Journal of Radiological
Protection

Official journal of the Society for Radiological Protection

PAPER • OPEN ACCESS

Recurrent CT imaging and strategies for patient radiation protection

To cite this article: Antonio Jreije *et al* 2026 *J. Radiol. Prot.* **46** 011513

View the article online for updates and enhancements.

You may also like

- Current situations and discussions in Japan in relation to the new occupational equivalent dose limit for the lens of the eye
Sumi Yokoyama, Nobuyuki Hamada, Toshiyuki Hayashida et al.

- Old enemy, new threat: you can't solve today's problems with yesterday's solution
Madan M Rehani

- On the value and costs of protective actions in a nuclear emergency
Keith Pearce

This content was downloaded from IP address 158.129.162.202 on 08/04/2026 at 12:42

IOP Publishing J. Radiol. Prot. 46 (2026) 011513 https://doi.org/10.1088/1361-6498/ae4521

Journal of Radiological Protection

Check for updates

OPEN ACCESS

RECEIVED
2 October 2025

REVISED
13 January 2026

ACCEPTED FOR PUBLICATION
12 February 2026

PUBLISHED
23 February 2026

Original content from this work may be used under the terms of the Creative Commons Attribution 4.0 licence.

Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.

PAPER

Recurrent CT imaging and strategies for patient radiation protection

Antonio Jreije[1,*], **Leonid Krynke**[1] **and Birutė Gricienė**[1,2]

[1] Vilnius University Hospital Santaros Klinikos, Vilnius, Lithuania
[2] Department of Radiology, Nuclear Medicine and Medical Physics, Institute of Biomedical Sciences, Faculty of Medicine, Vilnius University, Vilnius, Lithuania
[*] Author to whom any correspondence should be addressed.

E-mail: antonio.jreij@gmail.com

Keywords: computed tomography, recurrent exposure, cumulative effective dose, radiation protection

Abstract

Computed tomography (CT) contributes disproportionately to medical radiation exposure. While most patients undergo only a few examinations, a subset accumulates high cumulative effective doses (CEDs), raising concern for long-term stochastic risks. Recently, the concept of a recurrent exposure reference level (RERL) has been proposed as a benchmark for cumulative dose monitoring in recurrently imaged patients. To evaluate cumulative radiation exposure from recurrent CT imaging in a tertiary care hospital, determine the proportion of patients exceeding high-dose thresholds, and establish a local RERL. All adult CT examinations performed at Vilnius University Hospital Santaros Klinikos between 2022 and 2024 were retrospectively analysed. Recurrent patients were defined as those with at least one CT in 2023 and an additional CT in 2022, 2023, or 2024. Outcome measures included the annual and three-year incidence and prevalence of CED $\geqslant$ 100 mSv, dose distributions, and RERL determination as the 75th percentile of annual CED among recurrent patients. Over three years, 78 258 patients underwent 99 865 CT examinations. The annual number of patients and exams increased steadily, but the yearly incidence of high-dose patients (CED $\geqslant$ 100 mSv) remained stable at $\sim$2%. Across the full cohort, 1633 patients (3.6%) exceeded 100 mSv, and 29 patients (0.04%) surpassed 500 mSv. Among 9199 recurrent patients (35.6% of the total), 18.2% exceeded 100 mSv within three years. Most patients (68%) crossed this threshold with fewer than five CTs. The local RERL, defined as the 75th percentile of annual CED in recurrent patients, was 36 mSv. A subset of patients in a tertiary care setting accumulated high radiation doses from recurrent CT, often with relatively few examinations. The derived RERL aligns closely with values reported in other European studies, supporting its use as a practical benchmark for monitoring cumulative dose. Systematic dose tracking, integration of RERLs, and strict adherence to justification and optimisation are essential to mitigate risks while preserving the diagnostic value of CT.

1. Introduction

Computed tomography (CT) has become an essential tool in modern diagnostic medicine due to its high-resolution imaging capabilities and rapid acquisition times, making it invaluable in a wide range of clinical settings, from emergency care to oncology and chronic disease management [1]. Although CT accounts for only about 9%–10% of all radiological procedures, it contributes disproportionately to the collective effective dose (ED) from medical imaging, representing more than half of the total population exposure [2]. This significant dose contribution has raised concern within the radiology community, particularly regarding the potential long-term health risks associated with the growing use of CT.

A growing concern in radiology is the cumulative radiation exposure incurred by patients who undergo repeated CT scans over time [3, 4]. Over the past decade, accumulating evidence has shown

© 2026 The Author(s). Published on behalf of the Society for Radiological Protection by IOP Publishing Ltd

that a notable subset of patients may receive high cumulative EDs (CED), often reaching or exceeding 100 mSv, as a result of recurrent CT imaging [3]. Large-scale studies have quantified the extent of this issue: in a multicentre analysis involving 324 hospitals and approximately 2.5 million patients, 1.33% of individuals accrued a cumulative CT dose of 100 mSv or more within a 1–5 year period [5]. Similarly, data from a single-centre study conducted over 22 years revealed that 15% of adult patients received cumulative doses exceeding 100 mSv, with 4% surpassing 250 mSv [6]. Although high-dose patients constitute a minority, these findings highlight the potential for significant radiation burden in certain individuals, particularly those undergoing frequent or long-term imaging follow-up.

Cumulative exposures on the order of tens or hundreds of millisieverts raise legitimate concerns about long-term radiation risks, particularly radiation-induced cancers [7]. At around 100 mSv of ED, the probability of stochastic effects (such as cancer), while still small for any given patient, becomes measurable and significant from a public health perspective [5]. Notably, some patients can reach this threshold in a relatively short period, occasionally even during a single hospitalisation in complex clinical scenarios [5]. Moreover, a substantial proportion of individuals exceeding 100 mSv are younger adults, for whom the potential lifetime risk of radiation-related effects is amplified [5, 6]. These findings underscore the critical need for rigorous justification of each CT examination and strict adherence to the ALARA (as low as reasonably achievable) principle in clinical imaging practice.

To better manage and mitigate the risks associated with cumulative radiation exposure, professional bodies have recommended a range of strategies aimed at enhancing patient safety. Key recommendations include increasing awareness among physicians about patients' prior imaging and radiation history, implementing dose-tracking and management systems, using clinical decision support to avoid unnecessary scans, and continually optimising scanning protocols for dose efficiency [3]. On a broader scale, the radiology community has long relied on diagnostic reference levels (DRLs) as benchmarks for typical radiation doses associated with standard imaging procedures, an approach that has proven effective in driving dose optimisation [8].

However, no analogous reference metric existed to guide management of a patient's cumulative exposure from recurrent imaging. Recently, a concept paralleling the DRL has been proposed for this purpose: the recurrent exposure reference level (RERL) [9]. The RERL is defined as a patient-based reference level for the annual CED, calculated on a per-calendar-year basis among patients undergoing recurrent CT imaging. It is not intended as a regulatory dose limit or as a cumulative value averaged over multiple years, but rather as an alert threshold designed to identify patients whose annual radiation exposure is unusually high and may warrant review of imaging justification and optimisation strategies [9, 10]. In patients undergoing diagnostic imaging year after year, the RERL is therefore applied independently to each calendar year, with exceedance in any given year prompting prospective consideration of further imaging rather than retrospective restriction. A practical approach to establishing RERLs involves analysing local or national dose distribution data, with the threshold often defined at the 75th percentile of the annual CED among recurrently imaged patients [10]. Preliminary studies adopting this method have reported RERL values in the range of approximately 25–35 mSv per year [9, 10].

The prevalence of high cumulative radiation doses (⩾100 mSv) from CT varies substantially across institutions, with reported rates ranging from 0% to approximately 2.7% of patients, depending on local practices and population characteristics [3]. Notably, centres with a strong oncologic focus reported higher proportions of high-dose patients, reflecting the need for repeated longitudinal CT imaging for treatment response assessment and disease monitoring. These findings highlight that cumulative dose distributions, and consequently locally derived RERLs, are strongly influenced by institutional case mix and clinical imaging requirements rather than scanner technology alone. This underscores the importance of assessing imaging usage and radiation exposure patterns at the institutional level when developing ED optimisation strategies. Factors such as patient demographics, clinical referral practice, and scanner protocols can significantly influence cumulative dose distributions and the likelihood of high-dose exposures. As such, understanding these local determinants is essential for translating broad radiological protection recommendations, such as RERLs, into practical, site-specific thresholds and policies. The aim of this study was to evaluate CEDs resulting from recurrent CT imaging over a 3 year period in a single tertiary care centre, with a focus on identifying the proportion of adult patients exceeding a cumulative dose of 100 mSv and setting up RERL.

2. Methods

2.1. Patient population

This retrospective, observational and fully anonymised study was conducted at Vilnius University Hospital Santaros Klinikos with a high-volume radiology department, serving a diverse adult patient

Table 1. CT systems information.

Scanner ID	Manufacturer	Model name	Detector rows/slices	Technology type	Years in use (study period)
CT-01	GE healthcare	LightSpeed VCT	64	Conventional MDCT	2022–2024
CT-02	GE healthcare	Discovery CT 750HD	64	Spectral (gemstone) CT	2022–2024
CT-03	GE healthcare	Revolution	128	Wide-coverage CT	2022–2024
CT-04	GE healthcare	Revolution HD	256	High-definition CT	2022–2024
CT-05	GE healthcare	OMNI LEGEND	128	PET-CT (digital)	2022–2024
CT-06	Philips	GEMINI GXL	16	PET-CT (analogue)	2022–2024

population. The study included all adult patients (⩾18 years) who underwent at least one CT examination between 1 January 2022, and 31 December 2024. Patients with incomplete dose data were excluded. The middle year of the period (2023) was defined as the reference year. Patients who underwent a CT exam in the reference year of 2023 and had at least one additional examination in the years 2022, 2023 or 2024 were classified as recurrent patients. Diagnostic CT procedures performed on 6 CT scanners were included in this study, including data from two PET-CT systems (table 1).

2.2. Data collection

Radiation dose data were extracted from the hospital's dose management system. For each CT examination, the following parameters were collected: date of examination; examination type; procedure name; scanned anatomical region, dose-length product (DLP, mGy·cm); demographic data (age, gender).

For each exam, the ED was estimated by converting the DLP using anatomical region-specific conversion coefficients published in Radiation Protection Publication 154 of the European Commission [11]. The CED for each patient was then calculated as the sum of EDs from all CT examinations performed in a single year (2022, 2023, or 2024) and for the entire 3 year period (2022–2024).

2.3. Outcome measures and indicators

The yearly and three-year cumulative radiation dose in adult patients undergoing recurrent CT imaging was calculated. Specific metrics included yearly incidence proportion (%) of patients with CED ⩾ 100 mSv within a single year (2023); three-year incidence proportion (%) of patients who underwent CT in the reference year 2023 and accumulated a CED ⩾100 mSv during the three-year period 2022–2024; three-year prevalence proportion (%) of all patients who underwent a CT during 2022–2024 and accumulated a CED ⩾100 mSv within this period.

The RERL was calculated as the 75th percentile of the yearly CED distribution among recurrent patients. Subgroup analyses were conducted to assess CED variation by sex, age group, and scan type.

2.4. Data analysis

Descriptive statistics were used to summarise patient demographics, scan volumes, and CED distributions across the study period (2022–2024). Categorical variables, including sex and high-dose exposure rates, were reported as frequencies and percentages. Continuous variables, such as CED values and the number of CT exams per patient, were presented using median, interquartile range (IQR), mean, and maximum values.

Chi-square tests of independence were used to evaluate differences in sex distribution across years. To evaluate temporal trends in proportions, the chi-square test for trend in proportions was applied (e.g. for yearly changes in the proportion of patients with CED ⩾ 100 mSv and within dose categories). The chi-square goodness-of-fit test was used to assess differences in observed frequencies across years, such as the annual counts of high-dose patients. Comparisons of medians and means for continuous variables (e.g. CED and exams per patient) across multiple years were performed using the Kruskal–Wallis test, due to the non-normal distribution of the data. Normality of continuous variables was confirmed statistically using the Shapiro–Wilk test, which indicated significant deviation from normality ($p < 0.05$). A significance level of $p < 0.05$ was considered statistically significant. All analyses were performed using R software (version 4.5.1).

3. Results

During the study period, CT examinations were performed using six different scanner models. A total of 99 865 CT exams were analysed, with Discovery CT 750HD being the most frequently used scanner,

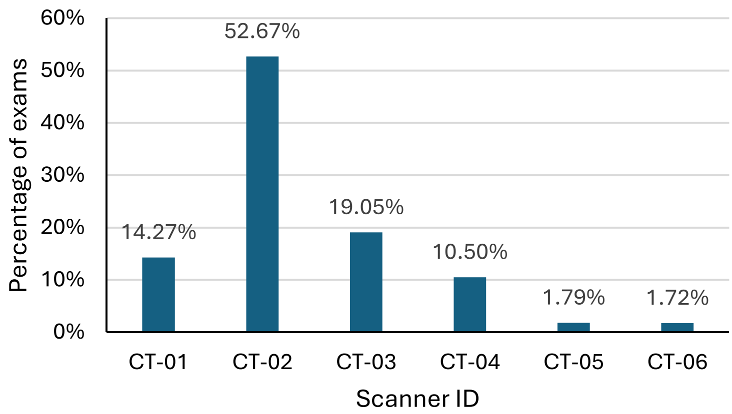

Figure 1. Distribution of CT examinations by scanner model over the study period.

Table 2. Annual patient demographics for CT examinations.

Year	N. of patients	Female	Male	*p*-value (sex distribution)	Age		
					median	1stQ	3rdQ
2022	24 568	12 945	11 623	<0.001	64	52	75
2023	25 864	13 605	12 259	<0.001	64	51	74
2024	27 826	14 663	13 163	<0.001	64	52	74
Total	78 258	41 213	37 045	<0.001[a]	—	—	—

[a] *p*-value from chi-square goodness-of-fit test comparing patient counts across years. Sex distribution *p*-values are based on tests comparing observed male and female counts to a 1:1 expected ratio. All differences were statistically significant.

accounting for 52.7% of all CT examinations (figure 1). The high percentage of exams performed on the Discovery CT 750HD is attributable to its location within the emergency department, where it functions as the institution's primary general-purpose scanner.

A total of 78 258 adult patients underwent CT examinations over the three-year study period (2022–2024). The annual number of patients increased significantly each year, from 24 568 in 2022 to 25 864 in 2023, and 27 826 in 2024 (table 2). This upward trend was confirmed by a chi-square goodness-of-fit test comparing annual patient volumes to a uniform distribution ($\chi^2 = 206.29$, df $= 2$, $p < 0.001$).

Across all years, the gender distribution remained relatively stable, with a slight predominance of female patients: 52.7% in 2022, 52.6% in 2023, and 52.7% in 2024 (table 2). However, within each individual year, the difference in male and female patient counts was statistically significant (all $p < 0.001$, based on chi-square goodness-of-fit tests), indicating a consistent overrepresentation of female patients.

The median age of patients was stable at 64 years throughout the study period. The interquartile age range also showed minimal variation, with the 1st quartile (Q1) ranging between 51–52 years and the 3rd quartile (Q3) consistently at 74–75 years. These consistent demographic patterns support the validity of pooled analyses and provide a reliable basis for longitudinal assessment of cumulative radiation exposure and dose distribution.

The distribution of CED among adult CT patients from 2022 to 2024 revealed that the majority of patients received relatively low cumulative exposures. Across the entire study period, 67.1% of patients had a CED of less than 20 mSv, and an additional 19.3% fell within the 20–<50 mSv range. Approximately 10.0% of patients accumulated a dose between 50–<100 mSv (table 3). High cumulative exposures ⩾100 mSv were less common but notable, accounting for 3.61% of the study population, while the highest exposure category (⩾500 mSv) represented only 0.04% of patients (table 3).

Statistical analysis using the chi-square test for trend in proportions revealed significant shifts in dose distributions over time. The proportion of patients receiving <20 mSv increased significantly from 64.5% in 2022 to 69.1% in 2024 ($\chi^2 = 126.54$, $p < 0.001$), indicating a consistent upward trend in low-dose exposure. In contrast, all higher dose categories, including 50–<100 mSv, 100–<150 mSv, and ⩾500 mSv, demonstrated statistically significant decreasing trends over the three-year period (all *p*-values < 0.05). For example, the proportion of patients with CED $\geqslant 500$ mSv declined from 0.07% in 2022 to 0.03% in 2023 and 2024 ($\chi^2 = 4.89$, $p = 0.027$).

Table 3. Distribution of cumulative effective dose (CED) among CT patients by year (2022–2024).

	CED (mSv)								
Year	<20	20–<50	50–<100	100–<150	150–<200	200–<300	300–<400	400–<500	⩾500
2022	64.46%	20.08%	10.59%	2.67%	1.06%	0.72%	0.24%	0.09%	0.07%
2023	67.51%	18.88%	10.18%	2.07%	0.82%	0.38%	0.10%	0.04%	0.03%
2024	69.11%	19.05%	9.23%	1.71%	0.50%	0.30%	0.05%	0.02%	0.03%
Chi-square	126.54	8.65	27.46	57.08	52.97	49.84	36.55	12.19	4.89
(*p*-value)	(<0.001)	(0.003)	(<0.001)	(<0.001)	(<0.001)	(<0.001)	(<0.001)	(0.0005)	(0.027)
Total	67.09%	19.33%	9.97%	2.14%	0.79%	0.46%	0.13%	0.05%	0.04%

Table 4. Yearly summary of CT examinations, patient dose metrics, and incidence of high-dose patients.

				Number of exams per patient	
Year	Number of exams	Number of patients with CED ⩾ 100 mSv	Yearly incidence of CED ⩾ 100 mSv	Mean	Max
2022	31 100	511	2.08	1.27	13
2023	33 045	571	2.21	1.28	19
2024	35 720	551	1.98	1.28	19
p-value	—	0.18[a]	0.392[b]	0.368[c]	—

[a] Chi-square goodness-of-fit test.
[b] Chi-square test for trend in proportions.
[c] Kruskal–Wallis Test.

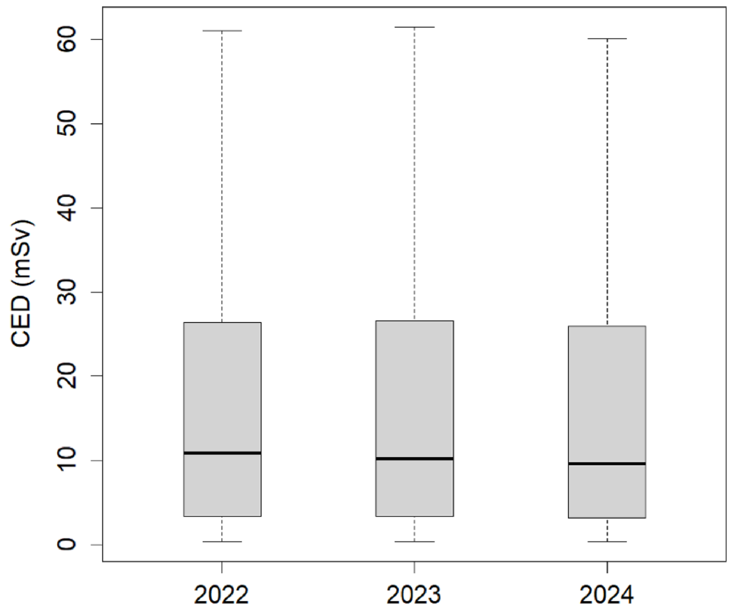

Figure 2. Yearly variation in cumulative effective dose (CED) among CT patients.

According to table 4, the annual scan volumes increased steadily over the study period: 31 100 exams in 2022, 33 045 in 2023, and 35 720 in 2024. However, the number of patients with a CED ⩾ 100 mSv per year remained relatively stable, ranging from 511 in 2022–571 in 2023, and 551 in 2024. The annual incidence proportion fluctuated slightly between 1.98% and 2.21%, with the highest rate observed in 2023. Statistical analysis confirmed that there was no significant trend in the proportion of high-dose patients over time (Chi-square test for trend: $\chi^2 = 0.73$, $p = 0.392$), nor a significant difference in the annual counts of these patients (Chi-square goodness-of-fit test: $\chi^2 = 3.43$, $p = 0.18$). Despite the increasing number of exams in 2024, the incidence of patients receiving CED ⩾ 100 mSv did not rise correspondingly (figure 2).

The median CED per patient showed no significant variation across the three years, ranging from 9.5 to 10.8 mSv (Kruskal–Wallis test: $p = 0.368$). The highest CED recorded in a single patient was 822 mSv

Table 5. Distribution for the total cohort of patients receiving CED ⩾ 100 mSv, ⩾200 mSv, and ⩾500 mSv during the 3 years period by age group and sex.

	CED ⩾ 100 mSv			CED ⩾ 200 mSv			CED ⩾ 500 mSv		
Age (years)	Male	Female	Total (%)	Male	Female	Total (%)	Male	Female	Total (%)
<20	2	1	3 (0.20%)	1	0	1 (0.23%)	0	0	0 (0%)
20–29	12	5	17 (1.02%)	3	0	3 (0.69%)	0	0	0 (0%)
30–39	48	13	61 (3.75%)	11	5	16 (3.66%)	3	0	3 (10.34%)
40–49	94	49	143 (8.75%)	21	12	33 (7.55%)	5	2	7 (24.14%)
50–59	212	94	306 (18.73%)	63	21	84 (19.22%)	7	1	8 (27.59%)
60–69	322	203	525 (32.17%)	104	69	173 (39.59%)	6	2	8 (27.59%)
70–79	238	167	405 (24.80%)	70	32	102 (23.34%)	1	2	3 (10.34%)
80–89	91	66	157 (9.61%)	20	3	23 (5.26%)	0	0	0 (0%)
90–99	7	9	16 (0.98%)	2	0	2 (0.46%)	0	0	0 (0%)
Total	1026	607	1633 (100%)	295	142	437 (100%)	22	7	29 (100%)

Table 6. Clinical indications for CT referral in patients with CED ⩾ 200 mSv during the 3 years period.

Clinical indication	N. of patient (%)	Mean age (years)	Median N. of CT [min–max]	Median CED (mSv) [min–max]
Cancer-related	167 (38.2%)	63.0 (11.8)	6.6 [3–26]	315.7 [253.9–758.2]
Pancreatitis	62 (14.2%)	54.6 (13.1)	7.3 [4–13]	431.9 [253.9–882.9]
Pulmonary embolism	48 (11%)	68.4 (12.9)	6.1 [3–12]	324.2 [253.2–561.8]
Bowel pathology	31 (7.1%)	54.6 (12.2)	7.2 [4–14]	310.5 [254.1–577.6]
Polytrauma	21 (4.8%)	53.0 (10.5)	8.5 [2–14]	427.5 [259.6–677.7]
Aneurysm	16 (3.7%)	71.8 (6.1)	6.5 [4–8]	290.0 [253.4–394.9]
Abscess	14 (3.2%)	59.6 (15.4)	4.6 [4–6]	325.5 [306.9–446.8]
Gastrointestinal bleeding	12 (2.7%)	53.4 (10.2)	8.0 [5–16]	307.9 [270.1–581.6]
Sepsis	7 (1.6%)	42.5 (14.8)	4.0 [3–5]	271.5 [257.2–285.7]
Other	59 (13.5%)	65.0 (11.1)	7.0 [3–13]	311.6 [253.4–604.2]

in 2023, observed in a patient with severe acute pancreatitis and subsequent complications requiring frequent CT examinations for dynamic follow-up, with additional contribution from elevated DLP values related to increased patient body weight. The IQR for CED remained consistent, with the 1st quartile at approximately 3.1–3.4 mSv and the 3rd quartile between 25.8–26.6 mSv (figure 2). Additionally, the mean number of CT exams per patient was stable across all years (1.27–1.28), with no statistically significant difference detected (Kruskal–Wallis test: $p = 0.368$). The maximum number of CT exams per patient was 19 in both 2023 and 2024.

A total of 1633 patients received a CED of ⩾100 mSv over the study period. Of these, 1026 (62.9%) were male and 607 (37.1%) were female (table 5). The highest proportion of high-dose patients was observed in the 60–69 age group, accounting for 32.2% of all patients with CED ⩾100 mSv, followed by the 70–79 age group (24.8%) and the 50–59 age group (18.7%).

Among those receiving a CED ⩾ 200 mSv, 437 patients were identified, with a similar age distribution pattern (table 5). The 60–69 age group again represented the largest share (39.6%), followed by the 50–59 (19.2%) and 70–79 (23.3%) age groups. Males consistently outnumbered females in all high-dose categories.

The most common clinical indication among patients with CED ⩾ 200 was cancer-related, accounting for 38.2% of cases (table 6). These patients had a mean age of 63.0 years and a median of 6.6 CT exams (CED: 315.7 mSv). Pancreatitis was the second most frequent indication (14.2%), followed by pulmonary embolism (11.0%), bowel pathology (7.1%), and polytrauma (4.8%). Pancreatitis and polytrauma cases had the highest radiation burdens, with median CEDs of 431.9 mSv and 427.5 mSv, respectively. Other less frequent indications included aneurysm, abscess, gastrointestinal bleeding, and sepsis. Patients with aneurysms were the oldest group (mean age: 71.8), while those with sepsis were the youngest (mean age: 42.5).

Notably, 29 patients between 30 and 79 (1.2% of the ⩾100 mSv group) received CEDs ⩾ 500 mSv (table 5). While patients under 30 made up a smaller fraction of the cohort, a measurable number still received high or very high cumulative doses, including 25 individuals aged 20–29 with CED ⩾ 100 mSv. These findings underscore that middle-aged adults (40–69 years) represent the core demographic at risk for elevated radiation exposure from recurrent CT imaging, with males disproportionately represented across all dose thresholds.

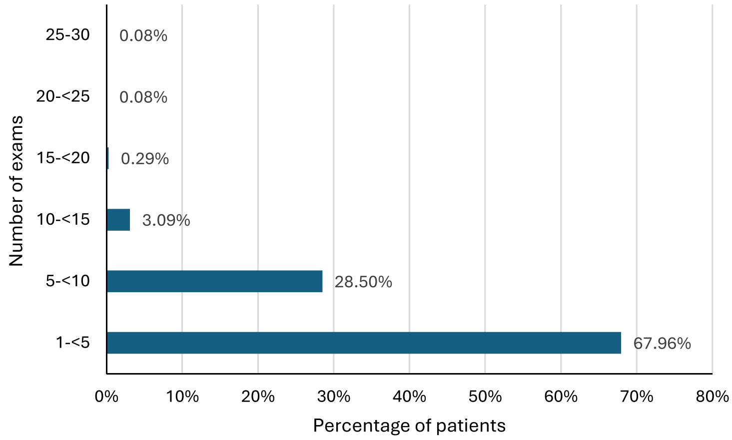

Figure 3. Number of CT examinations required for patients to reach CED ⩾ 100 mSv during the 3 years period.

Table 7. Distribution of number of patients with respect to number of CT exams in patients with CED ⩾ 100 mSv.

		Cumulative DLP (mGy*cm)		CED (mSv)	
Number of exams	Number of patients	Median	Maximum	Median	Maximum
1	73	7177.4	10 199.6	107.7	153.0
2	551	8115.0	17 309.8	121.2	259.6
3	639	9209.6	20 829.0	133.5	312.4
4	406	10 499.0	24 882.3	151.3	373.2
5	304	11 824.0	32 143.9	162.1	482.1
6	173	12 851.9	40 517.3	171.9	514.9
7	119	13 964.8	41 642.8	193.1	624.6
8	69	2034.0	41 383.0	184.7	550.6
9	35	14 750.0	50 544.8	203.8	758.2
10	21	15 033.3	50 724.9	217.8	760.8
11	16	17 637.1	58 859.0	264.5	882.9
12	18	16 265.3	44 330.7	166.2	664.9
13	15	18 597.1	59 068.7	213.0	862.2
14	6	16 269.6	40 186.2	222.5	570.8
15	2	13 616.3	18 567.5	141.8	153.7
16	1	—	6902.0	—	103.5
17	1	—	38 385.9	—	190.2
18	2	10 886.5	11 820.0	163.3	177.3
19	1	—	7875.0	—	118.1
20	1	—	10 855.0	—	147.8
22	1	—	23 504.8	—	212.9
26	1	—	24 612.3	—	341.7
27	1	—	39 957.9	—	134.6

Regarding the number of CT examinations required for patients to reach a CED of ⩾100 mSv, the majority of patients (67.96%) reached this threshold after fewer than five examinations, indicating that relatively few high-dose scans can result in significant cumulative exposure (figure 3). An additional 28.50% of patients exceeded 100 mSv after 5 to <10 exams, while only 3.5% required 10 or more exams to reach this dose level.

These results highlight that over 96% of patients who exceeded 100 mSv did so with fewer than 10 CT examinations, reinforcing the need for dose awareness and careful justification even early in a patient's imaging history.

Table 7 presents cumulative radiation dose metrics stratified by the number of CT examinations per patient. As expected, both cumulative DLP and CED increased progressively with the number of CT exams. Among patients with only one CT exam, the median CED was 107.7 mSv, with a maximum of 153 mSv.

As the number of CT exams increased, so did both the median and maximum cumulative doses. Patients with five CT exams had a median CED of 162.1 mSv and a maximum of 482.2 mSv, while those with 10 exams reached a median of 217.8 mSv and a maximum of 760.9 mSv.

The number of patients decreased with increasing scan frequency, from 551 patients with two CTs to only a few with more than 15 exams. Despite their small numbers, these high-frequency patients represent a critical subgroup with elevated radiation burden, often exceeding proposed RERL thresholds. This underscores the importance of closely monitoring recurrent patients and evaluating the justification for additional imaging, particularly when cumulative doses exceed 100 mSv.

Out of the total cohort, 9199 patients (35.57%) met the criteria for recurrent imaging, defined as undergoing at least one CT exam in 2023 and additional CT(s) in either 2022, 2023, or 2024. Among these, 1676 patients (18.2% of recurrent patients) accumulated a CED $\geqslant$ 100 mSv over the 3 year period.

The three-year incidence proportion of patients with CED $\geqslant$ 100 mSv was 6.48%, and the three-year prevalence proportion was 2.14%. These figures suggest that while high cumulative exposures are limited to a minority of patients, they are not rare, especially among those undergoing repeated imaging.

Among recurrent patients, the median CED was 12.9 mSv, with a maximum of 882.9 mSv. The IQR extended from 3.9 mSv (1st quartile) to 36.4 mSv (3rd quartile). On average, recurrent patients underwent 3.2 exams per year, with a maximum of 27 exams over the 3 year period.

4. Discussion

This single-centre study confirms that a small but significant subset of patients incur high cumulative radiation doses from recurrent CT imaging. Over the study 3 year period, about 3.6% of all CT patients at our institution accumulated a total ED $\geqslant$100 mSv. This proportion is on the higher end of what has been reported in multi-centre studies: for example, an analysis across 324 hospitals (2.5 million patients) found about 1.33% of individuals exceeded 100 mSv within a 1–5 year period (range 0.64%–3.4% across centres) [12]. A Europe-wide survey similarly reported that a median of 0.5% of patients received $\geqslant$100 mSv from imaging over ∼3 years, though with large variation between centres (0%–2.7%) [3]. Our single-centre result slightly exceeds those ranges, likely reflecting the high-volume, tertiary care nature of our hospital, where complex or ill patients undergo more frequent imaging. Notably, prior single-centre data with longer follow-up have demonstrated even greater proportions, e.g. Sodickson *et al* observed 15% of patients above 100 mSv (and 4% above 250 mSv) over 22 years, underscoring that given enough time or intensive care, a substantial fraction of patients can accumulate high doses [6].

Differences in imaging utilisation and practices across healthcare systems contribute to the observed range. High cumulative doses are most frequently seen in patients undergoing numerous follow-up CTs for chronic conditions—including oncology. Indeed, roughly 38% of our high-CED are oncological patients, which were being scanned for cancer staging, disease progression assessment, and evaluation of tumour-related complications, a pattern echoed in other studies [13]. On the other hand, analysis of CT scan usage across OECD countries (Organisation for Economic Co-operation and Development) indicated geographic variation: a recent estimate projected about 0.21% of the population in 35 OECD countries receives $\geqslant$100 mSv from CT in a 5 year span, but with nearly a sixfold country-to-country difference [12]. Notably, nations with very high CT utilisation, such as the United States and parts of Asia, showed the greatest fractions of high-dose patients, with Japan and South Korea among those exceeding 0.2% of the population (≈2 per 1000 people in 5 years) [12]. By contrast, some European countries with more conservative CT use or robust gatekeeping had substantially lower rates of patients reaching the 100 mSv threshold. For instance, Finland's rate was the lowest at roughly 0.05% over 5 years and other nations with strict imaging referral practices similarly kept this fraction low [12]. Technical factors also play a role: variations in scanner technology and protocol can lead to different per-exam doses. Reassuringly, ongoing dose-optimisation efforts including stricter adherence to DRLs, iterative image reconstruction, automated exposure control, and newer lower-dose hardware have generally reduced the dose per CT examination in recent years [14]. However, these gains are partly offset by the growth in CT utilisation, so the issue of cumulative dose remains noticeable.

Dose trends observed in this study over the 3 years period revealed increasing CT utilisation. The annual number of CT examinations and patients in our hospital rose each year, while the incidence of patients exceeding 100 mSv in a given year remained around 2% and did not significantly increase. Similarly, the mean number of CT exams per patient was stable across all years (around 1.3), with no statistically significant difference detected. This suggests that dose-optimisation efforts must be performed to shift cumulative doses toward lower values in the future through dose management strategies such as protocol optimisation, stricter justification of repeat scans, and improved training. In particular, increasing physician awareness of cumulative exposures, avoiding unnecessary multiphase scans, and using decision support are known to curb excessive imaging.

An important emerging concept in this context is the RERL, which our study supports and helps contextualise [13]. The RERL is a proposed benchmark for a patient's total accumulated dose over a defined period, analogous to DRLs for single scans [10]. Using the 75th percentile of annual cumulative dose among recurrently imaged patients as the threshold, we derived a local RERL on the order of 36 mSv per year. This value is consistent with those reported in recent studies that introduced the RERL framework. Brambilla *et al* for example, analysed nationwide data in Slovakia and determined an RERL of 25.7 mSv per year (based on the distribution of yearly doses) [9]. It is worth noting that the need for site-specific calibration of RERLs has been emphasised. In the Slovakian study, the incidence of high-dose patients varied dramatically between hospitals (five-year incidence of ⩾100 mSv ranged from under 1% to over 35% across facilities), and this heterogeneity did not simply correlate with hospital size or type [13]. This means each centre should examine its own dose distribution and patient mix when setting an RERL. Adopting an RERL as an institutional policy tool could prompt regular reviews of patients who exceed the threshold, ensuring that such cases receive special attention for justification and dose reduction strategies. In our practice, identifying patients crossing 36 mSv in a year (the local RERL) would create an opportunity to re-evaluate the necessity and frequency of further imaging, consider alternative modalities (e.g. MRI/US), or implement additional dose-sparing techniques going forward.

Finally, our findings underscore the critical importance of tracking cumulative radiation exposure in recurrent patients. Historically, without dedicated dose tracking, it was possible for patients to undergo numerous CTs at different times or institutions with little awareness of the total dose accrued. Now, with modern dose management systems and heightened concern for radiation safety, there is a strong incentive to monitor each patient's cumulative dose as a standard part of care. Recent guidelines and expert panels have explicitly called for routine monitoring of patients who undergo repeat imaging, to facilitate early intervention when dose accumulation becomes substantial. For example, the European EuroSafe imaging initiative has recommended implementing automatic patient dose registries with alert triggers for unusually high cumulative doses [15]. Complementary guidance from radiotherapy practice also emphasises structured management of imaging doses associated with treatment planning and delivery. Professional bodies such as the Royal College of Radiologists recommend optimisation of image-guided radiotherapy (IGRT) protocols, measurement of imaging doses, and maintenance of patient dose records for repeated verification imaging [16]. In addition, report from AAPM Task Group 180 states that imaging doses in IGRT should be calculated, justified, and optimised using the same radiological protection principles applied to therapeutic exposures, with systematic documentation and audit of imaging doses forming an integral component of quality assurance [17].

Our study highlights that nearly one-fifth (18%) of the recurrent patients (those imaged across multiple years) exceeded 100 mSv in just a three-year span. Identifying such individuals is the first step in managing their risk. Tracking enables personalised radioprotection: clinicians can be alerted when a patient's cumulative dose is approaching worrisome levels (such as the RERL benchmark) and can then consider modifying the imaging strategy. The value of this approach is evident in light of the elevated long-term risks associated with high cumulative exposure, especially for younger patients [18, 19]. In our cohort and others, a considerable proportion of those above 100 mSv are middle-aged or younger adults, who have more remaining years for potential radiation effects to manifest. For such patients, every effort to avoid unnecessary scans or to substitute non-ionising modalities can have a meaningful impact on lifetime risk. Moreover, each CT examination for a recurrent patient should be rigorously justified, and the imaging protocol tailored to use the lowest dose that still yields diagnostic quality (the ALARA principle), as repeatedly emphasised in the literature [20, 21]. By combining dose-tracking with such justification protocols, institutions can improve patient safety without compromising diagnostic care.

5. Conclusion

In this single-centre analysis, a substantial minority of adult patients undergoing CT received high cumulative radiation doses, with nearly one-fifth of recurrent patients exceeding 100 mSv within only three years. While these proportions are somewhat higher than many multi-centre averages, they reflect the realities of tertiary care populations, where repeated imaging is often clinically unavoidable. Importantly, we demonstrated that relatively few examinations were sufficient for most patients to cross the 100 mSv threshold, underscoring the need for dose awareness and justification from the earliest stages of care. By deriving a local RERL of approximately 36 mSv per year, our study adds institutional evidence to a growing body of literature that supports using the 75th percentile of annual dose in recurrent patients as a practical benchmark. Incorporating RERLs into routine dose-tracking systems can provide an actionable trigger for clinicians to reassess imaging strategies, consider non-ionising alternatives, and implement further optimisation measures when appropriate. These results reinforce current recommendations from international radiological protection bodies that each CT examination should be rigorously justified and performed with the lowest dose compatible with diagnostic quality. Systematic monitoring of cumulative doses, particularly in younger and middle-aged adults with recurrent imaging needs, should become an integral component of radiology practice. Adoption of dose-tracking infrastructure, integration of RERL thresholds, and sustained commitment to the ALARA principle will be crucial steps toward safeguarding patient safety while preserving the diagnostic benefits of CT in modern medicine.

Data availability statement

The data cannot be made publicly available upon publication because they contain sensitive personal information. The data that support the findings of this study are available upon reasonable request from the authors.

ORCID iD

Antonio Jreije 0000-0001-9774-9461

References

[1] Douek P C, Boccalini S, Oei E H, Cormode D P, Pourmorteza A, Boussel L, Si-Mohamed S A and Budde R P 2023 Clinical applications of photon-counting CT: a review of pioneer studies and a glimpse into the future *Radiology* **309** e222432

[2] Bos D, Guberina N, Zensen S, Opitz M, Forsting M and Wetter A 2023 Radiation exposure in computed tomography *Dtsch. Arztebl Int.* **120** 135

[3] Frija G, Damilakis J, Paulo G, Loose R and Vano E European Society of Radiology (ESR) 2021 Cumulative effective dose from recurrent CT examinations in Europe: proposal for clinical guidance based on an ESR EuroSafe imaging survey *Eur. Radiol.* **31** 5514–23

[4] Arellano R S, Yang K and Rehani M M 2021 Analysis of patients receiving ⩾ 100 mSv during a computed tomography intervention *Eur. Radiol.* **31** 3065–70

[5] Rehani M M, Yang K, Melick E R, Heil J, Šalát D, Sensakovic W F and Liu B 2020 Patients undergoing recurrent CT scans: assessing the magnitude *Eur. Radiol.* **30** 1828–36

[6] Sodickson A, Baeyens P F, Andriole K P, Prevedello L M, Nawfel R D, Hanson R and Khorasani R 2009 Recurrent CT, cumulative radiation exposure, and associated radiation-induced cancer risks from CT of adults *Radiology* **251** 175–84

[7] Martin C J and Barnard M 2022 How much should we be concerned about cumulative effective doses in medical imaging? *J. Radiol. Prot.* **42** 011514

[8] Vañó E, Miller D L, Martin C J, Rehani M M, Kang K, Rosenstein M, Ortiz-López P, Mattsson S, Padovani R and Rogers A 2017 ICRP publication 135: diagnostic reference levels in medical imaging *Ann. ICRP* **46** (1) 1–144

[9] Brambilla M, Chmelík M, Cannillo B, Klepanec A, Lacko M, Andreatta P and Šalát D 2025 Establishment of recurrent exposures reference levels for repeated computed tomography examinations in adult patients on a nationwide level in Slovakia *Eur. Radiol.* **35** 1658–68

[10] Bramilla M *et al* 2024 Optimisation of protection in the medical exposure of recurrent adult patients due to computed tomography procedures: development of recurrent exposures reference levels *Eur. Radiol.* **34** 4475–83

[11] European Commission 2008 European guidance on estimating population doses from medical x-ray procedures *Radiation Protection Series No.* 154 (Publications Office of the European Union)

[12] Rehani M M and Hauptmann M 2020 Estimates of the number of patients with high cumulative doses through recurrent CT exams in 35 OECD countries *Phys. Med.* **76** 173–6

[13] Brambilla M, Vassileva J, Kuchcinska A and Rehani M M 2020 Multinational data on cumulative radiation exposure of patients from recurrent radiological procedures: call for action *Eur. Radiol.* **30** 2493–501

[14] Vano E 2020 Challenges for managing the cumulative effective dose for patients *Br. J. Radiol.* **93** 20200814

[15] Loose R W, Vano E, Mildenberger P, Tsapaki V, Caramella D, Sjöberg J and Schindera S 2020 Dose management–requirements and recommendations for users *European Congress of Radiology-EuroSafe Imaging 2020* (https://doi.org/10.26044/esi2020/ESI-11078)

[16] Royal College of Radiologists, Society and College of Radiographers, Institute of Physics and Engineering in Medicine 2021 On target 2: Updated guidance for image-guided radiotherapy (The Royal College of Radiologists)

[17] Ding G X, Alaei P, Curran B, Flynn R, Gossman M, Mackie T R and Zhu T C 2018 Image guidance doses delivered during radiotherapy: quantification, management, and reduction: report of the AAPM Therapy Physics Committee Task Group 180 *Med. Phys.* **45** e84–e99

[18] Howard A, West R, Iball G, Panteli M, Pandit H and Giannoudis P V 2019 An estimation of lifetime fatal carcinogenesis risk attributable to radiation exposure in the first year following polytrauma: a major trauma center's experience over 10 years *J. Bone Joint Surg.* **101** 1375–80

[19] Vassileva J and Holmberg O 2021 Radiation protection perspective to recurrent medical imaging: what is known and what more is needed? *Br. J. Radiol.* **94** 20210477

[20] ICRP 2007 The 2007 Recommendations of the International Commission on Radiological Protection. ICRP publication 103 *Ann. ICRP* **37** (2–4) 1–332

[21] Brkljačić B, Karoussou-Schreiner A, Sosna J, Foley S, Bly R, Brady A and Szucsich M 2024 European co-ordinated action on improving justification of computed tomography: results and recommendations from a first-time multi-national study on CT justification in the EU