 (29.9)	
CT angiography	2,135 (11.2)	2,095 (10.6)	
Spine/MSK	1,937 (10.2)	2,009 (10.2)	
Scanner, n (%)			**.518**
A (64-slice)	7,617 (40.0)	7,825 (39.7)	
B (128-slice)	6,655 (35.0)	7,003 (35.5)	
C (dual-source)	4,747 (25.0)	4,872 (24.7)	

Percentages are column percentages. p values: Welch t test (age) and χ^2 test (categorical variables). MSK = musculoskeletal.

3.2 Primary outcome: unnecessary repeat CT

Unnecessary repeat CT fell from 35.4 per 1,000 exams (673/19019) pre intervention to 23.5 per 1,000 (463/19700) post intervention, an unadjusted rate ratio of 0.66 (0.59-0.75) (p<.001), a relative reduction of 33.6%. Monthly rates and fit of the segmented regression are presented in fig. 2. Prior to implementation the rate was sufficiently stable (p=.107) with an insignificant upward drift over time of 1.0% per month (p=0.412). Implementation was associated with an immediate change in the level of the outcome (RR 0.74 (0.57-0.95); p=.021), a 26.4% step reduction, and with a trend change in the slope (RR 0.96 (0.93-1.00); p=.067), a further trend shift over time in the post-implementation slope giving an estimated rate of decline of 2.5% per month (RR 0.97 (0.95-1.00); table 3). In the final month of observation the fitted rate was 20.3 per 1,000 exams, compared to the projected counterfactual of 42.4 per 1,000 exams.

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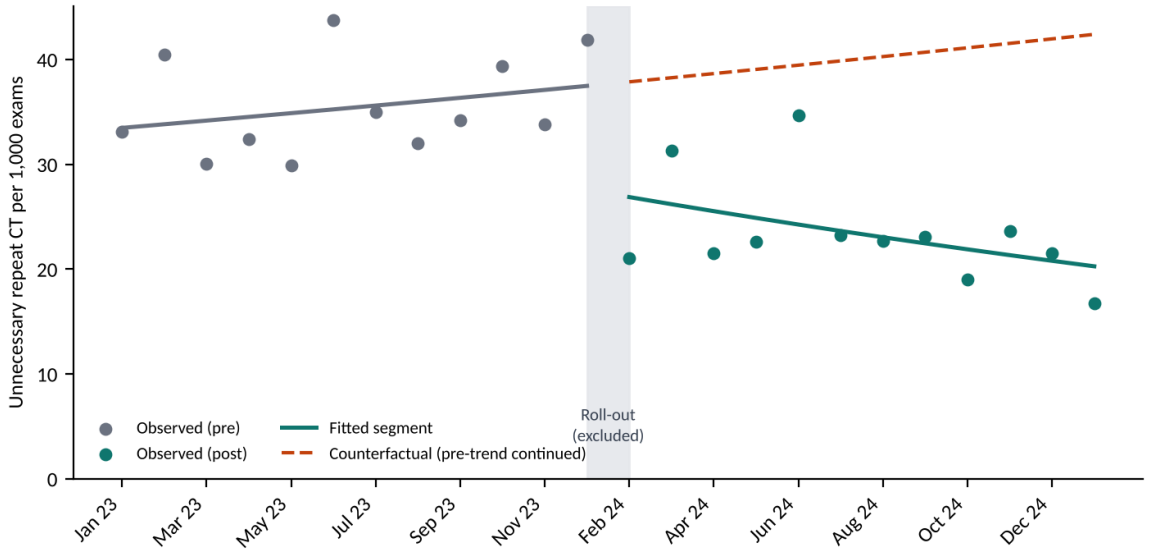


Figure 2. Interrupted time series of unnecessary repeat CT per 1,000 examinations. Points are observed monthly rates; solid lines are quasi-Poisson segmented-regression fits; the dashed line projects the pre-implementation trend (counterfactual). The grey band marks the roll-out month, excluded from the model.

Table 3. Interrupted time series regression of monthly unnecessary repeat CT

Parameter	Rate ratio (95% CI)	p	Interpretation
Baseline rate (per 1,000 at t = 0)	33.1	—	Fitted rate at start of series
Pre-implementation trend (per month)	1.01 (0.99–1.04)	.412	No significant drift before the bundle
Level change at implementation	**0.74 (0.57–0.95)**	**.021**	**Immediate 26.4% reduction**
Slope change (per month)	0.96 (0.93–1.00)	.067	Additional monthly decline
Post-implementation trend (per month)	0.97 (0.95–1.00)	.089	≈2.5% fewer repeats each month
Rate at month 12 post: fitted vs counterfactual	20.3 vs 42.4	—	Absolute difference 22.1 per 1,000
Estimated examinations avoided (12 months)	326 of 789	—	41.3% of counterfactual

Note. Quasi-Poisson regression with log-volume offset; dispersion = 1.24; Durbin–Watson = 2.77 (no positive residual autocorrelation).

The p-chart (Figure 3) confirmed this. Normal variation was level, and there was no month outside 3σ boundaries (centre line 35.4/1,000). The centre line moved post-intervention to 23.5/1,000, with all 12 months post-intervention falling below the previous centre line (a run well beyond the eight-point rule), and 4 months below the previous lower control limit (starting in Feb 24). These signals are consistent with special-cause improvement and not chance variation.

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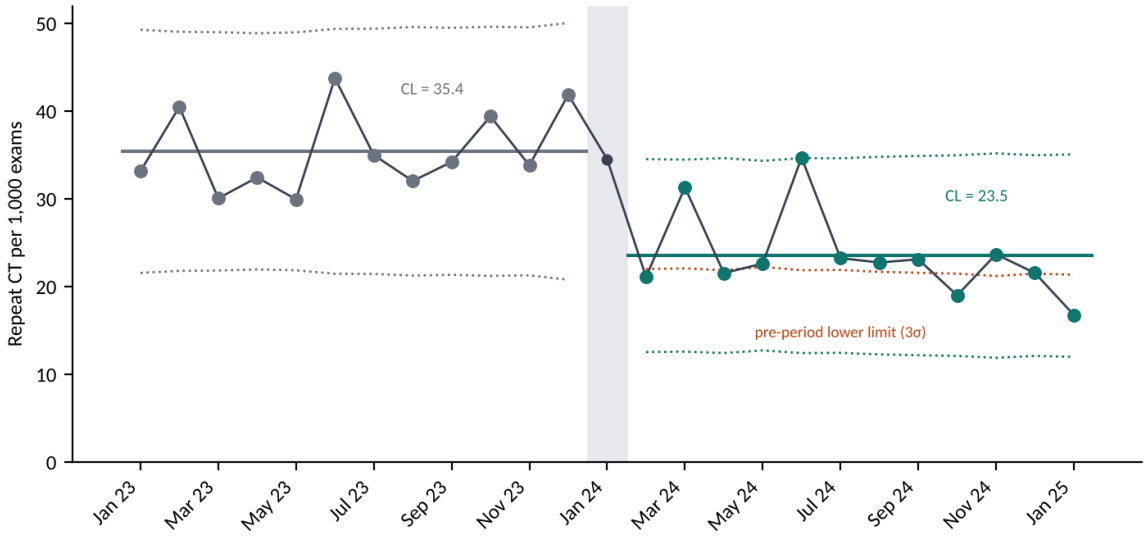


Figure 3. Statistical process control (p-chart) of monthly unnecessary repeat CT per 1,000 examinations. Solid horizontal lines are phase-specific centre lines; dotted lines are 3σ control limits; the dotted orange line shows the baseline lower limit projected into the post-implementation phase.

3.3 Root causes

Changes were not evenly distributed by cause (Table 4, Figure 4). The greatest absolute reduction was in suboptimal protocol selection (8.9 5.1 per 1,000; RR 0.57) and contrast phase/timing error (8.1 4.2; RR 0.51). The greatest relative reduction was in duplicate or redundant orders (RR 0.51). Incomplete coverage and positioning/metal artefact also fell significantly. Conversely, motion artefact (RR 1.03; p =.855) and technical or data-transfer failures (RR 1.24; p =.311) showed no change, as predicted, because no component of the bundle related to sedation, patient preparation or infrastructure reliability.

Table 4. Unnecessary repeat CT by root cause, before and after implementation

Root cause	Pre, n (%)	Post, n (%)	Pre rate	Post rate	Rate ratio (95% CI)	p
Suboptimal protocol selection	170 (25.3)	100 (21.6)	8.9	5.1	0.57 (0.44–0.73)	<.001
Contrast phase/timing error	155 (23.0)	82 (17.7)	8.1	4.2	0.51 (0.39–0.67)	<.001
Incomplete anatomical coverage	96 (14.3)	65 (14.0)	5.0	3.3	0.65 (0.48–0.90)	.008
Motion artefact	95 (14.1)	101 (21.8)	5.0	5.1	1.03 (0.78–1.36)	.855
Duplicate/redundant order	72 (10.7)	38 (8.2)	3.8	1.9	0.51 (0.34–0.75)	<.001
Positioning/metal artefact	47 (7.0)	28 (6.0)	2.5	1.4	0.58 (0.36–0.92)	.021
Technical/data-transfer failure	38 (5.6)	49 (10.6)	2.0	2.5	1.24 (0.81–1.90)	.311

Root cause	Pre, n (%)	Post, n (%)	Pre rate	Post rate	Rate ratio (95% CI)	p
All causes	**673**	**463**	**35.4**	**23.5**	**0.66 (0.59–0.75)**	**<.001**

Rates are per 1,000 CT examinations (denominators 19,019 pre, 19,700 post). Rate ratio = post/pre. Cause shares are percentages of all unnecessary repeats in the period.

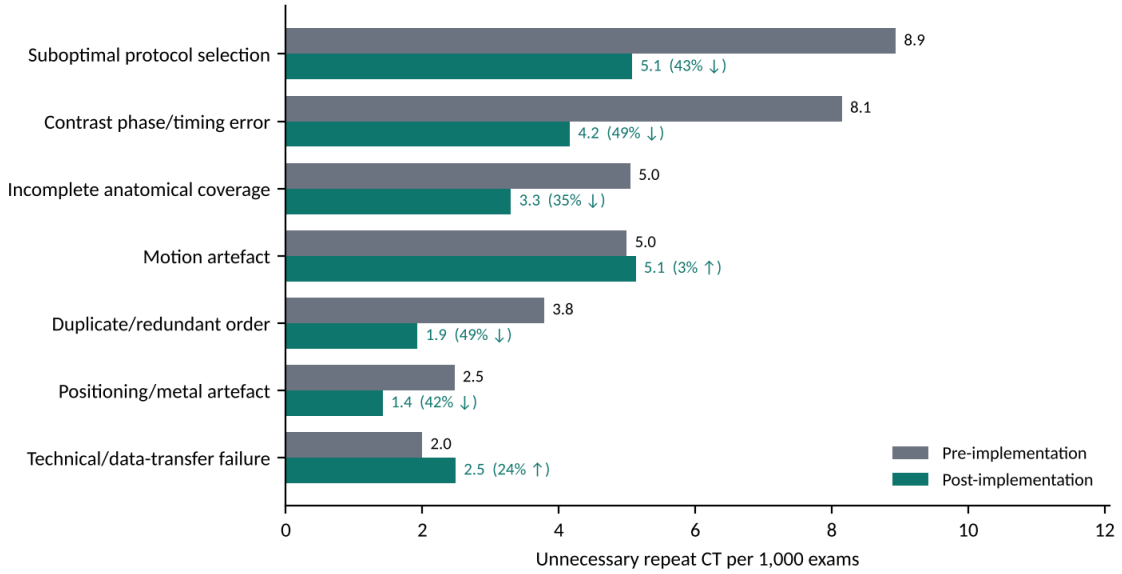


Figure 4. Unnecessary repeat CT per 1,000 examinations by root cause, before and after implementation. Labels give the post-implementation rate and the relative change.

3.4 Body region, clinical setting and scanner

All regions showed reductions, which were statistically significant for chest (0.62), abdomen/pelvis (0.64), CT angiography (0.59) and spine/MSK (0.65) and smaller, but non-significant, for head (0.85, CI 0.63-1.14) and neck/sinus (0.71, CI 0.48-1.04). These were the regions dominated by patient motion and in which the bundle was least effective. The greatest benefit was in CT angiography reflecting the distribution of contrast-timing errors (36). The benefit of the bundle was strongest in outpatients (RR 0.49), and weakest in the ED (RR 0.74), where end-of-shift time pressures and out-of-hours staffing levels precluded checklist use. Scanner B (RR 0.56) had the largest effect, Scanner C (RR 0.77) the smallest (Table 5, Figure 5) however, formal tests for heterogeneity were not undertaken given the post hoc exploratory nature of the subgroup analysis.

Table 5. Unnecessary repeat CT by body region, clinical setting and scanner

Subgroup	Exams pre	Exams post	Pre, n (rate)	Post, n (rate)	Rate ratio (95% CI)	p
Body region						
Head	4,144	4,308	95 (22.9)	84 (19.5)	0.85 (0.63–1.14)	.280
Neck/sinus	1,137	1,252	59 (51.9)	46 (36.7)	0.71 (0.48–1.04)	.079
Chest	3,966	4,152	130 (32.8)	84 (20.2)	0.62 (0.47–0.81)	<.001
Abdomen/pelvis	5,700	5,884	178 (31.2)	117 (19.9)	0.64 (0.50–0.80)	<.001

Subgroup	Exams pre	Exams post	Pre, n (rate)	Post, n (rate)	Rate ratio (95% CI)	p
CT angiography	2,135	2,095	110 (51.5)	64 (30.5)	0.59 (0.44–0.81)	<.001
Spine/MSK	1,937	2,009	101 (52.1)	68 (33.8)	0.65 (0.48–0.88)	.006
Clinical setting						
Emergency	7,240	7,659	287 (39.6)	226 (29.5)	0.74 (0.63–0.89)	<.001
Inpatient	6,389	6,728	229 (35.8)	161 (23.9)	0.67 (0.55–0.82)	<.001
Outpatient	5,390	5,313	157 (29.1)	76 (14.3)	0.49 (0.37–0.65)	<.001
Scanner						
Scanner A (64-slice)	7,617	7,825	317 (41.6)	229 (29.3)	0.70 (0.59–0.83)	<.001
Scanner B (128-slice)	6,655	7,003	231 (34.7)	135 (19.3)	0.56 (0.45–0.69)	<.001
Scanner C (dual-source)	4,747	4,872	125 (26.3)	99 (20.3)	0.77 (0.59–1.00)	.054

Rates are per 1,000 examinations in each stratum. Strata are not mutually exclusive across domains; p values are unadjusted.

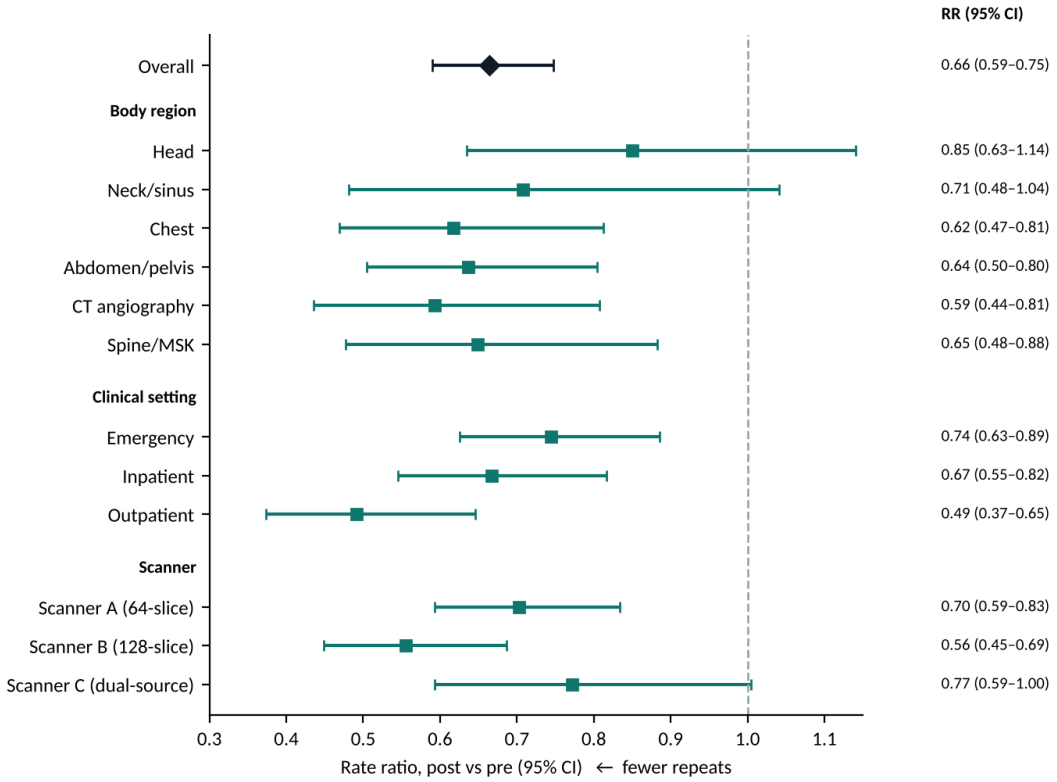


Figure 5. Forest plot of rate ratios (post vs pre) for unnecessary repeat CT overall and by body region, clinical setting and scanner. Values below 1 indicate fewer repeats after implementation; horizontal lines are 95% confidence intervals.

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3.5 Radiation dose

Protocol consolidation, locked default technique settings also decreased the dose per exam. The median DLP decreased across all sites (Table 6) (7% neck/sinus to 14% chest, all p <.001), as did the median effective dose per exam across the department (5.8 mSv, IQR 2.8-9.3 to 5.1 mSv, IQR 2.6-8.2; p <.001; Figure 6A). Department-wide, the median effective dose per repeated exam was 7.1 mSv (IQR 3.4-11.5). The 326 avoided repeated exams equate to around 2,310 person-mSv in collective dose averted during the first year (Figure 6B). This benefit is best understood as a reduction in low doses to a population of patients rather than as a way to estimate the number of cancers that might have been averted.

Table 6. Dose–length product and effective dose per examination by body region

Body region	DLP pre, mGy·cm median (IQR)	DLP post, mGy·cm median (IQR)	Change in median DLP	Effective dose pre (mSv)	Effective dose post (mSv)	p
Head	881 (656–1157)	817 (615–1077)	-7.3%	1.9	1.7	<.001
Neck/sinus	407 (317–528)	378 (290–496)	-7.2%	2.4	2.2	<.001
Chest	367 (268–487)	316 (231–433)	-13.8%	5.1	4.4	<.001
Abdomen/pelvis	613 (445–837)	538 (388–728)	-12.2%	9.2	8.1	<.001
CT angiography	563 (430–731)	490 (373–631)	-13.0%	8.4	7.3	<.001
Spine/MSK	542 (402–721)	491 (363–668)	-9.5%	8.1	7.4	<.001
All examinations	—	—	—	**5.8**	**5.1**	**<.001**

Effective dose estimated as DLP × region-specific conversion coefficient; median values shown. p values from Mann–Whitney U tests on DLP (all exams in each period).

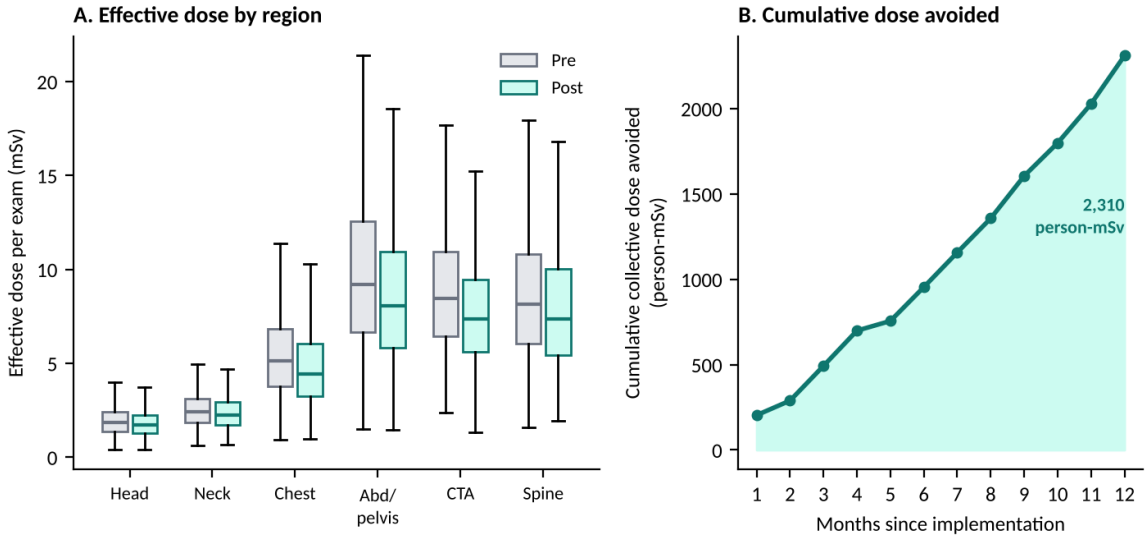


Figure 6. Radiation dose outcomes. (A) Distribution of effective dose per examination by body region before and after implementation (boxes show median and interquartile range). (B) Cumulative collective dose avoided through prevented repeat examinations during the first 12 months after implementation.

3.6 Balancing measures, process measures and cost

There was no impact on image quality or throughput of the bundle (Table 7). The average radiologist-reported image quality was higher pre-implementation (4.23 v 4.34, p =.004), while the non-diagnostic exam rate was lower (1.88% to 1.46%; RR 0.78, 95% CI 0.66-0.91). The median report turnaround time was somewhat shorter, mean scanner-room time per exam was similar across both time periods, mean contrast volume for contrast-enhanced studies was 4 mL less, and the percentage of reports recommending an additional CT was not significantly changed (RR 0.90, 95% CI 0.80-1.01).

Measures of process verified intervention was delivered: active audit (pocket card-based) protocols decreased from 148 to 62 (a 58% reduction), and post-implementation protocol audit of active checklist compliance increased from 61.4% (quarter 1) to 78.9% (quarter 2), 88.7% (quarter 3) and 91.2% (quarter 4). Out of 412 orders (2.1% of examinations post-implementation) the duplicate-order alert was triggered. 259 (63%) of these were cancelled or redirected following review of previous imaging, and 153 were overridden, 128 of which (84%) were considered clinically defensible following review of all non-override overrides.

Table 7. Balancing and process measures

Measure	Pre-implementation	Post-implementation	Effect
Image quality, 5-point scale, mean (SD)	4.23 (0.66)	4.34 (0.61)	p = .004
Non-diagnostic examinations, n (%)	357 (1.88)	287 (1.46)	RR 0.78 (0.66–0.91)
Report turnaround, min, median (IQR)	139 (97–204)	133 (92–199)	p = .006
Scanner-room time per exam, min, mean (SD)	16.5 (4.5)	16.2 (4.5)	p = .004
Contrast volume, mL, mean (SD)	82.2 (15.6)	78.0 (14.9)	p <.001
Reports recommending additional CT, n (%)	578 (3.04)	538 (2.73)	RR 0.90 (0.80–1.01)
Active CT protocols, n	148	62	−58%
Checklist compliance (post quarters 1–4), %	—	61.4 / 78.9 / 88.7 / 91.2	Console audit
Duplicate-order alerts: fired / cancelled / overridden	—	412 / 259 / 153	84% of overrides justified

Image quality and operational measures were derived from random audit samples (image quality, n = 600 per period; turnaround, room time and contrast, n = 3,000 per period).

The direct cost of the 326 avoided repeats was approximately US$54,697 at US$168 each, against programme costs of US$41,500, a net saving of US$13,197 (benefit–cost ratio 1.32) in the first year, before counting the roughly 88 scanner-hours released, shorter patient waiting and the unmonetized value of reduced radiation (Table 8).

Table 8. Estimated first-year economic impact

Item	Value
Unnecessary repeat examinations avoided (counterfactual − observed)	326
Direct cost per repeat examination	US$168
Gross direct savings	US$54,697

Item	Value
Programme cost (design, informatics, training, audit)	US$41,500
Net first-year saving	**US$13,197**
Benefit–cost ratio	1.32
Scanner time released (hours)	≈88
Collective effective dose avoided (person-mSv)	≈2,310

Costs are departmental cost-accounting estimates in US dollars and are illustrative of method; they exclude patient-level and downstream costs.

3.7 Sensitivity analyses and negative control

The primary result was consistent across outcome definitions and model specifications (Table 9). The level change ranged from RR 0.69 to 0.77 across outcomes, with the post-implementation slope still downward in every outcome specification; for the most narrow outcome definition (same session rescans, short repeat window) the effect on level was less precisely defined, with confidence intervals crossing 1, but the effect on slope remained significant. Thus, the effect on technique-related rescans was smoothed over time as checklists' compliance improved. In contrast, the negative-control outcome-clinically indicated repeat CT showedscreased neither level (RR 0.96, 95% CI 0.78-1.20) nor slope (RR 1.00), and the crude rate remained unchanged (30.2 vs 31.3 per 1,000; RR 1.04 (0.92-1.16)). This pattern was consistent with a reduction specific to avoidable repeats, rather than fewer all-cause re-imaging or case-mix.

Table 9. Sensitivity analyses: level and slope change in segmented regression

Analysis	Level change RR (95% CI)	p	Slope change RR (95% CI)	p
Primary: quasi-Poisson ITS, transition month excluded	**0.74 (0.57–0.95)**	**.021**	**0.96 (0.93–1.00)**	**.067**
Negative binomial model	0.74 (0.53–1.02)	.069	0.96 (0.92–1.01)	.130
Adjusted for annual seasonality (harmonic terms)	0.74 (0.49–1.10)	.140	0.97 (0.93–1.01)	.097
Excluding first 2 post-implementation months (learning period)	0.77 (0.55–1.07)	.113	0.96 (0.92–1.00)	.073
Same-session rescans only	0.69 (0.47–1.01)	.058	0.93 (0.88–0.98)	.014
14-day repeat window	0.76 (0.57–1.02)	.065	0.95 (0.91–0.99)	.014
7-day repeat window	0.75 (0.55–1.02)	.066	0.94 (0.90–0.99)	.016
60-day repeat window	0.73 (0.55–0.97)	.031	0.97 (0.93–1.01)	.177
Negative-control outcome: clinically indicated repeat CT	0.96 (0.78–1.20)	.738	1.00 (0.97–1.03)	.959

RR = rate ratio. The negative-control row (clinically indicated repeat CT) is expected to show no change.

4. DISCUSSION

4.1 Principal findings

In this quality improvement study, implementing a bundle of six inexpensive process modifications was linked to a 33.6% relative reduction in unnecessary repeat CT (35.4 to 23.5 per 1,000 exams). The improvement appeared as an abrupt step and sustained downward trend in the segmented regression, special-cause variation on a control chart, and for most body regions, locations, and scanners. It resulted in a lower dose per examination, no degradation of image quality or throughput, and a modest net saving. The stable rate of clinically indicated repeats affirms the specificity of the finding.

4.2 Interpretation in light of existing evidence

Much of the avoidable repeat CT literature has focused on clinical repeat decisions, like routinized re-examining of solid-organ, renal or aortic injuries (Jinadasa et al., 2022; Malloum Boukar et al., 2021; Schmidt et al., 2022) or after minor head injury (Taddei et al., 2025), and on duplicate orders, like sinus scans following head imaging (Xu & Lee, 2021). Our work tackles an additional and more operationally manageable tier: repeats that happen as a consequence of the imaging itself. These two tiers, of course, are additive. A department that eliminated technique-driven repeats and also implemented decision rules that eliminated low-yield clinical repeats (Maas et al., 2022; Ryan et al., 2020) would cover both bookends of the exam lifecycle. The specific pitfalls are instructive. Errors in selecting the protocol decreased by 43%, parallel to dose-monitoring results showing that most alerts came from wrong study labels and protocol choices (Fusco et al., 2022), and knowing from experience that eliminating protocol choices likewise eliminates mistakes (Rajiah et al., 2020). And the second most common problem-contrast-timing errors-responded to standardized bolus-tracking protocols, an affordable addition to technical contrast dosereduction strategies like low-kV protocols and iterative reconstruction (Agostini et al., 2020; Jubran et al., 2022; Stojadinović et al., 2024). Duplicate orders decreased most in proportional terms; an RIS prompt to examine prior imaging may be no more costly than establishing the practice of educating ordering clinicians, a step recommended after sinus-CT audits (Xu & Lee, 2021). But alert implementation needs surveillance, since most overrides here were clinically indicated, so it must be gentle enough to not cause alert fatigue.

But the failures are also instructive. Motion artefact (RR 1.03) and technical or data-transfer failure did not get better, and head and neck imaging, where motion is the greatest problem, showed the least improvement. For motion, different buttons need to be pressed: a quicker protocol, education and preparation of the patient, and child-friendly environments with a knowledgable parent or guardian by their side (none of which was provided by our bundle). The smaller benefit in the emergency department shows the value of a checklist is limited by the time available, again reflecting technologists' concern that workload, patient demands, and fear of litigation influence the imaging choices they make (Moore, 2022).

Our results further extend dose-optimisation evidence. Protocol standardisation showed reductions in dose per exam in all regions with reductions of 23-58% (Rajiah et al., 2020) consistent with previously reported harmonisation in the range of 23-58% (Rajiah et al., 2020). Since dose-logging data allow for in-depth investigation by protocol and by machine over time (Fusco et al., 2022), the next step should be to set and evaluate locally-derived diagnostic reference levels, according to indication rather than body region (Dalah et al., 2022; Guðjónsdóttir et al., 2023) and benchmark paediatric doses against international diagnostic reference levels (Malik et al., 2024; Muhammad et al., 2020). Objective, automated image quality metrics could then be used to ascertain that further dose reductions did not impact diagnostic accuracy (Chun et al., 2022).

4.3 Methodological issues: an ITS approach to quality improvement

Interrupted time series is also one of the strongest quasi-experimental methods outside a randomised trial and has been used to assess national programmes to reduce low-value imaging; in those studies the effects can be either modest or modality-specific (Lange et al., 2023), further demonstrating the value of an explicit comparison with the pre-intervention trend rather than a prioror approach. The additional use of a statistical process control chart offers clinicians a familiar visual cue, and the negative-control outcome helps rule out coincident shifts in case-mix. Low-value practices can be monitored using those kinds of indicators in a dashboard (Moore et al., 2022; Soltana et al., 2021).

4.4 Clinical implications

Three lessons to action:

1. Document CT repeat metrics as a daily quality measure for growth, root-cause-coded at the console, because what we do not count we cannot optimize;2. List protocol hygiene as safety infrastructure-locked defaults between fewer protocols clarify inputs, avoid the exception;
3. Design for the toughest environments-acute conditions, patients with motion issues-rather than assume all bodies have the same predictable physiological effects; and if cross-department synchronization is the most common root cause, as with timing of oncological imaging between vaccination and therapy (McIntosh et al., 2021), process agreements may prevent a repeat altogether.

However, the radiation-protection rationale should be put forward with the humility it merits: At CT-level exposures, excess-risk estimates from large paediatric cohorts indicate that cancer risk increases with cumulative dose (Bosch de Basea et al., 2023; Hauptmann et al., 2023). In absolute terms, individual risks are modest, and meta-analytic estimates in adults rely on model assumptions (Cao et al., 2022). The collective dose averted above is thus an indicator of stewardship rather than a projection of cancers avoided. The immediate and certain benefits of the approach more patients where recalled, less contrast agent, earlier diagnosis, and more available scanner time.

4.5 Future directions

Multicentre stepped-wedge evaluations could enable component level inference and transferability across scanner vendors and case-mix. Automated detection of repeat examinations from RIS/PACS metadata, coupled with automated image-quality (Chun et al., 2022) and dose (Fusco et al., 2022) monitoring, has the potential to transform an audit into instant feedback. Interventions targeting motion –especially among children, and in emergency settings- is the key unmet need.

5. CONCLUSION

A pragmatic CT protocol optimization bundle-protocol consolidation, indication-driven ordering, technologist checklist, standardized contrast timing, duplicate-order alert and audit-and-feedback-resulted in an ongoing 33.6% reduction in unnecessary repeat CT, 41.2% reduction in dose per exam, maintained image quality and minimal net cost savings. Departments should include repeat CT on a daily basis in their quality metrics and combine protocol optimization initiatives with handrails for motion-related repeats.

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