COMPUTED TOMOGRAPHY

Patients undergoing multiphase CT scans and receiving a cumulative effective dose of ≥ 100 mSv in a single episode of care

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Abstract

Objectives To estimate the number of patients who receive a cumulative effective dose (CED) of ≥ 100 mSv from computed tomography (CT) in a single day or episode of care.

Methods We examined 28,870 patients who underwent 49,834 CT examinations in a tertiary care centre in Italy in 2.5 years. Radiation exposures were retrieved from the hospital's automatic exposure monitoring system. Two cohorts were identified as those who received a CED of ≥ 100 mSv in a single day and within a month starting from the first examination. Organ doses were estimated for the first cohort.

Results Among the 1765 (6.1%) patients who received CED ≥ 100 mSv in the observation period, 427 received a CED of ≥ 100 mSv within a month (and 70 patients in a single day). This group represented 1.5% of all patients who underwent CT exams and 24% of those who received CED ≥ 100 mSv in the observation period. The clinical indication for referral included cancer in 132 patients (31%) and non-oncological indications in 295 patients (69%). In 68/70 patients with CED > 100 mSv in a single day, at least one organ/tissue received a dose of ≥ 100 mGy.

Conclusions The finding of a sizeable percentage of patients undergoing CT exams and receiving CED ≥ 100 mSv in a single episode of care points toward the need of imaging appropriateness criteria, to revise the routine protocols, to replace older machines, and to provide to the radiologist the patient's prior radiation history to facilitate an appropriate decision-making process.

Key Points

• *Patients can receive effective doses greater than 100 mSv in a single CT or in multiple CT examinations performed in a single episode of care in 1.5% of patients in a 2.5-year period.*

• *In this study, the clinical indication for CT referral was non-oncological in 69% of patients.*

• *The patient's prior radiation history should be provided to the referring physicians and the radiological medical practitioner to facilitate an appropriate decision-making process.*

Keywords Computed tomography · Radiation protection · Patient safety · Radiation dosage · Effective dose

Abbreviations

CED	Cumulative effective dose
CT	Computed tomography
$CTDI_{vol}$	Volumetric computed tomography dose index
DLP	Dose-length product
ED	Effective dose
H_T	Organ doses
PACS	Picture archiving and communication system

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Introduction

A cumulative effective dose (CED) of ≥ 100 mSv for patients undergoing radiological imaging has been recently the focus of several publications. According to ICRP [1], effective dose (ED) should not be used for individual risk assessment and

100 mSv of ED should not be interpreted as a threshold for radiation effects. Nonetheless, at this level of ED, many organs are susceptible to receive doses of 100 mGy or more and the recent review undertaken by the United Nations Scientific Committee on Effects of Atomic Radiation (UNSCEAR) evidenced radiation-related adverse effects (particularly cancer) at or above the absorbed organ dose greater than 100 mGy for certain cancers like of the bone marrow, thyroid, breast, and colon [2]. Moreover, a recent review shows that there is now convincing evidence of excess cancer risk at organ doses even below 100 mGy [3].

The widespread diffusion of automatic exposure monitoring systems has prompted the recollection of retrospective data aimed at identifying patients with different clinical condition who are likely to reach a high CED [4–7] or to assess percent of patients undergoing multiple computed tomography (CT) exams [8–10] or interventional radiology procedures [11] that lead to a CED of ≥ 100 mSv, in a set period of time.

Most of the published studies reporting patients with a CED of ≥ 100 extended their period of observation to years or even decades in which the doses were accrued. It is not clear if such high CED can be accrued in a single episode of care.

In this study, by retrospectively searching in our exposure monitoring system, we investigated the clinical condition of patients susceptible to receive a CED at or above 100 mSv from CT examinations in a single day (in those cases, also organ/tissue doses of ≥ 100 mGy were assessed) and within a month, since such a delay would embrace the usual duration of patient management for a usual "single-shot" disease or an episode of chronic disease.

Materials and methods

Source of data

Data was collected between 13 June 2017 and 18 November 2019 using the exposure monitoring system Gray Detector (Ver 2.0 EL.CO Healthcare Solutions) which stored data of all patients undergoing CT exams since 2017. Patient data were imported in the CT through the radiological information systems, and no examinations were performed to subsequent patients, without the required data entry. A single visit for a CT study (one accession number) was counted as single CT "exam," and thus, if multiple phases (CT scan acquisitions) were performed during the study, it was still counted as one CT exam. The CT scanners employed during the observation period were as follows: Brilliance 16, Ingenuity Core 64, Ingenuity Elite 128, Brilliance ICT Elite 256 (Philips Healthcare), LightSpeed VCT 64, Optima 540 (GE Healthcare), and an intraoperative CT scanner (AIRO, Brainlab).

Inclusion criteria

The CT machines provide volumetric computed tomography dose index ($CTDI_{vol}$) and dose-length product (DLP) values for each patient along with the patient's unique ID, which are automatically stored in the hospital picture archiving and communication system (PACS) and retrieved by the exposure monitoring system, by accession to the PACS.

DLP data indicate the total amount of radiation (i.e. intensity × scan length) used to perform the CT examination and are quantified in a cylindrical phantom of a specified size (i.e. 16 cm "head" or 32 cm "body" in diameter). Using the reference dose quantities provided by machines, the system then calculates ED using conversion factors ED/DLP: 0.0023 and 0.017 mSv mGy^{-1} cm^{-1} for the head and body phantom, respectively, as published in radiation protection publication 154 of the European Commission [12].

This method for estimating ED is a well-established one and has been used in many previous publications [9, 13]. A CED of ≥ 100 mSv accrued in single day or within a month was chosen as the criterion for inclusion in the study. The medical condition of each patient leading to referral for CT was identified in the medical record.

Organ dose estimates

$CTDI_{vol}$ and DLP are common methods to estimate a patient's radiation exposure from a CT procedure. The exposures are the same regardless of patient size, but the size of the patients is a factor in the absorbed organ doses (H_T). Therefore, after inclusion in the study, the software VirtualDose (ver.2017, Virtual Phantoms Inc.), in conjunction with body mass index (BMI) of the single patient, was used to compute H_T based on Monte Carlo simulations of radiation transport in virtual anthropomorphic phantoms (CED_{MC}) [14] in the cohort of patients with > 100 mSv in a single day. This code has been validated as an accurate tool to provide H_T from CT in both adults and paediatric patients [15, 16] and has been used in many publications [17, 18].

Statistical analysis

Data were described using mean and standard deviation or median, interquartile ranges, and percentiles. Box and whisker plots were used to provide a graphical representation of the organ doses. Outliers are points higher than the value of the 75th percentile plus 1.5 times the interquartile distance, or lower than the value of the 25th percentile minus 1.5 times the interquartile distance.

Results

Number of CT exams

In the database, there were 28,780 patients who underwent 49,834 CT exams. The average number of CT exams per patients was 1.73 ± 1.41. The 75th percentile in the distribution of CT examinations was 2 and the 95th percentile was 4.

Patients with a CED of $\geq$ 100 mSv

The study identified a cohort of 1765 patients who received $CED_{CC} \geq 100$ mSv in the observation period of 2.4 years, based on the ED/DLP conversion coefficient method. This represents 6.1% of all patients who underwent CT exams. The frequency distribution of patients reaching the threshold of 100 mSv in a set period starting from the first recorded examination is represented in Fig. 1. Since the follow-up period was not the same for each patient, the percentages of patients likely to overpass the threshold of 100 mSv in 3 months, 6 months, and 1 year might be seen as an underestimation since the ones having the first examination in the last year of the observation period might not have their doses recorded for the entire year (or semester, or trimester).

Patients with a CED of $\geq$ 100 mSv in a single day and in a month

The demographic characteristics of the patients are reported in Table 1. This study identified a subgroup of 70 patients who received CED $\geq$ 100 mSv in a single examination (66) or in multiple examinations performed on the same day (4). This group represented 0.25% of all patients who underwent CT exams and 4% of those who received CED $\geq$ 100 mSv in the observation period. The mean number of sequences per examination was 5.9 ± 1.8 with a maximum of 10 sequences in two exams performed in the same day in a polytrauma patient submitted first to a whole-body CT (1 head, 1 neck, 1 lumbar

Table 1 Demographic data of patients with CED $\geq$ 100 mSv in a single day and in a month

| Patient characteristics	Single day ($N = 70$)	Month ($N = 427$)
Age (years)	67 ± 13	63 ± 16
Age group		
1. (≤ 50 years)	10 (14%)	82 (19%)
2. (51–65 Years)	15 (21%)	116 (27%)
3. (> 65 years)	45 (64%)	229 (54%)
Male (N, %)	51 (73%)	303 (71%)

spine, 2 chest with and without contrast and a three-phase abdominal CT) and to a CT-guided intervention for vertebroplasty on the same day (2 sequences).

The study identified another subgroup of 427 patients who received CED $\geq$ 100 mSv within a month from the first examination. This group represented 1.5% of all patients who underwent CT exams and 24% of those who received CED $\geq$ 100 mSv in the observation period. The mean number of CT exams per patient was 2.5 ± 1.5 with a maximum of 12, and the mean number of sequences per patient in the period was 9.4 ± 3.5.

The patient's clinical indication for referral together with the estimated CED values is reported in Table 2 and included cancer in 132 patients (31%): among them, 33 were referred for cancer diagnosis, 15 for cancer follow-up, and 84 for cancer staging. The remaining 295 patients (69%) had non-oncological indications which were grouped in renal evaluation (22) including renal cysts, colic, and transplant; polytrauma (97); thoracic and abdominal evaluations (130) including aortic dissection, bowel obstruction, ischemia or diverticulitis, abdominal colic, and evaluation of liver cirrhosis; CT-guided interventions (7) for biliary drainage or vertebroplasty; and other indications (30).

An insight in the potential dependence of high doses from CT equipment is available in Fig. 2 in which the frequency distribution of patients with CED $\geq$ 100 mSv in a month depending on CT equipment is presented. For each type of scanner, also the mean CED is reported.

Fig. 1 Frequency distribution of patients reaching the threshold of 100 mSv in a set period starting from the first recorded examination
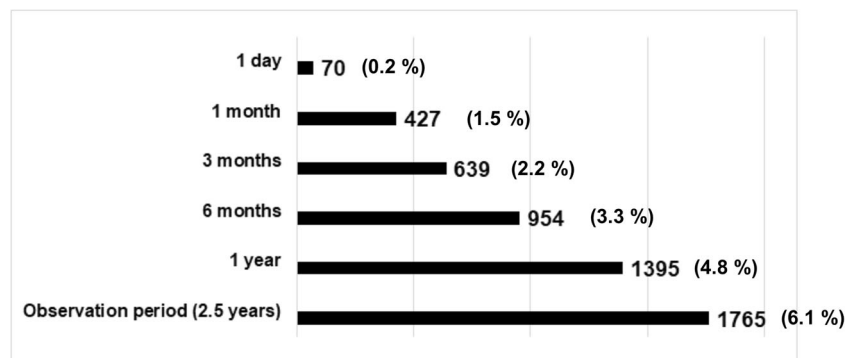
Table 2 Average CED (mSv), number of CT exams, and number of sequences needed to overpass 100 mSv, stratified according to clinical indications for CT referral in patients with CED ≥ 100 mSv in a month

| Clinical indication for CT referral	N (%)	Age (years)	No. of CT exams Median [min–max]	No. of sequences	CED$_{CC}$ (mSv)
Cancer	132 (31%)	66 ± 13			119 ± 24
Diagnosis	33	65 ± 11	2 [1–6]	9 [6–17]	126 ± 22
Follow-up	15	71 ± 12	1 [1–3]	6 [5–10]	118 ± 22
Staging	84	65 ± 13	1 [1–4]	7 [5–15]	117 ± 25
Non-oncological	295 (69%)	62 ± 18			137 ± 43
Renal evaluation	22	59 ± 16	2 [1–4]	8 [5–12]	128 ± 32
Stroke	9	63 ± 15	4 [1–12]	11 [5–22]	127 ± 21
Polytrauma	97	53 ± 20	2 [1–7]	10 [6–21]	138 ± 44
Thoracic-abdominal	130	68 ± 14			138 ± 46
Artery dissection	15	68 ± 6	3 [2–13]	9 [7–13]	138 ± 26
Aneurysm	13	68 ± 14	3 [1–11]	10 [6–23]	135 ± 32
Bleeding	12	73 ± 7	2 [1–4]	9 [6–13]	168 ± 94
Acute pancreatitis	11	61 ± 15	2 [2–4]	8 [7–11]	126 ± 40
GP, BO, GI, AA	31	69 ± 13	2 [1–4]	9 [6–13]	137 ± 43
Sepsis	10	65 ± 13	3 [2–4]	10 [7–15]	170 ± 57
Liver	7	62 ± 7	2 [1–5]	6 [5–18]	136 ± 46
Other	32	65 ± 14	3 [1–6]	10 [4–17]	136 ± 35
CT-guided interventions	7	63 ± 10	2 [2–5]	11 [9–17]	119 ± 47
Other	30	65 ± 13	3 [1–11]	10 [5–31]	137 ± 32

GP, gastrointestinal perforation; *BO*, bowel obstruction; *GI*, gastrointestinal ischemia; acute abdomen

A better insight into the dose optimisation is available through Table 3 in which the median value of dose-length product (DLP) in mGy cm is presented overall and for different CT scanners. It indicates that on average radiation doses of CT patients were lower than the European Diagnostic reference levels as published in EC publication Radiation Protection n.180 [19] but higher than the US national benchmark as obtained through the American College of Radiology Dose index registry [9].

Organ doses

Table 4 and Fig. 3 show summary statistics for H_T estimated with the Monte Carlo simulation in the subset of 70 patients with CED ≥ 100 mSv in a single day. Noteworthy, in all but two patients, there was at least organ/tissue receiving an H_T ≥ 100 mGy. The percentage of patients receiving H_T ≥ 100 mGy ranged from 21% for the brain to 87% for the liver.

Fig. 2 Frequency distribution of patients with CED ≥ 100 mSv in a month depending on CT equipment
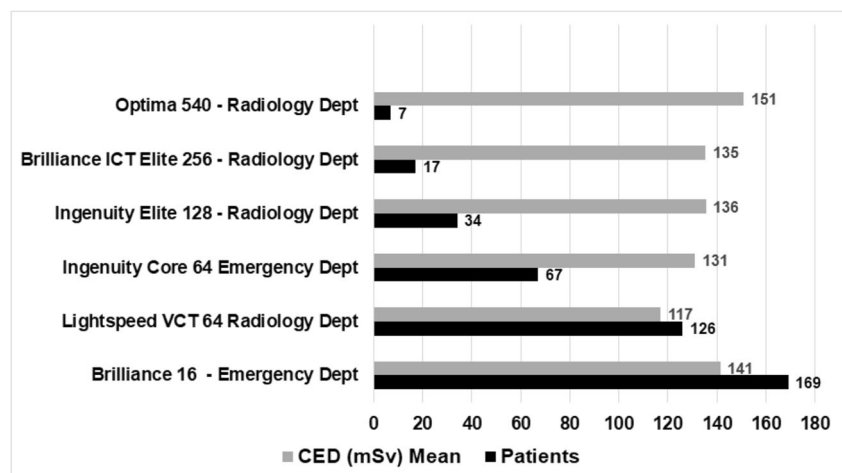
Table 3 The median value of dose-length product (DLP) in mGy cm for cohort with CED ≥ 100 mSv in a month

	CT head/brain	CT abdomen/pelvis
European DRLs (Radiation Protection 180)	1000	800
American College of Radiology Dose index registry	869	682
Optima 540	1160	559
Brilliance ICT Elite 256	1147	585
Ingenuity Elite 128	1116	652
Ingenuity Core 64	1024	698
LightSpeed VCT 64	570	1107
Brilliance 16	985	845
Overall	985	734

Discussion

CT imaging provided immense benefits in the diagnosis and management of many health conditions, which far outweigh radiation risk when the procedure is justified and optimised to achieve the required diagnostic objective. Nevertheless, attention has been raised recently to patients who require repeated imaging for both diagnostic and therapeutic purposes. Information has become available that the number of patients who accumulate an effective dose of 100 mSv and higher in a few years from recurrent CT procedures is greater than previously known and might concern nearly half million patients per year in OECD (Organization for Economic Co-operation and Development) countries [10] and one out of five such patients is likely to be below 50 years of age [9].

Data analysed in this study show that overall, 6.1% of patients undergoing CT exams in a tertiary care centre received doses from CT exams with CED ≥ 100 mSv in an observation period of 2.4 years and that a sizeable percentage of them (1.5%) accrued such CED in a single day, due to a single CT examination or in a single episode of care involving multiple CT examinations within a month starting from the first examination.

Although the finding of patients receiving CED > 100 mSv in a set period of time has been recently the topic of several publications [8–11], the existence of a sizeable subgroup of patients susceptible to receive such value in a single episode of care is unprecedented and add information on the current framework of CT usage.

There is a need to develop models for predicting patients with clinical indications that are likely to accumulate relatively high doses due to recurrent CT imaging. Noteworthy, in our study, 69% of such patients were referred to CT for non-oncologic indications and, among them, the polytrauma subgroup, showing a mean age of 53 years, was on average 13 years younger of the subgroup of patients referred for diagnosis, follow-up, or staging of a suspected or already-known cancer.

The current study was not aimed at examining the CT acquisition parameters like voltage, current, rotation time, tube current modulation, and iterative image reconstruction.

Table 4 Values of equivalent organ doses H_T (mGy) in patients with CED ≥ 100 mSv in a single day and % of patients with $H_T ≥ 100$ mGy

	Number	Mean (mGy)	Median (mGy)	SD (mGy)	1st quartile (mGy)	3rd quartile (mGy)	Range (mGy)	$H_T ≥ 100$ mGy (% of patients)
$H_{T,brain}$	70	53	7	66	4	98	3–269	21
$H_{T,breast}$	19	112	107	22	93	135	83–147	63
$H_{T,colon}$	70	135	133	50	95	171	50–260	71
$H_{T,gonads}$	70	115	114	57	69	144	21–276	60
$H_{T,heart}$	70	118	115	32	91	145	59–220	67
$H_{T,kidneys}$	70	152	152	47	115	186	65–270	86
$H_{T,liver}$	70	144	143	37	116	170	65–238	87
$H_{T,lungs}$	70	118	117	28	97	138	65–207	71
$H_{T,red\ bone\ marrow}$	70	77	76	22	60	92	35–139	10
$H_{T,stomach}$	70	120	119	34	97	144	46–197	73
$H_{T,thyroid}$	70	99	99	78	19	144	9–273	49
$H_{T,uterus/prostate}$	70	112	106	46	76	134	34–234	60

Fig. 3 Summary statistics for H_T estimated with the Monte Carlo simulation in the subset of 70 patients with CED ≥ 100 mSv in a single day
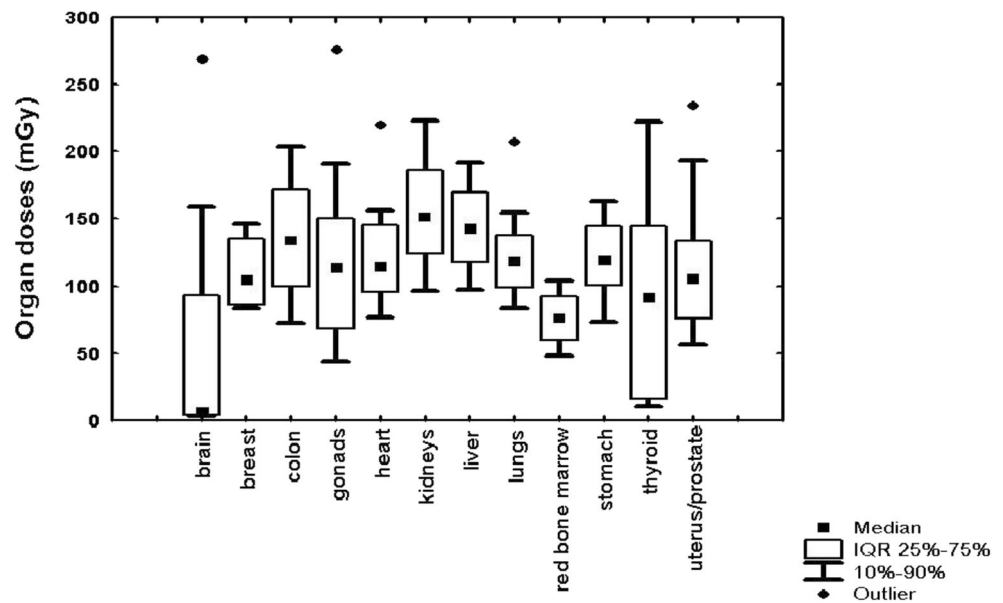
Nonetheless, the impact of CT techniques can be indirectly assessed from the DLP values for individual exams reported in Table 3. Among the CT devices, there were significant differences in terms of average DLP values. The LightSpeed VCT and the Brilliance CT exhibited the highest median values for DLP in body examinations (1107 and 835 mGy cm, respectively), well above the European DRLs and accounted for nearly 70% to the number of patients with high CED (126 and 169 patients, respectively). Both CTs were not equipped with iterative reconstruction methods and were eventually dismissed from routine clinical practice at the end of 2018–beginning of 2019. This provides, although only "a posteriori", a reason why older machines should be replaced with modern equipment and points toward the role that industry plays in dose reduction, by improving hardware and software.

Concerning the protocols, it must be underlined the high number of acquisitions per examination: while the median number of CT exams needed to overpass 100 mSv was in the range of 1–4, the median number of acquisitions was in the range 6–11 demonstrating the high prevalence of multiphase examinations. This finding emphasises the need of customising imaging protocols for clinical situations that require repeated imaging in order to minimise the cumulated radiation dose, since such imaging situations might often need fewer doses than other exams for the same anatomical region.

Our study has some limitations. Due to the retrospective collection of data, patients were followed for different time periods. This will likely affect the percentage of patients with CED ≥ 100 mSv in a set period of time, but should have only a limited impact on the assessment of patients who overpassed the same threshold in a single episode of care, defined arbitrarily as 1 month after the first examination. Although, as a rule in our hospital, care is taken to repeat successive examinations on the same patient with the same CT machine, not always this was the case. Therefore, the distribution of patients with CED ≥ 100 mSv with respect to different CT equipment should be interpreted with caution. We did not include radiation dose from other exams such as interventional procedures and nuclear medicine studies, both of which involve significant radiation doses. This is expected to result in an underestimation of the number of patients with CED ≥ 100 mSv in the period. The conversion factors used to calculate E are not standardised and there can be significant differences in values of E derived with different methods, and the uncertainties associated might be high. However, the estimation of ED by "simpler" methods based on easily measurable dose metrics and the application of conversion factors that have been determined through scientific research have been promoted by UNSCEAR in 2015 [20].

Despite these limitations, our results are the first assessment of the number of patients receiving relatively high doses from repeated CT examinations in a single episode of care that should prompt actions from the different stakeholders involved in patient's radiation protection including the need for medical societies to develop imaging strategies for clinical conditions that require repeated imaging, for industry to further development of lower dose CT including sub-millisievert CT, for developers of exposure monitoring systems to make patient's prior radiation history available to the referring physicians, and for radiological medical practitioners to facilitate a decision-making process based upon weighing benefits and risks.

Conclusions

This study showed that 1.5% of the patients submitted to CT in a 2.5-year period can receive a CED greater than 100 mSv in a single episode. The clinical indication for CT referral was non-oncological in 69% of patients. Actions are needed from various stakeholders to ensure that the patient's prior radiation history is taken into consideration as a factor to re-evaluate current radiation risk management policies.

Compliance with ethical standards

Guarantor The scientific guarantor of this publication is Marco Brambilla.

Conflict of interest The authors of this manuscript declare no relationships with any companies whose products or services may be related to the subject matter of the article.

Statistics and biometry The expert in statistics is Marco Brambilla, who is among the authors of the paper.

Informed consent Written informed consent was not required for this study because no change of intervention in patient management was part of the work that involved data analysis retrospectively.

Ethical approval Institutional Review Board approval was not required because only summary data (total numbers) were needed for the analysis.

Methodology
• retrospective
• observational
• performed at one institution

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