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Patients Undergoing Recurrent Computed Tomography Procedures: Indications, Risks and Exposure Assessment

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SUMMARY

The rising dependency on computed tomography (CT) for diagnostic and monitoring purposes has led to an increase in the total radiation dose among certain patients. While a single CT scan is usually a low-risk procedure that is clinically justified, the repeated imaging can lead to cumulative effective doses (CED) that overreach the thresholds corresponding to the increased cancer risk. Since many of these exposures are occurring over long periods of time—especially in oncology, trauma, and chronic disease management—this thesis is about the request for a systematic assessment of CED accumulation and the risks that are associated with it in recurrent CT imaging.

The central idea in this thesis is to study the incidence of cumulative effective dose in patients subjected to recurrent CT procedures, particularly in those being categorized in high-dose subgroups, clinical associated indications driving imaging frequency and the potential for radiation-related harm. The research was constructed around three objectives: (1) to describe and quantify cumulative radiation exposure using data from recent multicentre and national studies, (2) to identify and characterize the clinical contexts most frequently associated with high cumulative dose, and (3) to evaluate associated patient risks, particularly the proportion of individuals exceeding thresholds such as 100 mSv.

A structured retrospective analysis of 15 peer-reviewed studies published between 2017 and 2024 was created. These studies included multicentre audits for dose monitoring, analyses of national registries, and clinical cohorts from a single centre. The data collected made it possible to display the sample size, imaging frequency, cumulative dose thresholds, clinical indications, and risk estimation models. Descriptive analysis was conducted to find dose accumulation trends, indication frequency, and patient risks.

The results depicted that in the case of most patients having CT imaging, the majority are exposed to moderate cumulative doses; however, there is a subgroup of patients accumulating doses ranging from 0.65% to 6.7% and above 100 mSv. Oncological, trauma, and chronic disease follow-up were the main indications related to the rehiring of the images. Some studies used lifetime cancer risk models based on ICRP and RadRAT that were predicted by some high-dose patients with a share-up to 9.2%.

Cumulative exposure from the recurrent CT imaging therefore imposes a measurable and clinically relevant risk for certain groups of patients. The data obtained are a strong endorsement for the importance of the dose tracking systems, the implementation of stricter justification protocols, and optimization strategies directed particularly to the areas of outpatient care with high-frequency visitation and the settings for oncology treatment.

Keywords: recurrent CT, CED, DRL, radiation risk, recurrent imaging, dose tracking,

LIST OF ABBREVIATIONS

Abbreviation	Full Term
AIS	Abbreviated Injury Scale
AAPM	American Association of Physicists in Medicine
BMI	Body Mass Index
CED	Cumulative Effective Dose
CF	Cystic Fibrosis
CT	Computed Tomography
DLP	Dose-Length Product
DRL	Diagnostic Reference Level
ED	Emergency Department
FDG	Fluorodeoxyglucose
I100;1	Incidence of patients exceeding 100 mSv within 1 year
I100;3	Incidence of patients exceeding 100 mSv within 3 years
I100;5	Incidence of patients exceeding 100 mSv within 5 years
IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiological Protection
ISS	Injury Severity Score
LAR	Lifetime Attributable Risk
LNT	Linear No-Threshold (model)
LPD	Lymphoproliferative Disorder
LT	Lung Transplantation
mGy	Milligray
mGy·cm	Milligray-centimetre
mSv	Millisievert
NCRP	National Council on Radiation Protection and Measurements
NHS	National Health Service
OECD	Organization for Economic Co-operation and Development
PET	Positron Emission Tomography
RadRAT	Radiation Risk Assessment Tool (U.S. National Cancer Institute)
RDMS	Radiation Dose Monitoring System
RERL	Recurrent Exposure Reference Level
UNSCEAR	United Nations Scientific Committee on the Effects of Atomic Radiation
V/Q	Ventilation/Perfusion (scan)

1. INTRODUCTION

1.1 Background of the Study

Computed tomography (CT) is a crucial part of modern diagnostic medicine, giving the possibility of fast and accurate imaging of body structures in high-getting resolution. The technology, which has been on the market since the 1970s, has progressed through a series of improvements-from primitive axial scanners to the present-day multidetector CT (MDCT) systems-and as a direct result, it has been embraced almost universally in practically all medical disciplines.

Although the use of computational tomography has clinically changed the game, the rapid and exponential increase in its usage has led to issues with respect to population-level exposure to ionizing radiation. Even though CT is a small part of imaging processing, it bears the disproportionate medical radiation dose to overall imaging. The excessive share has necessitated reconsidering the pattern of CT scans, particularly in the repeat cases on the same person over a span of time [1].

Ionising radiation from CT scans causes both deterministic and stochastic biological risks. While deterministic effects like skin injury or cataracts need relatively high threshold doses that are unlikely to be reached with diagnostic imaging alone, stochastic effects mainly cancer induction are probabilistic and might occur without a threshold [2]. The primary worry about repeated CT imaging is the slow buildup of cumulative effective dose (CED), which may be the reason for the increased long-term risk of cancer, particularly when the individual organ doses go above 100 mGy [2].

The idea of CED has come out as the authentic metric for defining the radiation risk in the patients getting several diagnostic procedures. Though it has its flaws, such as the inclusion of population-averaged weighting factors in calculations, and it cannot be applied for individual risk estimation, it still is a viable option for assessing the comparative risks in different types of patients and imaging modalities [3]. Recent calculations indicate that many patients in specialized or tertiary care can accrue doses greater than 100 mSv in a relatively short time period (e.g., 2-3 years), which corresponds to an increased risk of cancer as epidemiological studies have shown [2], [4].

As long as the problem gets more and more addressed, notable global institutions such as the International Atomic Energy Agency (IAEA) and the International Commission on Radiological Protection (ICRP) have highlighted the need for justification, optimization, and long-term dose tracking in radiological practice [1]. These rules are the principles of the modern radiation protection order, and they have been placed in regulatory texts like the IAEA Basic Safety Standards and numerous official regional guides.

To deal with the problem of dose accumulation, technological applications have also been recommended. Dose management systems (DMS) are the ones that have made it possible to automatically capture and monitor patient exposure data, and thus, those patients who received the higher doses can be identified retrospectively. However, due to the fact that such systems are not uniformly implemented in all healthcare institutions, both nationally and abroad, some clinical settings are left without the necessary infrastructure or the rules to adopt cumulative dose tracking [1].

The Recurrence Exposure Reference Levels (RERLs) concept has been introduced to bridge the gap between single-procedure optimization and long-term patient safety. These are the values of the threshold for the combination of doses for a certain time period, which are meant to make clinicians and radiology departments aware when the patients get closer to the possible harmful levels of exposure. Recent multinational initiatives of Brambilla et al. have put RERLs into practice at the national level by using percentile-based dose distributions from large patient cohorts in Italy and Slovakia to set pragmatic yet protective exposure thresholds [4], [5].

Though there has been progress, a lot of difficulties still exist. This involves a lack of knowledge about the subject matter among the referring clinicians, no interoperable dose-tracking systems in the different institutions besides the nonuniversal accepted thresholds. The problems above illustrate the necessity of conducting additional research, developing appropriate policies, and integrating new technologies that will ensure the obvious advantages of CT are not neutralized by the long-term avoidable risks.

1.2 Clinical Relevance of CT Imaging

Computed tomography serves a critical purpose in the diagnosis, management, and treatment planning of various medical conditions. Due to its speed in producing high-resolution and cross-sectional images, it has become a necessary and widely used device in almost all medical specialties. CT is notably common in the case of chronic disease, it is applied in complex surgical situations, and it is preferred in acute cases which need a quick diagnosis.

Recurrent imaging with advanced CT is essential for various diagnostic areas, particularly for oncology. Indrakanti et al. revealed that 40% of patients with cancer who were subjected to sequential ^18F-FDG PET/CT scans were exposed to a cumulative effective dose (CED) of ≥50 mSv during a period of 12 months, whereas 12–13% of the patients received ≥100 mSv in the same duration [6]. This highlights the considerable radiation dose associated with the cumulative imaging of a patient during the process of cancer diagnosis, treatment, and surveillance.

In the same manner, renal transplant and haemodialysis patients undergo a series of imaging procedures frequently that are necessitated by the complicated nature of their medical management. De Mauri et al. noted that the average total CED involved in the evaluation process of renal pre-transplant was 72 mSv per patient, of which 43%of them were classified as "very high risk" and had a dose of ≥50 mSv/year [7]. Acquiring radiation doses at those levels poses a risk, especially for younger people who are candidates for transplantation, as they will have a longer life ahead of them in which they might experience damage from radiation exposure.

The very recent global medicine evaluations have also verified the importance of the repeated CT scan among the patients with long-term diseases. The authors Vassileva and Holmberg pointed out that patients who have cancer, trauma, need for replacement kidney, heart disease, Crohn's disease, and cyst can frequently have repeated CT scans, which may be an impression of heightened radiation risk for them [8].

Even with these risks, the systematic integration of cumulative dose thresholds into imaging governance has not yet been accomplished by the standard clinical practices. Conventional Diagnostic Reference Levels (DRLs) are applicable to separate interventions only and do not consider the repeated exposures. As a countermeasure, the concept of Recurrent Exposure Reference Levels

(RERLs) was brought to the fore. Brambilla et al. confirmed the possibility of such implementation of RERLs at a national level in Italy and Slovakia by using the 75th percentile of the annual CED distributions as reference points for the intervention. These studies detected a large amount of inter-institutional difference, with the initial RERL point of reference set at 34.0 mSv in Italy [4], [5].

1.3 Problem Statement

The use of computed tomography (CT) in the clinic is not being disputed, yet its emerging role in the management of patients over time has raised serious concerns about the cumulative radiation dose. This conversion from episodic to recurrent imaging—mainly in the treatment of long-standing diseases like cancer, kidney failure, and inflammation—led to the introduction of difficulties in the knife-edge diagnosis of the necessity against the long-term radiological safety. An increasing amount of literature that shows some patients receive cumulative effective doses (CED) that are markedly above the thresholds which were found earlier to be stochastic risks, including radiation-induced disturbances in cancer [2], [6], [7].

In contrast to the growing dose tracking technologies and international guidelines for the optimization of the dose, the existing clinical systems are primarily procedure-driven. The Diagnostic Reference Levels (DRLs), which are the primary tools for ensuring patient protection from radiation in medical imaging, are created for standalone examinations in radiology. They cannot be able to reveal the total exposure that a patient receives in time or from different hospitals. For instance, patients who have been recommended to undergo various CT scans may receive CEDs of 100 mSv or even more without the system alerting or the doctor revising it, within everyday clinical practices [4], [8].

On top of that, the level of implementation of the all-encompassing dose monitoring systems within hospitals is far from the same. Quite a few of the medical facilities have difficulties attaining the required interoperability between the radiology information systems (RIS), picture archiving and communication systems (PACS), and electronic medical records (EMRs) that can be applied for the precise and accurate computation of the cumulative patient exposure. This lack of technology standardization is the reason for the poor coverage of clinician information mainly when imaging is conducted in several places or by different departments. In cases where local tracking tools are available, even doctors may not have the habit of routinely viewing radiation histories when they are performing decision-making, which is often caused by time constraints or not having the training of the fundamentals of radiological protection [1].

Additionally, the situation is complicated due to the unavailability of global protocols for recurrent exposure management. Although the launch of Recurrent Exposure Reference Levels (RERLs) shows a bright prospect, the national and regional level scales are only in the initial phases of acceptance and have not yet been part of the standard process for clinical audit [4], [5]. For instance, the research conducted in Italy and Slovakia highlighted the vast difference in the RERL value based on patient cohorts and institutional practices, thus pointing out the necessity for contextualized and flexible frameworks that would be suitable for the local imaging environment [5].

Given the persistent issues, an urgent priority arises to bring together the existing evidence regarding cumulative radiation exposure, recognize the patient cohorts that are most at risk, and assess the acceptability of dose monitoring instruments and the risk-adjusted reference levels. If these steps are not taken, the break-even point of modern CT imaging is likely to be breached by preventable damage to susceptible patients who are scanned several times but missed receiving the proper management measures.

1.4 Aims and Objectives

This thesis has the aim to explore the repercussions of recurrent computed tomography (CT) imaging with a particular emphasis on the cumulative effective dose (CED), patient risk profiles and optimization strategies for radiological protection in high-dose populations.

- To quantify cumulative radiation exposure in patients undergoing recurrent CT imaging using recent multicentre and national studies
- To identify and characterize clinical indications most frequently associated with recurrent CT use and high cumulative dose
- To evaluate the associated patient risks, including the proportion of individuals exceeding dose thresholds such as 100 mSv

2 Literature Review

2.1 Rehani et al. (2019): Global Assessment of High-Dose CT Patients

Rehani and colleagues (2019) carried out a large-scale international research project under the guidance of the International Atomic Energy Agency (IAEA) in order to mark patients taking the highest total effective doses (CED) through several CT scans. The research combined data from four entities covering a total of 2,504,585 CT scans performed on 1,894,936 patients at 324 hospitals with 488 CT scanners [9].

The main aim was to measure the number of patients who have a CED of ≥100 mSv. In total, 33,407 patients were found to meet this requirement, equivalent to 1.33% of the total number of patients who underwent CT scans in the institutions. Variations among institutions were observed; Institute A said 3.4% of their patients are in this category (n = 8,952), Institute B 1.4% (n = 5,888), Institute C 1.5% (n = 12,198), and Institute D 0.64% (n = 6,369) [9].

The high-dose patients' median CED also differed from site to site: Institute A had a median of 146.9 mSv, Institute B 129.9 mSv, Institute C 130.7 mSv, and Institute D 125.5 mSv respectively. The overall median CED for all sites combined was 130.3 mSv [9]. Reaching these doses via the number of CT films varied considerably: at Institute A the median number of films each patient was 19, at Institute B 11, at Institutes C and D it was each 6. The highest number of CT exams per one patient was recorded as follows: 109 at Institute A, 57 at Institute B, 67 at Institute C, and 89 at Institute D [9].

Tracking the distribution of age among patients, the results revealed that among those achieving CED ≥100 mSv. Specifically, 72–86% of the individuals were older than 50, while 13–28% were aged 50 or younger. The finding discerns that high cumulative doses cannot be confined to certain age groups, and high doses are also evident in the imaging processes of some of the younger adults who need continuous medical images [9].

Specific organ dose data were accessible in Institute A, from which the following median organ doses were indicated: lungs 174 mGy (range 3–2502), red bone marrow 119 mGy (range 57–668), eye lens 34 mGy (range 0–5900), and breast 42 mGy (range 0–2800). Besides, the most lens dose registered is 5900 mGy which represents some patients undergoing repeated head CT scans [9].

Through the duration of the study, the dose-length product (DLP) values at selected anatomic regions for Institutes C and D were also included. The median DLPs (mGy·cm) in Institute C were: chest 632, abdomen 917, and pelvis 794. In Institute D, values were chest 381, abdomen 550, and pelvis 514 [9].

Rehani and his team pointed out that notwithstanding that patients with CED ≥100 mSv are a smallest part, the real number is great and increasing. They brought forth the fact that the monitoring of the patients' radiation doses, knowledge of the clinicians regarding the cumulative exposure, and the determination of the reference levels that need to be met will help out in the quality of the imaging protocols have to go through the review and optimization. Their research is vital in the framework of the establishment of the Recurrent Exposure Reference Levels (RERLs), which adds to the protection of medical staff and patients by mitigating this new threat [9].

2.2 Stopsack & Cerhan (2019): Cumulative Dose in a General Population

Stopsack and Cerhan (2019), as part of a major study within the Rochester Epidemiology Project (REP), sought to determine the cumulative effective radiation doses from CT scans and the relevant patient characteristics of participants in Olmsted County, Minnesota. The study was based on the data of 54447 adults eyeing a residual of three years after the 10-year study observational period (2004–2013) and excluding the instances of radiation exposure which were examined only in conjunction with the relevant long-term results [10].

From the population in the study, 26377 individuals, which accounted for 48.4%, had at least one CT examination during the research period. The cumulative effective dose (CED) was classified over the period of 10 years into specific categories: 0 mSv (28116 individuals, 51.6%), 0.1–9.9 mSv (8593, 15.8%), 10–24.9 mSv (9205, 16.9%), 25–99.9 mSv (7492, 13.8%), and ≥100 mSv (1041, 1.9%). The median dose to all those who received at least one CT scan was 14.0 mSv. It should be especially mentioned that the abdominal and pelvic CT imaging were responsible for 67.2% of the cumulative dose for all the patients, marking the enormous contribution of the abdominal scans to the general radiation burden [10].

The analysis of age-specific data showed that the doses of radiation also significantly increased with age. In comparison with the individuals in the age bracket of 18–29 years, the CEDs of people in the age group of 70–79 years, who had received any CT scan, were 2.16-fold higher, and the doses of those aged 80 years and above were 2.17-fold higher [10]. Besides, the body mass index (BMI) and tobacco use were singled out as the strongest predictors of the radiation exposure. The obese people (BMI≥40 kg/m^2) had received 1.33 times more radiation than normal weight ones, and the current smokers received 1.22 times more radiation than never smokers after the multivariable analysis was done. A level of education was also a relevant factor: individuals with less than a high school education received 1.23-fold higher dose compared to those with a four-year college degree [10].

The authors studied the high-dose subgroup (CED≥100mSv) by looking at the medical records of 200 randomly selected individuals. They were the ones who underwent several CT scans (600 CTs). The commonest indications for the imaging included restaging of solid cancers (18.3%), abdominal pain (17.2%), restaging of lymphoma (12.2%), infection evaluation (7.0%), nephrolithiasis (5.7%), and nodule/mass follow-up (5.2%) [10]. It is important to note that seven indications accounted for 70.5% of CT scans in this high-dose group and beyond that 93% of the scans were removed in outpatient or emergency settings which make it obvious that recurrent imaging outside the inpatient hospitalization setting is the most prevalent.

Ordering providers' distribution showed that 47.7% of high-dose CTs were requested by subspecialists, 27.7% by emergency physicians, 17.5% by primary care providers, and 7.0% during hospital admission. As for diagnostic yield, 29.7% of the CTs revealed positive findings, while 24.7% showed changes in comparison to the previous scans. Incidental findings were noted in 10.7% of all the CTs reviewed, so the chances for unintended clinical problems and further tests could be significant [10].

2.3 Howard et al. (2019): Cumulative Dose in Polytrauma Patients

A study was conducted by Howard et al. (2019), which is a retrospective cohort study performed to examine the cumulative radiation exposure and estimated the cancer risk in polytrauma patients who were treated over the ten-year period (2007-2016) at a major trauma centre located in the United Kingdom. The research was carried out on 2,394 adult patients with an Injury Severity Score (ISS) ≥16 who luckily survived at least 30 days after being injured. A total of 38,495 radiographic studies were identified via the hospital's Picture Archiving and Communication System (PACS), including 12,600 CT scans and 25,895 plain radiographs. The investigations which were found in the PACS included the average of 5.26 CT scans and 10.82 X-rays during the first year following injury [11].

The mean cumulative effective dose (CED) was for all patients 30.45 mSv in 12 months with a median of 18.46 mSv. A subsample of 115 patients (4.8%) received a CED of ≥ 100 mSv, and a mean dose of 158.82 mSv (range 100-292 mSv). These high-dose patients had a mean age of 34.3 years and a mean injury severity score (ISS) of 32.16. Mechanisms of injury in this group included road traffic collisions (53.8%), falls from height (19.7%), crush injuries (12%), stabbings (3.4%) [11].

The survey demonstrated a robust ISS-CED link especially for the increase in the ISS based on injuries incurred below 50. An anatomical-region specific analysis of the Abbreviated Injury Scale (AIS) revealed that radiation dose increased linearly with pelvic and limb injuries while in thoracic, abdominal, and spinal injuries, it plateaued or even declined at higher AIS scores—most probably due to the increased early mortality in those groups. These results indicate that radiation exposure is not consistently distributed by injury pattern but is profoundly influenced by both anatomical site and survivability [11].

The writers made a lifetime risk assessment of fatal carcinogenesis with the help of the ICRP risk models. In the whole cohort, the mean additional lifetime risk was 3.56% due to the medical imaging which corresponds to around 85 patients developing fatal cancer because of imaging-related radiation exposure. This risk was significantly higher in the younger patients and they had a need for dose reduction strategies in survivors of high-energy trauma especially for those with a long life-expectancy [11].

In conclusion, Howard et al. mentioned polytrauma as the associated clinical scenario with high cumulative imaging burden. The study promotes the use of imaging protocols which save dose without affecting the diagnostic value like the use of ultrasound or MRI where it is possible; and also endorse stricter radiation monitoring in trauma settings. These actions can lower the long-term stochastic risks for this at-risk patient cohort [11].

2.4 De Mauri et al. (2017): Cumulative Exposure in Renal Transplant Candidates

De Mauri et al. (2017) conducted a retrospective single-centre study to quantify cumulative radiation dose in haemodialysis patients undergoing renal pre-transplant evaluation. The study involved 70 patients (mean age 46.4 ± 12.0 years) over a 5.5-year period (June 2009 to December 2014). Radiological procedures were extracted from the Radiology Information System and dose data for computed tomography (CT) were derived from dose reports archived in the Picture Archiving and Communication System (PACS). Nuclear medicine doses were calculated using ICRP conversion coefficients [7].

A total of 744 imaging procedures were performed across the cohort, generating an aggregate radiation dose of 3,869 mSv. Of these, conventional radiology, CT, and nuclear medicine accounted for 78%, 14%, and 8% of all procedures, respectively. However, in terms of dose contribution, CT was the dominant source, accounting for 83% of total CED, followed by nuclear medicine (9%) and conventional radiology (8%) [7].

The mean cumulative effective dose (CED) per patient was 72 mSv, with a median of 32 mSv. Annual dose estimates were 35 mSv (mean) and 7 mSv (median). Stratification by transplant status showed that 37 patients on the active transplant waiting list received an average of 47 mSv during their pre-transplant evaluation and an additional 36 mSv during the monitoring period while awaiting transplantation [7].

In terms of cancer risk classification, 4 patients (7%) were categorised as low-risk (<3 mSv/year), 19 (35%) as moderate-risk (3–<20 mSv/year), 8 (15%) as high-risk (20–<50 mSv/year), and 23 (43%) as very high-risk (≥50 mSv/year) [7].

The study also examined the association between comorbidities and dose burden. Patients with diabetes mellitus, ischaemic heart disease, or a history of malignancy tended to accumulate higher CEDs, though these associations did not reach statistical significance. For example, patients with ischaemic heart disease had a mean total CED of 160 mSv compared to 58 mSv in those without it [7].

The authors concluded that patients undergoing renal pre-transplant evaluation are subjected to substantial ionising radiation doses, with CT being the principal contributor. They emphasised the need to implement strategies to reduce unnecessary imaging, favour non-ionising modalities when feasible, and develop robust systems for longitudinal dose tracking. Given the additive effect of post-transplant exposures, they noted that patients may accumulate over 120 mSv within a 5–6 year interval, potentially surpassing occupational dose limits [7].

2.5 Arenallo et al. (2020): High Doses from Single CT-Guided Interventions

Arenallo et al. (2020) did a retrospective analysis of the patients who had the most single computed tomography (CT)-guided interventional procedures with the highest recorded radiation exposures. The research, which was based on data collected per Radimetrics dose-tracking protocol from a single hospital between January 2013 and December 2017, sought to classify the frequency, the clinical settings, and the amount of radiation doses ≥100 mSv delivered during a single intervention [12].

As a result of the analysis, 33 patients were found who went through 37 CT-guided procedures and whose cumulative effective dose (CED) was more than 100 mSv. Among these procedures, 15 were ablations, 8 were myelograms, 7 were drainages, 6 were biopsies, and 1 was classified as "other." The CED in these cases varied from 100.2 mSv to 235.5 mSv, where the average dose was 125.7 mSv and the median was 111.8 mSv [12].

Out of the 33 high-dose patients, 6 (18%) were below the age of 50, which shows that high doses are not only found in oldest or complicated chronic cases. The research stated that one of the largest doses of radiation can be delivered in just a single intervention, which is against the common paradigm of per-scan accumulation to achieve a given dose of radiation [12].

Clinical follow-up through electronic health record review, covering periods from 0.2 to 7 years, revealed no observed deterministic effects (e.g., skin injury) or stochastic outcomes (e.g., malignancy) attributable to the exposures in this cohort. Nonetheless, the authors pointed out that just because there was no identified radiation-related pathology during the follow-up period, it does not mean that patients would not be affected in future, especially those who are younger [12].

The study points out that CT-guided interventional procedures may be a significant source of high radiation exposure. Arenallo et al. encourage referring physicians and interventional radiologists to be more vigilant about the matter, especially when treating children. They also suggest considering dose reduction strategies and the use of alternative imaging technologies, such as fusion imaging or MRI-guided interventions, instead of CT scans when it is clinically feasible [12].

2.6 Martin & Barnard (2021): Organ Doses and Non-Cancer Effects from Diagnostic CT

Martin and Barnard (2021) performed a retrospective analysis of patient-level radiation exposures from diagnostic computed tomography (CT) in three UK hospitals for a period of 5.5 years, covering a group of 105,757 patients. The trial was meant to measure organ-absorbed doses and evaluate the possible non-cancer effects on the brain, heart, and lens of the eye [2] via organ-specific conversion coefficients applied on dose-length product (DLP) data extracted from Radimetrics dose management software.

The research discovered that part of the population received organ doses that were above the threshold appropriate for the incidence of deterministic early effects. Thus, for instance, as many as 5,609 patients (9.6%) suffered from the brain receiving a dose higher than 100 mGy, while among them, 47 individuals remained above the ceiling of 500 mGy with the aforementioned factors (i.e., repeated head CT scans) as the main cause. Moreover, among the group undergoing >500 mGy, 41% were 49 years old or younger, which is a significant proportion of the patients who were exposed to radiation of such a magnitude. Besides, the whole group had 2.4% of cases who received heart doses more than 100 mGy, with the most extreme case being one patient who accumulated more than 600 mGy. Such observations indicate that repeated CT imaging may have similar dose levels to corresponding non-cancer risks such as cognitive and cardiovascular effects [2].

While there was no lens dose distribution measurement made, the article underlined the need for going beyond the monitoring of the effective dose and also the monitoring of organ-specific doses. The authors proposed the introduction of organ dose metrics as a standard practice, especially in the context of high-throughput imaging and the setting up of diagnostic reference thresholds for non-cancerous biological endpoints. They also suggested that the organ dose estimates be an integral part of the radiological practice and using tracking systems which can point out abnormal exposure at the organ level, clinicians would be advised on decision-making regarding patients' long-term health and safety [2].

2.7 Martin & Barnard (2022): Cumulative Dose Risk in Hospital Patients

Martin and Barnard (2022) executed a retrospective analysis with the purpose of assessing the distribution and clinical impact of cumulative effective dose (CED) in a large group of patients who had undergone CT imaging in a UK National Health Service (NHS) Trust. Having had the exposure data of 215,194 CT examinations performed on 105,757 patients over a period of 5.5 years (from October 2015 to May 2021), they sought to assess the prevalence of high-dose radiation exposure and examine the possible cancer risks associated with it based on the linear no-threshold (LNT) model [1].

Among the total patient population, a CED exceeding 100 mSv was recorded in 719 individuals (0.68%) who is usually considered as the threshold related to incremental stochastic risk. By ICRP-derived risk coefficients, this concentration of radiation could lead to about two cases of additional cancer. For individuals receiving doses of 50 to 100 mSv, the estimated additional cancer incidence was five cases. The authors also emphasized that these estimations are likely to be higher than the real risk because they do not take into consideration the fact that the patients' health conditions are often compromised which results in them having shorter long-term survival and thus the longer latency period for radiation-induced tumours [1].

The patient population was categorized according to age and sex so as to get clearer risk forecasts. Age-specific cancer incidents for 100,000 people per mSv were calculated using ICRP Publication 147 data. For instance, females between 0-9 years of age who were submitted to chest-abdomen-pelvis CT received a coefficient of 18 cancers per 100,000 per mSv, while this rate fell to 1 per 100,000 for the elderly (over 80 years). Such gradients were also applied to males and for head CT exposures [1].

The analysis of age distribution showed that besides the prevalence of high-dose exposure in elderly segments of the population, it was not exclusive to them. There were twenty-two patients who took a dose of >100 mSv and were under 40, while 38 were in their 40s. The majority of patients who exceeded 100 mSv were in their 50s, 60s, and 70s [1].

Despite the fact that only a few of the overall cohort received doses more than 100 mSv, the number of 719 people forest of UK NHS Trust was significant in both clinical and administrative aspects. The authors asserted that this conclusion emphasizes the need for integrated incremental exposures tracking and evaluation systems in the facilities. They advanced the argument that clinical protocols targeting specifically the imaging that is repeated were the measure that the International Atomic Energy Agency (IAEA) and the International Commission on Radiological Protection (ICRP) are already calling for [1].

Martin and Barnard stressed that it is crucial not only to justify and optimize on a per-scan basis but also concerning the cumulative exposure history of the patient. They opine that, notwithstanding the fact that the likelihood of getting cancer from one isolated CT scan is very low, the total exposure from many such procedures demands consideration, particularly in the case of patients afflicted with chronic disease and undergoing normal frequency imaging [1].

2.8 Indrakanti et al. (2022): Dose Accumulation from PET/CT in Oncology

Indrakanti et al. (2022) performed a retrospective assessment in order to determine the total radiation exposure to patients who underwent multiple ^18F-FDG PET/CT scans in a two-year span at a tertiary academic hospital in the United States. The research was specifically focused on the patients who underwent two or more scans in a single calendar year and it aimed at assessing dose burden, disease classification, and imaging frequency [6].

From 2019 to 2020, a total of 6,831 unique patients received 10,714 ^18F-FDG PET/CT examinations, with an overall average of 1.6 scans per patient. Among these, 1,428 patients were the ones who got two or more scans in the course of the study. In that group, 834 had multiple scans in 2019, 825 in 2020, and 231 in both of the years. The greatest number of PET/CT procedures done by a single patient during a year was seven, while in the course of both years there were patients that received even twelve scans altogether [6].

On the basis of age, the majority of those who got multiple PET/CT scans were elderly: 52.0% between 61-80 years, and 26.8% between 41-60 years. In addition, there were 11.6% of the individuals who were 40 years or less [6].

The median effective dose for each PET/CT examination was 25.1 mSv, of which the CT part added a median of 14.5 mSv and the PET part brought in an addition of 10.5 mSv. The dose difference was significant; maximum rate was found to be 1.7 to 2.9 times the median, mostly depending on the patient's body mass index [6].

Cumulative effective dose (CED) data indicated that in 2019 12.2%, in 2020 12.5%, and in the combined two-year period 12.9% of the patients received a CED ≥100 mSv from PET/CT procedures. All quartile statistics for CED - including 25th, 50th, and 75th percentiles – surpassed the 100 mSv threshold value for the joint years, 25th percentile: 109 mSv, and 75th percentile: 178 mSv [6].

The study also pointed to the most prevalent tumours that led to repeated imaging: melanoma, non-Hodgkin's lymphoma, GI cancers, breast cancer and Hodgkin's lymphoma were majority in the list of high cumulative exposures [6].

The main point of this study is the substantial radiation dose burden with repeating PET/CT scans in oncology patients. The authors state that more than 12% of patients participating in the serial PET/CT exam series surpass a CED of 100 mSv, confirming the need for dose optimization and clinical justification approaches, especially with patients who have a longer term of survival [6].

2.9 Fitton et al. (2019): Radiation Burden and Malignancy Risk Following Lung Transplantation

Fitton et al. (2019) retrospective study on the total, cumulative effective dose (CED) of ionizing radiation and its potential relation to the development of malignancy in cystic fibrosis (CF) patients who underwent lung transplantation (LT) at a single centre from January 2001 to December 2006. The study comprised 52 patients (27 men and 25 women) who survived at least three years following the LT procedure, with a mean age of 24.4 ± 9.2 years old at the moment of operation. Of these, 11 patients were under 18 years of age at the transplantation time [13].

The cumulative radiation dose was calculated starting from the time of the transplantation to the time of June 2016 or up to the point of the de novo malignancy development. The mean CED was 110.0 ± 51.6 mSv (range: 13.0–261.3 mSv). Nineteen of the 52 patients (37%) received over 100 mSv in five years. Imaging in the first six months after the organ transplantation accounted for the most significant part of the radiation exposure with a mean 6-month CED of 26.5 ± 15.1 mSv (range: 5.0–69.7 mSv), in contrast to 6.0 ± 2.5 mSv for every other 6-month period following these [13].

The main origin of radiation was chest CT, which added 73% (80.5 mSv) of total CED per patient. V/Q scans (8.5 mSv, 8%), the upwards-looking chest X-rays (1.9 mSv, 2%), and bedside chest X-rays (1.5 mSv, 1%) were the additional contributors. Most of these procedures were performed during routine follow-up visits and were clinically indicated for postoperative surveillance purposes [13]. The study in addition considered outcomes of malignancy for an average follow-up of 8.1 ± 3.6 years. A total of 9 patients (17%) were diagnosed with 10 different de novo malignancies, which included lymphoproliferative disorders (LPDs), skin, and colon adenocarcinomas, and lung adenocarcinoma, respectively. No remarkable difference was noted in the mean radiation dose or CED between patients with and without malignancies. The patient diagnosed with lung adenocarcinoma received a total lung dose of 87.1 mGy over 3 years, which is similar to the cohort mean of 89.7 ± 28.4 mGy [13]. The authors, although the sample size was small, stated that about 20% of CF patients subjected to lung transplantation were the ones that got cumulative radiation doses over 100 mSv in just a few years. This issue is a worry especially for the younger population with a long post-transplant life expectancy. The study also showed the importance of monitoring the doses and the necessity for custom-made imaging protocols, which interplay the clinical utility with long-term safety [13].

2.10 Brambilla et al. (2024, Italy): RERL Development and National Dose Benchmarks

Brambilla et al. (2024, Italy) performed a multicentre retrospective analysis with the aim of studying the cumulative radiation exposure from repeat CT scans and of producing Recurrent Exposure Reference Levels (RERLs) that are applicable in the Italian health care system. The collected data was sourced from Radiation Dose Monitoring Systems (RDMS) in nine hospitals which were connected between 2020 and 2022. The analytical cohort was composed of 103,154 adult patients who received CT scans in 2021, and these were enrolled by the hospitals that ranged from a contribution of 1,900 to 22,000 patients [4].

The research replaced incidence for cumulative effective doses (CED) ≥100 mSv with innovation-based metrics: I100;1 for one year and I100;3 for three years. The I100;1 (%) ranged from 0.1% to 5.1%, a fiftyfold variation, while I100;3 (%) ranged from 1.1% to 11.4%, reflecting a tenfold difference among institutions. These variations indicated that the inter-hospital practices in recurrent imaging had substantial discrepancies, regardless of the type of hospitals or patient case mix [4].

In order to establish a benchmark for dose optimization, the national RERL was calculated by the authors on the basis of the third quartile of the annual CED distributions per hospital. The 75th percentile of these values across all the centres added up to a proposed RERL of 34.0 mSv. This figure was meant to be a statistical reference point that is not regulatory and will help in identifying the sites where, due to recurrent patient exposures, clinical or administrative review is needed [4].

The research also maintained that the study did not reveal a statistically significant association between high-dose incidence rates and hospital classification (secondary or tertiary). Moreover, the percentage of recurrent patients in an institution had no relation with the overall I100;3 incidence, which means that high cumulative exposures were not only due to the patient complexity but also to the local protocols and differences in referral behaviour [4].

The variable effective dose (ED) was calculated through the multiplication of constant conversion coefficients to the dose-length product (DLP): 0.017 mSv/mGy·cm for body CT and 0.0023 mSv/mGy·cm for head CT. Even though this approach may yield an inflated ED estimate for the high-BMI populations, it fostered reliable dose estimation and inter-hospital comparability [4].

The authors underlined that the proposed 34.0 mSv RERL should be treated as a provisional benchmark for the whole country as well as the basis for the broader dose optimization campaigns. Their suggestion was to entail the refinement of this value through the inclusion of a more nationally representative sample in new studies. In the meantime, its integration into the RDMS and dose audits could be used for standardizing the practices and enhancing the patient radiation safety [4].

2.11 Brambilla et al. (2024, Slovakia): Nationwide RERL Assessment

A thorough national-level analysis has been conducted by Brambilla et al. (2024, Slovakia) with the aim of quantifying and establishing CT imaging Recurrent Exposure Reference Levels (RERLs) specific to the Slovak healthcare system. The retrospective study focused on the analysis of the data obtained from a total of 328,321 adult patients collected from 102 CT scanners for a period of five years (2018–2022) and covering 93.6% of Slovakia’s total CT activity.

The dataset comprised of 2,157,508 CT examinations, which indicates an average of 1.7 scans per patient. In order to reflect the amount of high-dose imaging, the authors suggest incidence-based indicators: I100;1, I100;3, and I100;5, standing for the percentage of patients who reached a cumulative effective dose (CED) ≥100 mSv within 1, 3, and 5 calendar years, respectively. The nationwide occurrences were I100;1 = 1.1%, I100;3 = 3.9%, and I100;5 = 6.0%, which together indicate a progressive increase in the patient's dose burden over time.

An unexpected high inter-institution variability was found in the healthcare facilities in Slovakia. The I100;1 incidence had its strengths seen in the range of 0% to 6.2%, while the I100;3 factors ranged from 0.26% to 23.2%, with I100;5 being 0.3% to 36.9%. Such a broad disparity was primarily due to the different imaging strategies, trends in referrals and dose optimization practices used by hospitals.

To assist in the congruence of practice and safeguard patient safety, a national RERL of 25.7 mSv was jointly recommended by the authors. This figure was obtained by the calculation of the 75th percentile of the third quartiles of yearly CED distributions from individual hospitals. It is like the one used for Diagnostic Reference Levels (DRLs), both of which can be implemented through Radiation Dose Monitoring Systems (RDMS) [5].

The research strongly stands out showing the positive aspects of incidence-based indicators compared to prevalence metrics in the field of dose surveillance. Contrary to prevalence, which all the high-dose patients from the past have been in and is also subject to the duration of follow-up, incidence does specifically refer just to the cases that exceed a determined dose threshold in a defined period of time. The authors came up with the idea of using I100-based metrics as the gold standard for RERLs establishment and audits [5].

Brambilla et al. noted that the Slovak model can be a template for other health systems in the world. The combination of incidence metrics with the infrastructure associated with RDMS would mean that the patients at risk would have to be identified on time and the institutions would then be able to work according to the national dose optimization plan. This study is one of the most extensive population-based assessments concerning the repeated CT exposure of the population, has been done, is one of the detailed population-level assessments made, and setting a framework for the implementation of the national RERLs which proved to be valid [5].

2.12 Brambilla et al. (2019): Multinational Patterns in CT Overuse

Brambilla et al. (2019) disclosed the data obtained from a global and widespread survey that was organized by the International Atomic Energy Agency (IAEA) with the intention of evaluating the number of patients who attain high cumulative effective doses (CED) from repeated computed tomography (CT) scans. The study's main concern was to find out if the situation of being diagnosed with over 100 mSv from CT is a rare event or a common occurrence among contemporary healthcare systems [3].

The study analyzed the data collected retrospectively from health facilities and institutions from various regions including North America, Europe, Asia, Africa, and Latin America. It specifically targeted the assessment of the number of patients whose CED surpassed 100 mSv, a dose before which the stochastic risk cannot be considered high. Based on local and national surveys, they showed that the accumulated dose was in the range of 50 to 500 mSv in quite a number of clinical situations, often for a brief duration, mostly among patients with conditions like chronic or complex medical conditions that needed to be monitored with serial imaging [3].

The authors pointed out that at Massachusetts General Hospital, a number of the patients had already received more than 100 mSv. The survey result indicated that the case was not a rare one since the institutions from other countries also reported many high-dose patients, even those that did not have electronic dose tracking systems. This evidence puts forward the idea of cumulative dose being one of the primary instruments for justification and optimization, especially where imaging is performed following the physician's order and is clinically necessary [3].

Brambilla et al. cautioned that the existing radiation protection mechanism is limited primarily due to the focus on only the single-procedure Diagnostic Reference Levels (DRLs). These types of metrics cannot measure dose accumulation over time and, therefore, are ineffective in determining which patients may have a cumulative risk due to repeated imaging [3].

The authors urged the need for a worldwide partnership to help with the development of dose tracking facilities and to foment the use of cumulative monitoring techniques. They have supported the concept of Recurrent Exposure Reference Levels (RERLs) as a useful addition to current protection frameworks. RERLs would help doctors and facilities by giving them benchmarks for the populations regarding the exposure they have had over time, which is twofold compared to DRLs, but instead of per patient they refer to entire cohorts [3].

The overall conclusion reached by the study was that large CED from CTs no longer seem to be the exception, but rather the more frequent outcome within different medical settings. The main points in this case identified were i.e. the reinforcement of surveillance systems, standardization of international methodologies, and training health workers on cumulative risks [3].

2.13 Vassileva & Holmberg (2021): Radiation Protection Perspective to Recurrent Medical Imaging

Recurrent medical imaging trepidations linked to radiation protection were considered in detail by Vassileva and Holmberg (2021). Their review concentrated on the worldwide growing imaging, the patients' increased level of radiation exposure, and the missed parts in the monitoring and regulatory schemes, with a special emphasis on the people who are subjected to several procedures during the passage of time [8].

The article stressed the fact that medical imaging continues to rise worldwide, especially in the respect of low- and middle-income countries, which are deprived of the necessary infrastructure developed for the radiation safety monitoring when access is being expanded. This disparity brings about a higher risk for patients to get accumulation of high cumulative effective doses (CED) without proper control [8].

The authors referred to the recurrent radiological imaging as the repeated ionizing imaging procedures that are performed on the same patient over time, usually in relation with chronic or complex conditions. It is estimated that nearly 0.9 million people have been exposed to CED exceeding 100 mSv in a conservative range of estimates with about 20% of those people being under 50 years old. This result is contrary to the common belief that recurrent imaging primarily impacts with aged persons only or persons who are in palliative care [8].

The review disclosed that despite the fact that some of the high-risk patients such as those with malignancies, trauma, cardiovascular disease, end-stage renal disease, Crohn's disease, cystic lung disease, and urolithiasis are among cancer patients, they are not the only ones. Additional CT and PET/CT scans are sometimes needed by these patients due to the accumulated doses they have. Nevertheless, the authors emphasized the lack of comprehensive information from most areas, hence a call for global surveillance systems to be improved and for the study of doses by the inclusion of not well represented populations [8].

Moreover, Vassileva and Holmberg hit on the problems arising from the fact that the current Diagnostic Reference Levels (DRLs) are not adequate as they are based only on one's examination and don't represent cumulative dose risk. To fill in this empty space, they proposed the introduction of Recurrent Exposure Reference Levels (RERLs)—a suggested method for monitoring longitudinal dose accumulation in individual patients and setting a benchmark for the institution [8].

On the other hand, the installation of automated Radiation Exposure Monitoring (REM) systems much more widely was also one of the points brought forward by the authors. While these REM technologies could indeed be a way of dose tracking and optimisation, there is no standardisation or widespread adoption yet. The current platforms lack specific dose calculation for organs, and they don't provide integration with electronic health records or clinical decision-making tools [8].

Their visions for the future revolved around the idea of having REM platforms standardised, production of imaging protocols that are suitable for the recurrent-use populations and increase the number of trainings for clinicians and radiologists. Besides, they requested the improved efforts for the communication of patients' risks and the establishment of explicit guidelines for the number of repeat imaging and their justification to be done on the priority basis [8].

2.14 Griciené et al. (2023) – Recurrent CT Procedures and Cumulative Exposure Assessment (Lithuania)

Griciené et al. [14] conducted a single-centre retrospective study to evaluate cumulative radiation exposure and associated cancer risk from repeated computed tomography (CT) imaging in adult patients over a three-year period in Lithuania. The study drew upon a database of 30,313 patients who had undergone at least one CT scan between 2019 and 2022. Of these, 5,060 patients (16.7%) underwent two or more CT examinations and were included in the analysis of recurrent imaging exposure [14].

The most common indication for repeat CT was monitoring of neoplastic disease, reported in 83% of the recurrent imaging subgroup. Other less common indications included infectious and non-neoplastic conditions, although these represented only a minority of the total. Patients were subdivided into groups based on the number of CT exams (ranging from 2 to 18), and dose metrics were recorded using dose-length product (DLP) values. The average DLP values for groups ranged from 3,713.5 to 11,620.4 mGy·cm, with maximum values reaching up to 42,533 mGy·cm [14].

Further analysis was conducted on a high-dose subgroup of 103 patients with the highest number of scans. In this subgroup, 75.7% (78 patients) received a cumulative effective dose (CED) ≥ 100 mSv, and 92.2% received a CED ≥ 50 mSv. The highest recorded CED was 637.9 mSv, associated with 13 scans for gastric cancer monitoring [14].

The effective dose was estimated using anatomical region-specific conversion factors (k-values) as recommended by the American Association of Physicists in Medicine (AAPM), and the lifetime attributable risk (LAR) for cancer induction was computed using the RadRAT tool from the United States National Cancer Institute. The calculated LAR values in the high-dose subgroup ranged from 0.02% to 9.2%, depending on dose, age, and sex [14].

Griciené et al. concluded that while repeat CT imaging poses a tangible risk of radiation-induced malignancy, this risk can be mitigated through protocol optimisation, critical clinical evaluation of imaging necessity, and the consideration of non-ionising alternatives. The study reinforces the importance of systematic dose tracking and cumulative dose awareness in oncology care, where CT remains indispensable for staging and surveillance [14].

2.15 Rehani & Hauptmann (2020) – Global Estimates of High-Dose CT Patients in OECD Countries

In a modelling-based study, Rehani and Hauptmann [15] projected the number of patients receiving cumulative effective doses (CED) of more than 100 mSv due to recurrent CT imaging in 35 OECD countries. The article using a population-level projection model based on data available for the public exploited a CT frequency dataset and national census data as well as earlier publications dealing with the incidence of high cumulative doses.

The analysis drew on country-specific data on CT examination frequency (per 1,000 population) from the OECD and took the previously referenced figure of 1.92 CT exams per patient stringently developed from multinational data involving over 2.5 million patients. In addition, it applied 1.33% of high-dose incidence rate that was originally derived from Rehani et al. [9] in order to calculate the number of patients per country who might get a dose above the threshold of 100 mSv CED in five years. This resulted in the estimated number of high-dose patients in OECD countries being approximately 2.5 million, which is nearly 0.21% of the entire population. The by-country estimates aggregated from 0.51 to 2.94 patients per 1,000 population with the United States (2.94 per 1,000), Belgium, France, Iceland, Japan reporting the highest rates and Finland and Slovenia announcing the lowest ones [15].

Although being broad, the model uniformly assumed that each and every country has similar imaging practices and dose per exam, furthermore, age, sex, and clinical indication variations were not part of it. Besides, radiation exposure from PET/CT, interventional radiology, and other modalities was excluded from the projection. The authors were aware of the fact that these simplifications might have led to underestimations of the true high-dose burden in some places [15].

Notwithstanding that, the study was of macro-level perspective and due to its recurrent CT cumulative dose nature it was very informative, too. It however, rather than exposing specific areas, covered the need for systematic tracking along with harmonisation of exposure standards, and called for the coordinated international effort of the radiologists, regulatory bodies, and health systems to deal with these emerging problems concerning radiological protection [15].

3 MATERIALS AND METHODS

3.1 Study Design and Scope

This study was conducted as a structured retrospective analysis of published data on cumulative radiation exposure in adult patients undergoing recurrent computed tomography (CT) imaging. The analysis was guided by three core objectives: (1) to quantify cumulative effective dose (CED) across patient populations exposed to multiple CT scans, (2) to identify and characterize the clinical indications most frequently associated with such imaging patterns, and (3) to evaluate the patient risks linked to high cumulative exposure, including the proportion of individuals exceeding the 100 mSv threshold.

3.2 Inclusion Criteria and Study Selection

Studies were selected based on the following inclusion criteria:

- Publication from the last 10 years in a peer-reviewed journal or international scientific conference
- Involvement of patients who had undergone two or more CT procedures
- Reporting of quantitative CED metrics or equivalent dosimetric data
- Inclusion of either high-dose patient subgroups (e.g., CED ≥ 100 mSv) or dose stratification across cumulative ranges
- Provision of data relevant to at least one of the three thesis objectives

Studies were excluded if they:

- Reported exclusively on non-CT modalities
- Lacked patient-level dose data or quantitative thresholds
- Were review-only articles without original cumulative exposure results
- Involved experimental imaging protocols with no clinical relevance.

After analysis of scientific papers, 15 studies were selected which best met the eligibility criteria. These are numbered [1] through [15] in the thesis reference list.

3.3 Literature Search Strategy

The literature search was performed using the databases PubMed, Scopus, and ScienceDirect, covering the period from the last 10 years. Only English-language publications were included. Search terms/ keywords used:

recurrent CT, recurrent computed tomography, cumulative effective dose, CED, multiple CT scans, repeat imaging, high dose CT, ≥100 mSv, cancer risk, cumulative dose, dose tracking, Radimetrics, DLP, Reference lists of key studies were manually screened to identify additional eligible publications and relevant methodological sources, including ICRP and IAEA technical reports.

3.4 Included Studies

The 15 included studies span a variety of geographic regions, clinical settings, and patient populations. They comprise:

- Multicentre and national registry analyses
- Single-centre cohorts in trauma, oncology, nephrology, transplantation, and interventional imaging
- Dose monitoring system evaluations using Radimetrics or equivalent platforms
- Risk-modelling studies incorporating ICRP coefficients or the U.S. RadRAT tool

3.5 Methodological Synthesis

This study applied a descriptive comparative method, structured to align with the three thesis objectives:

- For Objective 1, CED values were extracted from each study and compared in terms of sample size, imaging frequency, mean and median doses, and the proportion of patients exceeding the 100 mSv threshold
- For Objective 2, studies reporting clinical indications for CT were reviewed to identify common medical indications of recurrent imaging, including malignancies, trauma, and chronic conditions
- For Objective 3, available cancer risk modelling data (e.g., lifetime attributable risk from LNT-based models or RadRAT) were collected and summarized, with emphasis on CED thresholds and dose-response interpretation

Due to methodological and reporting heterogeneity, no meta-analysis was performed. Data were retained as reported in the original publications, including dose categories (e.g., <20 mSv, 50–100 mSv, ≥100 mSv) and incidence metrics (e.g., I100;1, I100;3). Descriptive comparisons were presented in tabular format.

3.6 Limitations

Several limitations apply to this study:

- The study of cumulative exposure occurring from recurrent CT procedures is relatively recent, with few long-term or prospective studies available
- The number of high-quality studies providing both CED data and clinical indication breakdowns remains limited

- Considerable heterogeneity exists in how dose is reported, including variation in DLP conversion factors, organ dose models, and risk stratification metrics
- The majority of cancer risk estimates are model-derived rather than based on observed epidemiological outcomes

4 RESULTS

The present chapter is the outcome of a thorough investigation of thirteen peer-reviewed studies that were selected because of their relevance to the topic of cumulative radiation exposure that is associated with medical imaging. The main focus of the chapter is on the recurring computed tomography (CT) procedures.

A collapsed view of the included studies that were compiled in the chart is given in Table 1. Inside the entry, the author, publication year, country of origin, sample size, imaging modality, study design, and reference number are mentioned. The most part of the studies have as a point of interest CT imaging, however, there are a few that highlight the use of other modalities such as radiography, PET/CT, and nuclear medicine, which is the reasoned choice of the broader diagnostic setting where cumulative radiation exposure can take place.

It is worth mentioning that not all studies are equally concentrated on the recurrent imaging subject. A group of the studies, which can be found in the section after this one, puts the emphasis on rebuffed CT sequences that include metrics of the radiated doses that would be concerned with a high cumulative exposure. These studies on the recurrent CT imaging are the starting point as they provide the evidentiary basis to address the primary thesis objectives that commences with the quantification of the radiation burden in patients who undergo multiple CT scans.

Table 1. Summary of analysed studies on recurrent imaging procedures

Author	Year	Country	Sample Size	Imaging Procedure	Study Design
Martin & Barnard	2022	UK	105,757 patients	CT	Retrospective cancer risk estimation using ICRP 147
Martin & Barnard	2021	UK	105,757 patients	CT	Retrospective organ-dose cohort via Radimetrics
Brambilla et al.	2019	International	≈3.2 million patients (estimated)	CT	Multinational data collection on cumulative CT dose
Brambilla et al.	2024	Italy	103,154 patients	CT	Multicentre RDMS-based

					retrospective cohort
Brambilla et al.	2024	Slovakia	1,278,928 patients	CT	National RDMS-based retrospective registry
Indrakanti et al.	2022	USA	6,831 patients	PET/CT	Retrospective PET/CT dose burden study
De Mauri et al.	2017	Italy	54 patients	CT, radiography, nuclear medicine	Retrospective single-centre cohort on renal transplant evaluation
Vassileva & Holmberg	2021	International	Not applicable	General radiological imaging	Expert review on recurrent imaging and radiation protection
Rehani et al.	2019	International	1,894,936 patients	CT	Multicentre IAEA retrospective cohort (324 hospitals)
Stopsack & Cerhan	2019	USA	54,447 patients	CT	Population-based retrospective cohort (Olmsted County)
Howard et al.	2019	UK	2,394 patients	CT, radiographs	Retrospective trauma cohort with CED analysis
Arenallo et al.	2020	USA	8,952 patients	Interventional CT	Retrospective high-dose single-procedure analysis
Fitton et al.	2019	France	52 patients	CT, V/Q scans, radiography	Retrospective post-lung transplant cohort in CF patients

Quantitative Estimates of high Cumulative Radiation Exposure in Recurrent CT Imaging

The present section is devoted to the main objective of this thesis: the quantification of cumulative radiation exposure in patients undergoing recurrent CT imaging using recent multicentre and national studies. The analysis was based on seven out of the thirteen studies from the included studies that provided the measurable data on cumulative effective dose (CED) in cohorts exposed to the repeated CT procedures. These studies were different in size and methodology but, in general, they gave the patient-level or institutional-level estimates of the dose burden, especially to the patients who reached or exceeded the 100 mSv threshold—an exposure level identified by the International Commission on Radiological Protection (ICRP) that increases the likelihood of stochastic risk [1–13].

Among the seven studies that reported incidence data for high cumulative exposure, the percentage of patients who exceeded 100 mSv varied between 0.65% and 6.7%, which reflected the inter-institutional and international variations in CT utilization, referral practices, and dose management protocols. In one of the studies, Martin and Barnard (2022) in the UK, out of 105,757 patients assessed who underwent CT scans during a period of 5.5 years found that 719 individuals (0.68%) received a cumulative dose of at least 100 mSv [1]. In a previous study by the same authors using the same patient cohort and Radimetrics dose tracking system, a similar result of 713 patients (0.67%) above this threshold was reported, which indicates high internal consistency in repeated analyses [2].

Similar estimations were seen in a multinational study conducted by Brambilla et al. (2019) which included the dose data from 20 hospitals in different countries. Even though the total estimated cohort was around 3.2 million patients, dose analysis was only carried out on 702,205. From this group, the average percentage of patients who reached or passed the 100 mSv threshold was 0.65%, which linked to an estimated 4,564 individuals. What is interesting is that the proportions differed considerably across the institutions, which ran from 0% to 5%, and thus pointed to the fact that recurrent CT imaging was manifested in different clinical settings to varying extents [3].

On a national scale, Brambilla et al. (2024) performed two large retrospective research studies that used data gathered from Radiation Dose Monitoring Systems (RDMS). The Italian analysis, entailing 103,154 patients, revealed a median three-year incidence (I100;3) of 6.7% for patients exceeding 100 mSv thus giving rise to an approximated 6,914 individuals [4]. The Slovakian study evaluated a wider sample of 1,278,928 patients and reported a five-year incidence (I100;5) of 6.0%, which pinpointed 20,895 individuals who were above the same threshold [5]. Not only do these results prove that the issue of recurrent imaging is a significant one in national health systems but also, they show the increasing use of standard incidence-based measures such as I100;3 and I100;5 for monitoring cumulative doses.

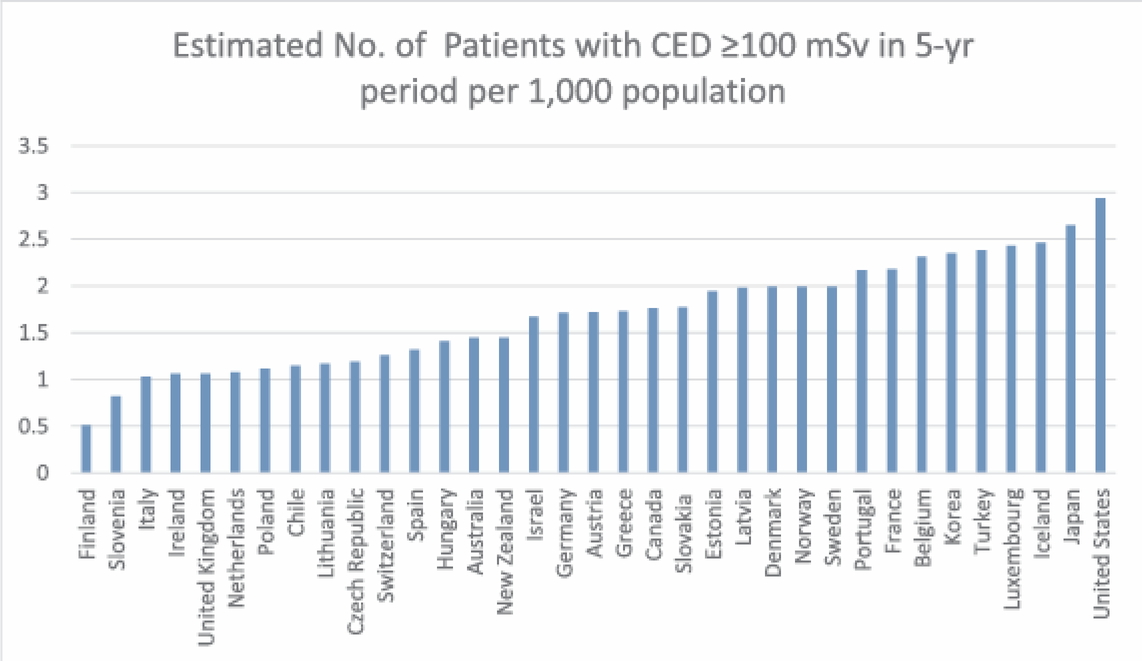

Figure 1. Estimated number of patients with CED ≥ 100 mSv per 1,000 population across 35 OECD countries, based on a five-year modelling projection. The incidence varies from under 1 per 1,000 in some countries to nearly 3 per 1,000 in the United States. [15].

In the United States, the two most recent studies impacted clinical indication and imaging duration on the accumulated dose. Stopsack and Cerhan (2019) observed that 1,041 of 54,447 adults (1.91%) accumulated doses over 100 mSv of cumulative CT scans in a decade, using Rochester Epidemiology Project data population [10]. In a different case, Howard et al. (2019) examined imaging exposure among 2,394 TBI patients and identified that 115 patients (4.8%) exceeded the 100 mSv dose in just one year of follow-up, highlighting the extremely high radiation burden associated with acute polytrauma care [11].

The emergence of 100 mSv as a clinically relevant and elevated cumulative exposure in patients undergoing repeated CT imaging. Although the absolute percentages are different depending on the study population and timeframe, the presence of high-dose patients was consistent in every setting analysed. Moreover, the advent of digital tools for monitoring dose and the standardized format for reporting in recent years have made it increasingly practical to observe such individuals and, consequently, measure their radiation exposure with more precision over the years [1,2,4,5].

In order to deal with the first objective more specifically, Table 2 gives a detailed summary of the seven studies that contained the number and percentage of patients who have received the cumulative effective dose (CED) from recurrent CT imaging exceeding the 100 mSv threshold. This table presents a direct comparison of sample sizes, high-dose patient counts, and incidence rates in different healthcare settings.

Table 2 Summary of studies reporting the number and proportion of patients with cumulative effective dose (CED) ≥ 100 mSv from recurrent CT imaging.

Author	Year	Sample Size	CED ≥ 100 mSv (n)	Percentage
Martin & Barnard	2022	105,757	719	0.68%
Martin & Barnard	2021	105,757	713	0.67%
Brambilla et al.	2019	≈3,200,000 (est.)	≈4,564	~0.65% (subset)
Brambilla et al.	2024	103,154	≈6,914	~6.7% (estimated)
Brambilla et al.	2024	1,278,928	20,895	1.63%
Stopsack & Cerhan	2019	54,447	1,041	1.91%
Howard et al.	2019	2,394	115	4.80%

Clinical Indications Associated with Recurrent CT Imaging and High Cumulative Dose

This part of the writing discusses the second objective, that is, identifying and describing the clinical situations which are most frequently associated with the use of CT scans and with high cumulative doses. Recurrent effective cumulative dose (CED) evaluates the ecological burden of ionizing radiation that is absorbed by patients, but it is in the therapy field that medical imaging justifications such as diagnostic evaluation, disease monitoring, or acute care influence the frequency, anatomy, and repetition of CT operations most. Out of the 13 studies, 3 gave detailed clinical indications to high-dose cohorts in the form of membership allowing the first measure to be established on medical contexts mostly tied to increased cumulative exposure.

The most troublesome data to enforce came from Stopsack and Cerhan (2019); they took 200 randomly selected members from their subgroup which they had defined as CED ≥ 100 mSv and had a population-based cohort of 54,447 adults with a follow-up period of 10 years [10]. There were various reasons for the repeat imaging that were reportedly requested in this subgroup; however, a strong tendency was visible. The biggest share of imaging was set for solid tumours restaging (18.3%) which was the first indication followed by abdominal pain evaluation (17.2%), restaging of lymphoma (12.2%), infection (7.0%), nephrolithiasis (5.7%), and follow-up of nodules or masses (5.2%). Only these six reasons were responsible for 70.5% of high-dose groups' all CT procedures. Remarkably, outpatient and emergency settings did 93% of the scans, which pointed to the fact that it is inaccurate to say that high-frequency imaging concerns only inpatient hospital care.

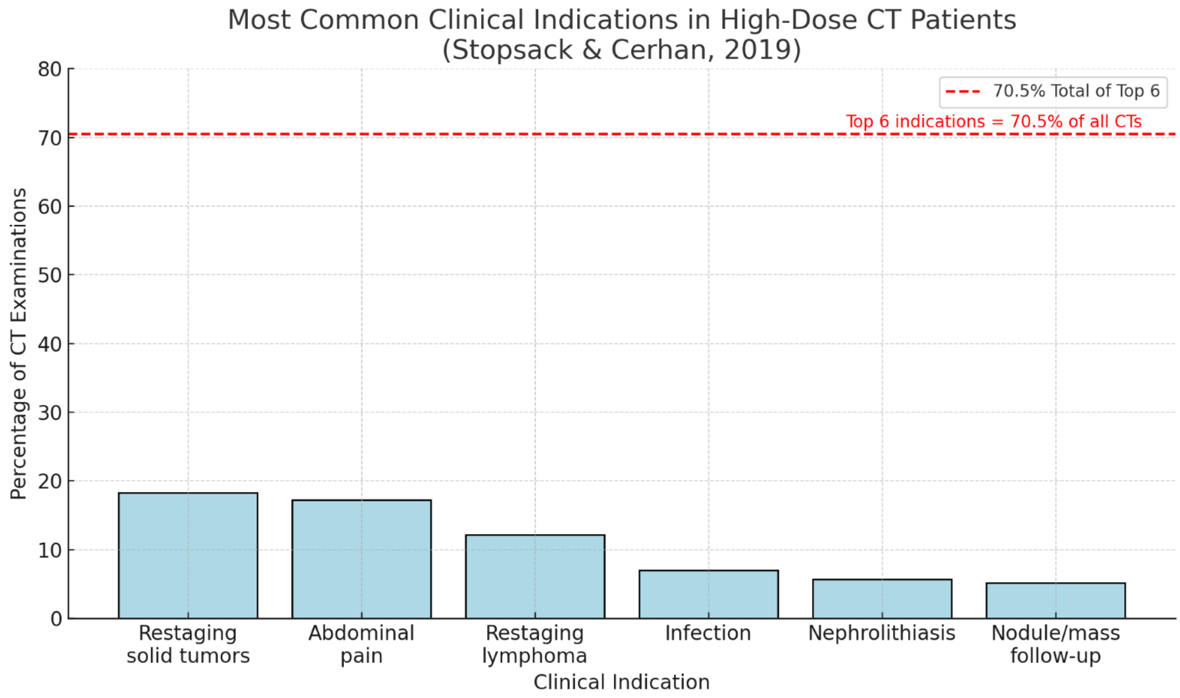

Figure 2. Distribution of clinical indications for CT imaging among patients with cumulative effective dose ≥ 100 mSv sourced and adapted from [10]

Another medical trend was articulated by Howard et al. (2019), who looked into the radiation exposure of 2,394 polytrauma patients that were admitted to a major UK trauma hospital [11]. In the subgroup of 115 persons who exceeded CED of 100 mSv, the main causes of injury comprised traffic accidents (53.8%), falls from height (19.7%), crush injuries (12.0%), and stabbings (3.4%). These acute presentations often involve the activation of pan- trauma protocols leading to multi-slice CT imaging, a method that is typically performed over time and often changed to reflect the development of clinical findings. The study made clear that damaging injury patterns create a demand for extensive imaging that should be performed especially in the early stages of patient treatment.

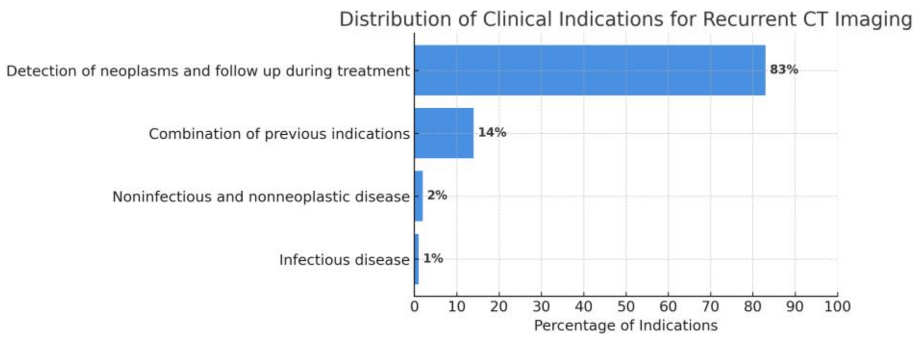

Figure 3. Repeated CT scans among these patients may be divided into patient groups based on the diagnoses and indications of repeated CT scans. sourced from [14].

The research conducted by Gricienė et al. (2023) not only provided the evidence of oncologic diseases being the most common indication for CT examination but also exposed the risk of patients being subjected to recurrent CT examination due to their original health conditions. The authors reported on a sample of 5,060 patients with two or more CT scanned out of the 30,313 adult patients scanned at the medical centre in the period of 2019-2022. Among the patients involved in the study, 83% were offered more CT scans mainly for follow-up of oncologic diseases, like gastric, prostate, and sarcoma, and also for post-treatment surveillance. The most extreme dose received was 637.9 mSv, which was registered for a gastric cancer patient who had 13 scans. On the other hand, lower yearly doses were seen in repeat scanning of multiple myeloma, supporting the routine use of low-dose whole-body CT, and for fungal and pulmonary infections [14].

Indrakanti et al. (2022), who studied 6,831 PET/CT scans in 1,428 patients who underwent multiple ^18F-FDG PET/CT examinations in a two-year period [6]. Even though PET/CT is a hybrid imaging modality, the CT part is still clinically beneficial and dosimetrically influential. The authors discovered that the patients who receive high radiation exposure are mainly those who have the scanning series for the following malignant tumours: melanoma, non-Hodgkin lymphoma, gastrointestinal cancers, breast cancer, and Hodgkin lymphoma. These results additionally confirm that the long-term follow-up of cancer and restaging examinations play a significant role in the patient's overall imaging exposure.

It has been observed that even if only three studies have given explicit data on imaging indications, they have been converging to a permanent conclusion: the most commonly recurrent imaging in high-dose patients is committed to oncologic surveillance, trauma evaluation, and chronic disease monitoring. This shows the importance of having specific imaging protocols and justification practices for these patients. Furthermore, it is worth mentioning that they sent a message saying that the full range of health care must be the target of dose optimization strategies beyond just the inpatient frame as outpatient and emergency settings represent the larger part of imaging runs according to Stopsack and Cerhan (2019).

Evaluation of Patient Risk Associated with Recurrent CT Imaging

This section addresses the third objective of the thesis: to evaluate the associated patient risks, including the proportion of individuals exceeding dose thresholds such as 100 mSv. Although cumulative effective dose (CED) alone does not directly quantify clinical harm, several of the included studies incorporated risk models or stratified dose data to assess the likelihood of radiation-induced health effects—particularly cancer and selected non-cancer outcomes. The most comprehensive risk quantification was provided by Martin and Barnard (2022), who applied age- and sex-stratified risk coefficients from ICRP Publication 147 to their cohort of 105,757 CT patients [1]. Using this model, they estimated that exposure to cumulative doses above 100 mSv would result in approximately two additional cancer cases, while the 50–100 mSv subgroup would account for five additional cases, and the 20–50 mSv group for eleven cases. These estimates were derived from a linear no-threshold (LNT) model, with the authors noting that the real-world risk might be lower in some cases due to underlying disease and reduced life expectancy in heavily imaged populations. Importantly, they emphasized that even in the presence of frequent imaging, the overall population-level cancer risk attributable to CT remains low but not negligible.

The earlier study by Martin and Barnard (2021) offered additional detail by analysing organ-specific radiation dose distributions using Radimetrics software [2]. Among their cohort, 9.6% of patients received more than 100 mGy to the brain, and 2.4% exceeded 100 mGy to the heart. These thresholds are of particular interest as they approach or exceed levels associated with early biological effects in non-cancer endpoints. For example, the study referenced existing data on cerebrovascular and cardiovascular outcomes following high-dose diagnostic imaging, highlighting that some patients in their dataset likely fall into at-risk categories for such effects. One patient even received a heart dose of over 600 mGy, indicating a level of cumulative exposure that warrants attention under deterministic risk frameworks.

In a different patient population, Howard et al. (2019) retrospectively evaluated 2,394 trauma patients and reported that 115 individuals (4.8%) received a CED ≥ 100 mSv within the first year after injury [11]. Although this study did not calculate individual cancer probabilities, the authors used ICRP risk models to estimate that radiation from trauma imaging could contribute to a mean additional lifetime fatal cancer risk of 3.56% in the high-dose subgroup. They concluded that the long-term cancer risk, while not the most immediate concern in trauma care, is sufficiently relevant to warrant dose optimization, especially in younger patients with high survival probabilities.

Stopsack and Cerhan (2019) stratified their 54,447-patient population into five cumulative dose brackets: 0 mSv, 0.1–9.9 mSv, 10–24.9 mSv, 25–99.9 mSv, and ≥100 mSv [10]. While the study did not explicitly estimate cancer risk, the structured dose bands facilitate indirect modelling using ICRP coefficients. Notably, 13.8% of patients in their study fell into the 25–99.9 mSv category, indicating that a substantial portion of patients receive cumulative doses within the "intermediate-risk" range—often overlooked when attention is focused solely on the 100 mSv threshold.

By contrast, none of the three Brambilla studies ([3–5]) included in this review directly estimated health risks such as cancer incidence or deterministic effects. Their focus was primarily on dose quantification, incidence-based reference levels, and inter-hospital variation. However, by identifying high-dose subpopulations and standardizing incidence metrics like I100;3 and I100;5, these studies provide the necessary infrastructure for future risk modelling.

Taken together, these findings confirm that a quantifiable subset of patients undergoing recurrent CT imaging accumulate radiation doses consistent with thresholds associated with elevated cancer risk. Furthermore, a smaller but not insignificant number of patients also approach or exceed dose levels relevant for deterministic effects such as cardiovascular or cerebrovascular complications. These results support the ongoing use of cumulative dose surveillance and risk stratification tools in radiological practice, particularly in settings involving chronic illness, trauma care, or oncology follow-up.

5 DISCUSSION

5.1 Interpretation of Cumulative Exposure and Clinical Drivers

A comparative observation of the existing studies offers the departure point for the thesis wherein it is presented that the cumulative effective dose (CED) from repeated CT imaging encompasses a considerable amount of dose variation, both in and between patient cohorts. The differences in clinical need, imaging protocols, and delivery systems are responsible for such a wide range of doses. Most CT-imaged patients experience a gradual accumulation of low doses, but a small but consistently measurable subgroup exceeds clinically significant thresholds. In the 15 studies included in this thesis, the percentage of patients receiving a CED ≥ 100 mSv fluctuated between 0.65% and 6.7%, with the highest individual cases reaching up to 1,185 mSv in some instances [3, 4, 5, 9, 10, 14]. The evidence of very high cumulative doses being reached, even though it is infrequent and not associated with specific institutions or geographical locations but is a general property of the use of imaging in health care.

There was no chance of random variation in the prevalence of high doses but differences in the implementation of institutional practice, imaging protocol, and clinical population were the reasons. As an example, the multi-centre study done in Italy by Brambilla et al. discovered I100;3 values (the number of patients reaching ≥100 mSv within three years) varied between 1.1% and 11.4% in nine hospitals respectively [4]. Likewise, the overall Slovakian national data presented a huge institutional variability where I100;5 (the five-year high dose incidence) fluctuate between 0.3% to 36.9% [5]. The observed differences were more pronounced in made definitions of recurrent exposure and in the used common methodologies, indicating that the achieved outcomes were heavily reliant on local imaging practices, referral styles, and dose optimization policies within the institution.

Referring to the absolute dose levels, among the high-dose cohort, the median CED ranged between 125.5 mSv and 146.9 mSv in the multinational Rehani et al. study depending on the corresponding institution [9], while the median number of CT exams per high-dose patient was between 6 to 19, although patients who were found to be receiving as many as 109 CT scans were classified as outliers [9]. The population study from the US by Stopsack and Cerhan also identified a small independent subgroup (1.9%) with getting up to ≥100 mSv based on the ten-year imaging history and reported a median dose of 14.0 mSv through all patients who were subjected to at least one CT [10]. This case shows that the repeated imaging procedures can create significant distortion in the averages of the population level.

The studies that were focused on the frequency of causes for repeated imaging and the raising of cumulative exposure gave an account of a limited number of the clinical indications responsible for most high-dose cases. The most evident trend was disclosed in oncology. Patients who had got restaging or surveillance for malignancies, particularly concerning solid tumours, lymphomas, melanoma, and gastrointestinal cancers, accounted for the main population in studies like these by Stopsack and Cerhan [10], Gricienė et al. [14], and Indrakanti et al. [6]. In the last one, it was stated that over 12% of PET/CT patients exceeded the 100 mSv threshold within the two-year period, and most of them were under surveillance for their oncologic diseases [6]. Gricienė et al. found that 83% of recurrent CT patients were imaged for cancer follow-up, with a maximum individual dose of 637.9 mSv accumulated across 13 exams for gastric cancer [14]. These results back up the claim that the cumulative exposure in oncology is not an artifact of high use but the actual clinical need prevailing in patients with long-term treatment. However, the amount of the detected doses also illustrates the importance of the improvement of the process in each stage of the surveillance of the disease.

Another frequently cited contributor was the management of acute trauma, particularly in individuals with multiple traumata. According to Howard et al., a significant proportion (4.8%) of trauma victims in one UK major trauma centre accumulated radiation doses of 100 mSv and above in just the first year, with traffic accidents (53.8%), falls from height (19.7%), and crush injuries (12.0%) being the responsible factors [11]. The excessive number of imaging procedures in this subpopulation is indicative not just of the high number of seriously injured patients but also of their need for rapid imaging techniques addressing a broad spectrum of vital organ systems. In spite of the fact that the majority of these exposures occurred in the acute period, the total effect can still surpass stochastic thresholds when additional follow-up imaging is done.

Other reasons for the high cumulative doses were abdominal pain and suspect infection, along with follow-up of nephrolithiasis having indeterminate masses, especially in conditions like high-frequency settings such as emergency departments. In the Stopsack and Cerhan cohort, the case was high-dose imaging patients primarily (93%) receiving outpatient or emergency imaging with excess doses making it clear that it is not just hospitalization which brings dose accumulation [10]. The insight of this data will have a considerable impact on the strategy of dose management: the protocol for justifications often points at the requests for inpatient imaging, while the findings show that the surveillance of dose tools must be also part of the workflows in the emergency and outpatient sectors, where the cumulative burden can be introduced discretely.

Therefore, the recurrent CT usage pattern that leads to high cumulative doses is not random neither is it just due to over-imaging. Instead, it is treating the structured needs of oncology, trauma, and selected chronic cases, generally in a more extended time period and in multiple locations through time. The disparities seen among institutions and nations argue that not only is optimization possible but also is it required, and that there is an integrated reporting system which, if implemented, could aid the reduction of unwarranted variation without interference in the diagnostic efficaciousness.

5.2 Patient Risk and Dose Thresholds

One key query that has been the main theme of this thesis is whether the cumulative exposure resulting from a recurrent CT imaging poses a quantifiable risk to the patient. The reviewed studies have provided not only the modelling-based evidence but also the consistent proof that very high cumulative doses imply a probability of stochastic effects that must be taken into consideration, particularly radiation-induced cancer. Although the deterministic effects like lens opacities or skin injury are typically referred to with respect to a single-event exposure, the major concern of recurrent diagnostic imaging in this case is the accumulated likelihood of the induction of cancer, especially in young patients or patients with long-term survival prognosis.

Some studies used the formal dose-risk models to explore imaginary potential harm. For instance, Martin and Barnard [1] specified and applied sex-and age-stratified coefficients from ICRP Publication 147 to the analysis of a cohort of over 100000 patients. Their projections indicated that approximately two extra cancers would arise among patients exposed to >100 mSv, out of which another five cases would be found among those exposed to 50-100 mSv; they even estimated eleven cases for the doses in the range of 20-50 mSv. Their conclusion was that significant risk could arise from even intermediate dose levels when extrapolated in the large population [1].

The additional modelling data include a trauma-focused study by Howard et al. [11], who evaluated CT imaging in 2,394 polytrauma patients. Out of the subgroup with CED ≥ 100 mSv, the estimated lifetime risk of having fatal cancer due to medical imaging was 3.56%. These patients were rather young, with a generally high baseline life expectancy, and therefore, they were especially susceptible to the induction of radiation-induced stochastic effects. The authors have made their point about concerning imaging doses in the trauma survivors, especially those subjects who have been followed up by means of repeated scans during the follow-up [11].

To demonstrate the analysis granularity Griciené et al. [14] have applied the U.S. National Cancer Institute's RadRAT tool to 103 high-dose patients. The results indicated that the lifetime attributable risk (LAR) values showed a broad range of 0.02% to 9.2%, the choice of which was dependent on patient age, sex, and scan location. Young women were particularly subjected to the risk of organ radiosensitivity and longer latency times, as a result, they were found to be at greater risk. This shows that the cumulative dose alone without demographic and anatomical background information is not enough when assessing the risks at the level of the patient [14].

Importantly, finding all those risk projections are just model-based estimates and not clinically verified outcomes. The long-term epidemiological data for CT-induced cancer are still limited because of the latency period of most solid tumours and the frequent lack of survival among patients subjected to repeated imaging-especially in oncology. However, these models still provide constructive grounds for identifying the profiles of patients at higher risk, and for altering the imaging protocols applying the available methods of protection [1, 10, 11, 14, 15].

The references such as 50 mSv and 100 mSv have risen to the level of standard markers in radiation protection literature. The 100 mSv figure is especially common and is frequently used by ICRP and various national health authorities as the point beyond which, the epidemiologically detectable increases in cancer incidence become measurable. This figure has been employed as a stratification element in many studies, such as the Stopsack and Cerhan [10] and the Rehani et al. [9] studies. In the latter, 1.33% of patients from four major institutions were found to exceed 100 mSv, and this small cohort absorbed a disproportionately large share of total cumulative dose [9].

However, even though most people have CT imaging below the actual risk threshold, a small group of the patients will be above the levels where there is a tangible risk of radiation-related malignancy. The studies' findings show the advantages of using the modelling-based risk assessment tools for the determination of the vulnerable patient population and reaffirm the importance of employing dose tracking systems which can alert the clinicians timely if the cumulative exposure comes close to or even exceeds the described thresholds.

5.3 Methodological and Data Limitations

While the included studies provide valuable insights into recurrent CT imaging's cumulative radiation exposure, several methodological limitations need to be recognized. These limitations affect both the interpretation of findings and their generalizability to broader clinical or policy contexts.

A major difficulty is the retrospective design of nearly all the articles included in this assessment. The majority of the information was extracted from radiology information systems, dose management platforms, or administrative databases that already exist. Although this gives room for broad sample sizes, it tends to be counterproductive when the researchers cannot control confounding variables and might miss important clinical details. For example, gender and age were the only demographic variables available for many studies, while only a few gave details on imaging indications or clinical outcomes.

The diversity in dose estimation methods is another major issue. Although most studies relied on dose-length product (DLP) and applied standardised conversion coefficients to estimate effective dose (e.g., 0.017 mSv/mGy·cm for body CT), there were significant distinctions in how the dose was calculated and reported. Some institutions had the opportunity to work with advancing software tracking systems such as Radimetrics® [1, 2, 4, 5, 14], while others were only able to use estimated values or average conversion factors without directly measuring scan parameters. As a result, this variability makes it difficult to achieve certainty when comparing cumulative dose values between studies, mainly when the studies are diversely stratified by 50 or 100 mSv.

On top of that, the lack of standardization in cumulative dose reporting is responsible for the cross-study comparison being an insurmountable challenge. In some studies, the total effective dose is given directly in mSv; while some others are only DLP or suggest institutional metrics such as I100;1 (the one-year incidence of patients exceeding 100 mSv) or I100;3 (the three-year incidence). For instance, Brambilla et al. [4] defined dose accumulation in I100-based metrics, while Stopsack and Cerhan [10] used classical stratification bands. Even though their methods are both justifiable, they cannot be compared directly.

A related difficulty is the inconsistent incorporation of organ-specific dose information. Though some studies—especially Martin and Barnard [2] and Griciené et al. [14]—specified doses to the brain, heart, lens, or breast, the majority, however, reported only the total body CED. This simplification makes it impossible to deeper understand the tissue-specific risks which might be more significant than whole-body dose in the determination of some specific stochastic effects like breast or thyroid cancer.

Another methodological complication is the underreporting of imaging indication data. Despite having great clinical implications concerning the efforts to clinicians in understanding the reasons for radiological investigations, only a minority of the studies—namely Stopsack and Cerhan [10], Indrakanti et al. [6], and Griciené et al. [14]—provided a structured breakdown of indications. In several datasets, the repeat scans were noted, and the dose was recorded, but the clinical justification was missing. This makes it very hard to tell if the high-dose imaging (i.e., cancer restaging) was necessary or if it was the case that the repetition was potentially avoidable.

Also worth noting is the absence of prospective or longitudinal outcome data. Even though many studies adopted predictive risk models like LNT-based cancer risk coefficients or the RadRAT platform [1, 11, 14, 15], none of them provided observational follow-up which could confirm or refute these predictions. Therefore, all the findings about risk factors are only hypothetical. This gap is especially relevant given that latency periods for radiation-induced malignancy often exceed 10–20 years, which falls outside the design of most retrospective analyses.

The vast geographic and institutional inclusion of the studies can be seen as a potential weakness since it also entails a variety of healthcare practices. The research conducted in the rich countries with advanced imaging technology (for example, the United States, United Kingdom, Italy, Slovakia) could not have been generalized to the countries that have dissimilar imaging facility referral criteria, access to imaging, or radiation safety protocols.

To sum up, while the research papers considered in this thesis provide valuable data to the risks associated with cumulative dose accumulation, their findings can only be interpreted under some methodological limitations. Their limitations include being retrospective, lack of consistent dose estimation techniques, limited clinical detail, reliance on modelled risk, and underrepresentation of long-term outcomes.

6 CONCLUSIONS

1. Patients undergoing recurrent CT imaging are exposed to a wide range of cumulative radiation doses. Several studies revealed that a significant proportion of individuals reach or exceed high-dose thresholds such as 100 mSv
2. The most frequent clinical indications associated with high cumulative CT exposure are oncologic surveillance, trauma evaluation, and chronic disease monitoring
3. Modelling data from multiple studies show that patients exceeding 100 mSv cumulative dose face a quantifiable increase in lifetime attributable cancer risk

7 RECOMMENDATIONS

Drawing from the conclusions of this work, a great number of ideas can be put forward to the matter of improving the radiation safety, the performance of the clinician, and the future research on the cumulative exposure arising from repeated CT scans. The suggested actions are in sync with the previously identified requirement of the better dose monitoring, the stronger justification frameworks, and the further standardization in practice both and research.

Initially, the clinical institutions should put into practice the formal dose tracking systems, which have the capability of monitoring the cumulative effective dose (CED) at the patient level. Platforms like Radimetrics® or the similar software should be mainly involved into this process and be auto preset into radiology departments each month along the way to flag patients who are in the risk area or have overcome the limits, of course, the 50 mSv and the 100 mSv ones. The above change would provide a chance for the radiologists and referring physicians to consider all factors in their decisions about follow-up imaging, especially in long-term care situations.

At the same time, the justification protocols for the recurrent imaging should be pushed further. Every CT examination must be clinically warranted, nevertheless, both particular attentions must be given to imaging that is repeated frequently, especially in outpatient or emergency settings where cumulative burden often is left unnoticed. The radiology departments must portray together with clinical teams the reasons for imaging and think about using non-ionising methods (e.g., MRI or ultrasound) when they are appropriate for diagnostics.

The clinical oncology and trauma are the high-risk clinical areas where the specific optimisation strategies must also be made. A general observation about referring these specialties is that they play with high levels of cumulative exposure in the studies along the way. Diagnostic reference levels (DRLs) specific to indications along with protocols aimed at dose reduction without hampering diagnosis should be considered by the institutions. If the situation allows it, the use of low-dose CT protocols for screening imaging should be considered.

For the practical implementation, it is necessary to provide specifically timed education missions on the risks of total body radiation. Interventional physicians, radiologists and technologists should periodically receive training regarding the interpretation of cumulative dose metrics, threshold of detecting hazards and the application of dose-efficient imaging strategies. Concerning the health issues, the patients who are exposed to the most radiation should also be enlightened on the importance and risks of follow-up imaging. The full disclosure about the total exposure and the causes for the repeated scans will lead to a mutual agreement in the making of decision concerning the curative and supportive care interventions.

The research and policy aspects that will be addressed in the future should particularly deal with putting an end to the current evidence gaps. There are long-term studies needed to be done on the many cases faced by the high-dose patients and also a lack of research these days needs to be covered. Most of the existing risk data are from models e.g. LNT or RadRAT and appropriate validation would come from the cohort studies. For the moment, the clinical studies that are being conducted on CT imaging need to report on cumulative dose values consistently, use the same units, dose bands (e.g., <50 mSv, <50–100 mSv, ≥100 mSv) and follow-up periods. The standardisation of terminology would help in the achievement of a common base and thus would allow for the comparison and the meta-analytical synthesis of risk data.

In the final instance, both the national and the international health authorities have to put efforts into the establishment and the maintenance of cumulative dose benchmarks in the healthcare system. I100;1 (one-year incidence of patients exceeding 100 mSv) and I100;3 (three-year incidence) are two of such efforts which are being used as indicators at present in multicentre operations and should be introduced as national quality standards. It will be good, therefore, that an action which will contribute to dose optimization and at the same time will be used in health technology assessments and setting the grounds for investment in tracking infrastructures.

To summarize, the evidence provided in the paper supports a multi-dimensional plan: installing the cumulative dose tracking in clinical practice, getting imaging justification improved, tuning up the protocols in high-risk groups, going deeper into research into the issues related to dose, and having strong, national monitoring frameworks. The recommendations, in their turn, are meant to reduce the risks associated with the patients while allowing them to keep the diagnostic information at the normative level for successful medical treatment.

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