Review Article

Radiation Exposure in Computed Tomography

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Summary

Background: Computed tomography (CT) studies are requested by specialists from most medical disciplines and play a vital role in the diagnosis and treatment of patients. It follows that physicians of all specialties should possess basic knowledge of computed tomography, its proper use, and the radiation exposure associated with it.

Methods: This review is based on publications retrieved by a selective search of the literature.

Results: Approximately 12 million CT studies are carried out in Germany each year, and the trend is rising. Approximately 9% of all diagnostic studies involving ionizing radiation are CT studies. On average, more than 60% of the collective effective dose due to medical radiation exposure is attributable to CT. There are two types of radiation effects caused by ionizing radiation: stochastic and deterministic. The additional, individual relative lifetime cancer mortality risk due to ionizing radiation with whole-body exposure at a low single dose is estimated at 5% per sievert. Radiation exposure from CT studies of the head and trunk, e.g. of a patient with polytrauma, corresponds to an additional lifetime cancer mortality risk of approximately 0.1% at an effective dose of approximately 20 millisievert.

Conclusion: The radiation exposure due to CT, and the risks to which patients are subjected by it, have become more important with greater use of CT. Technical advances, targeted dose monitoring, and analyses of dose data can help identify areas where improvement is necessary, in furtherance of the overriding goal of lowering patients' radiation exposure while preserving adequate image quality.

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As an imaging modality, computed tomography (CT) has become an indispensable part of everyday clinical practice. CT offers sub-millimeter cross-sectional imaging of a region of the body, high-resolution multi-planar reconstruction (MPR) and three-dimensional volume-rendering techniques (VRT), thus allowing for complete, seamless imaging of the anatomy. The basic principle of computed tomography is to perform axial scanning of the object under examination, using a tightly collimated, fan-shaped X-ray beam (1). The first CT scanner was developed by Godfrey Hounsfield and produced by EMI in 1971. Today, multislice (multidetector) CT scanners with continuous tube-detector rotation and continuous patient table motion through the gantry are used almost exclusively (2). Images are displayed in gray levels, with attenuation values in a volume unit represented by CT numbers in Hounsfield units (HU). Since only a certain number of gray levels can be differentiated by the human eye, the image detail is reduced to fewer gray levels by windowing, resulting in enhanced contrast.

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Effects of radiation and explanation of dose terms

Deterministic radiation effects are distinguished from stochastic effects. Deterministic radiation damage results from massive cell death and the associated loss of function—especially in skin and hair—when a certain dose threshold is exceeded. This type of damage does not usually occur with computed tomography. Stochastic radiation damage is caused by DNA alterations in radiation-exposed cells and occurs only with a certain probability (e.g., cancer). The probability of

BOX 1

Dose parameters of computed tomography (CT)

- **Volume CT dose index ($CTDI_{vol}$ in mGy)**
  - Describes the mean radiation exposure within a collimated CT slice (3).
- **Dose-length product (DLP in mGy × cm)**
  - Product of $CTDI_{vol}$ and the length of the scan in cm.
  - Describes the total radiation exposure in the examined area.
- **Effective dose (in mSv)**
  - Takes into account the type of radiation and the different sensitivity of different organs to ionizing radiation.
  - The effective dose is calculated by multiplying the empirically determined conversion factors for specific regions of the body by the DLP (4).
  - Alternatively, dose-monitoring algorithms based on Monte-Carlo simulations can be used for a more precise calculation of the effective dose.
  - This approach permits a better stochastic extrapolation of the risk to individuals (5).

occurrence is dose-dependent. By contrast, the severity of the damage (e.g., the severity of the cancer) is independent of the dose. Furthermore, unlike with deterministic radiation damage, there is no threshold dose.

Knowledge of dose parameters is important for evaluating radiation exposure during computed tomography examinations. These measures include the volume CT dose index ($CTDI_{vol}$), the dose-length product (DLP) and the effective dose (*Box 1*).

In the wake of the dropping of atomic bombs on Hiroshima and Nagasaki, an extrapolation of the risk of radiation-induced malignancy was performed. However, multiple factors (e.g., age) contribute to the development of cancer. The hematopoietic system as well as the hollow and solid organs of children and adolescents are more sensitive to ionizing radiation compared to those of adults.

CT-related exposure to radiation in Germany

In 2016, approximately 137 million X-ray applications were performed in Germany (excluding dentistry, almost 78 million), including approximately 12 million CT examination (9%) (6). The latest annual Report on Environmental Radioactivity and Radiation Exposure of the German Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection (BMUV, Bundesministeriums für Umwelt, Naturschutz, nukleare Sicherheit und Verbraucherschutz) identified computed tomography as the main contributor (approximately 67%) to the annual collective effective dose from artificial radiation in the German population that amounted to 1.6 mSv per inhabitant in 2016 (6, 7).Over a nine-year period from 2007 to 2016, a steady increase in the mean effective dose per inhabitant was observed, which was largely due to the increased numbers of CT examinations (6, 7). In the period from 2007 to 2014, this translated into an increase from 1.4 mSv to 1.6 mSv (8). While the number of CT studies is continuously increasing, the radiation exposure from a single CT study is decreasing thanks to technical advances. In their study on CT practice in Germany, Schegerer et al. found for 11% of all medical CT scanners operated in 2013/2014 that the effective dose per CT examination was reduced by about 15% compared to the CT practice prior to 2010 (in 2013/2014: 4.6/5.9 mSv per scan/examination) (9).

Diagnostic reference levels in computed tomography

The German Federal Office for Radiation Protection (BfS, Bundesamt für Strahlenschutz) issues diagnostic reference levels for diagnostic and interventional X-ray examinations on a regular basis, the observance of and compliance with which is periodically reviewed by the so-called “Ärztliche Stellen“ (Medical Authorities) (10, 11). The establishment of the diagnostic reference levels is based on large amounts of data of patient exposures for different CT examinations, which are provided by the above-mentioned Medical Authorities, among others. The diagnostic reference levels are based on the 75th percentile of the distribution of the respective exposure. For this reason, diagnostic reference levels do not serve as threshold values, but as guideline values, enabling comparisons of radiation exposure recorded for different scanners and sites. Diagnostic reference levels are not to be used for the individual CT examination. Rather, the mean values for the respective CT examinations are key and should not be routinely exceeded over a given period of time. The most recent update of the Diagnostic Reference Levels for Diagnostic and Interventional X-Ray Procedures was published in November 2022 (10).

Dose monitoring in routine clinical practice

As a general rule, any use of computed tomography requires a review of the justifying indication by a physician with expertise in computed tomography. Here, the rigorous review of indications for CT examinations is one of the most important measures for dose reduction. The radiologist is responsible for establishing the strict justifying indication for the CT study. This is done in close consultation with the referring physician during which the clinically relevant question to be answered is also discussed.

In routine clinical practice, CTDIvol and DLP per scan series are automatically documented with each CT examination. By analyzing the acquired dose data, so-called local diagnostic reference levels can also be determined within a hospital or hospital group. In this context, an in-hospital automatic dose recording system is useful, which several commercial suppliers now offer. By monitoring, it is possible to identify outliers of radiation exposure and to respond to them in an appropriate manner. Today, with the newer generations of CT scanners, it is possible to simulate radiation exposure prior to the actual scan and respond to preset dose alarms (12). Our own experience with a

TABLE 1

Means of the dose parameters $CTDI_{vol}$, DLP and effective dose for a selection of common CT examinations in Germany, based on a national survey (adapted from [9])*

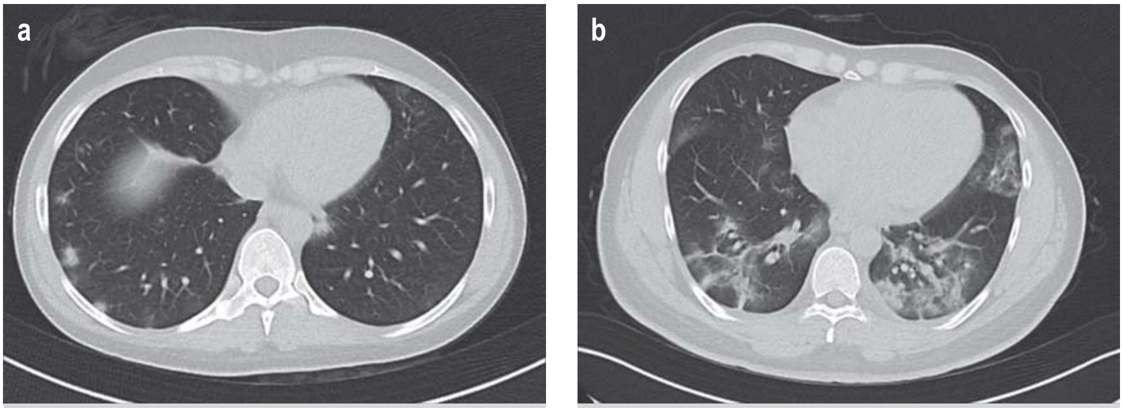
CT protocol	$CTDI_{vol}$ (mGy)	DLP (mGy × cm)	Effective dose (mSv)
Cranium	53	740	1.6
Sinus	9	114	0.3
Carotid CTA	14	487	4,8
Neck	13	312	3.3
Chest	12	279	5.1
Pulmonary angiography	12	240	4.3
Chest low dose	2.6	87.9	1.7
Trunk (chest + abdomen)	11	686	11
Upper abdomen	11	251	4.8
Abdomen	11	496	7.9
Complete aorta	10	641	10
Lumbar spine bone	19	347	6.5
Calcium scoring	5.8	90.3	1.9
Prospective ECG-triggered coronary CTA	19	270	5.7
Polytrauma – head	64	1 105	4.6
Polytrauma – trunk	14	1 037	15

* Most CT scanners had detectors with 16 (32.4%) or 64 (26.7%) rows.
A minority of scanners had less than 16 detector rows, 20 to 40 detector rows or more than 64 detector rows (16.9%, 19.3% and 4.7%, respectively) (9).
CT, computed tomography; CTA, computed tomography angiography; $CTDI_{vol}$, volume CT dose index; DLP, dose-length product

commercially available dose acquisition system showed that using a specially trained “dose team”, CT protocol harmonization and an alarm function when the reference level was exceeded, a partly significant reduction in radiation dose was achieved without compromising image quality (13). This was primarily achieved by optimizing CT examination protocols (including patient positioning, centering, gantry tilting, adjustment of kV and mAs, scan length), maximizing utilization of the scanner‘s native dose-saving mechanisms (tube current modulation), and limiting CT series.

Common CT examinations and associated radiation exposures

The German Federal Office for Radiation Protection (BfS) publishes diagnostic reference levels for specific CT studies (10). These values can be used to estimate the radiation exposure associated with CT examinations performed in Germany. In a survey on the German CT practice, dose values ($CTDI_{vol}$, DLP) were obtained for 34 standard CT examinations for various percentiles (9). Effective doses were determined using the corresponding tissue-weighting factors (5). The mean effective doses were 4.6 mSv and 5.9 mSv for a scan series and a complete examination, respectively. To help get a better understanding of radiation exposure, *Table 1* provides an overview of the effective doses of selected CT studies (9). For the most common CT examinations, effective doses of 1.6 mSv (neurocranium), 5.1 mSv (chest, including adrenal glands) and 7.9 mSv (abdomen) are stated. Strikingly, there is considerable variability in the estimated effective doses of the various CT protocols between different institutes and hospitals in Germany. Generally, it is advisable to establish local diagnostic reference levels that reflect the dose distribution in the respective institute or hospital (13). Of course, the patient population, the imaging equipment and the range of examinations performed differ considerably between the various institutes and hospitals, and this has a relevant effect on dose values. Thus, it is possible to establish local diagnostic reference levels for CT studies that are rare overall, but frequently performed in the respective institute, and to publish them as a benchmark for comparison (14, 15). For a better understanding, it is useful to compare the radiation exposure of computed tomography with natural radiation sources, such as cosmic radiation. The calculated effective doses vary slightly due to the solar cycle and differences in flight altitudes. For a transatlantic flight from Frankfurt to New York City or Munich to Tokyo, an exposure of 0.01 mSv from cosmic radiation is assumed (16). In comparison, the mean exposure associated with a standardized CT scan is in the range of 3 to 7 mSv; however, it can be significantly higher, depending on the CT protocol and the complexity of the examination (*Table 1*).



Patient 1: Chest CT; low-dose protocol, non-contrast
100 kV, 45 mAs/37 reference mAs
Dose-length product (DLP) of 61 mGy × cm
Effective dose of 1.6 mSv

Patient 2: Chest CT; standard protocol, non-contrast
100 kV, 95 mAs/60 reference mAs
Dose-length product (DLP) of 120 mGy × cm
Effective dose of 3.2 mSv

Figure: Two axial images of a non-contrast chest computed tomography (CT) scan to rule out inflammatory infiltrates using a low-dose protocol (a) and a standard dose protocol (b) with twice the dose. The effective dose was calculated using the conversion factor of Shrimpton et al. (2016) (23). Despite the differences in image quality and radiation dose, the diagnostic significance remains the same for the two CT studies, as both allow detection of atypical inflammatory infiltrates in the lower lobes.

International comparison

Data of an international dose registry with more than 2 million analyzed CT studies from seven countries and a total of 151 contributing institutions showed considerable variation of effective doses when countries were compared (17). So, for example, effective doses for standard CT examinations, such as the pulmonary embolism scan, were up to 15-fold higher in some countries than in others while using the same type of scanner. The reason for variations in CT scan doses observed across countries and institutes appears to be primarily related to differences in the handling of CT scanners rather than patient-specific or institutional or manufacturer-specific differences (17, 18). International comparisons between European and US institutes showed significantly lower radiation doses for the most common CT indications for 9 of 10 indications at European institutes and hospitals (18).

Dose reduction strategies

The preceding sections have shown that there is a striking variation in CT dose distribution across different institutes and countries (9, 17). Some institutes and hospitals can answer the same diagnostic question with a significantly lower radiation dose compared to others. In order to optimize the radiation dose while achieving satisfactory image quality, it is key to select the proper CT protocol for the right and specific diagnostic question (*Figure*). Modern CT scanners feature detectors with high detective quantum efficiency (DQE) and advanced filter technologies. In addition, there are effective dose reconstruction mechanisms, such as automatic tube current modulation and tube voltage modulation, tube current modulation when scanning particularly sensitive organs, and iterative or deep learning-based reconstruction algorithms. By leveraging these mechanisms, as well as using state-of-the-art scanners, it is possible to keep the radiation dose well below the diagnostic reference levels (14, 19–21). The computed tomography-related increase in collective effective dose is less than what would have been expected from the increase in the number of CT examinations performed (6, 8). In the period from 2007 to 2014, the number of CT studies in Germany had increased by about 40%, but the collective effective dose had increased by only about 30% (8). This is best explained by the above mentioned equipment-integrated radiation protection measures featured by modern CT scanners. But even simple measures can help to lower the dose of a CT study, most notably by reducing the number and length of the CT scan. For specific queries, low-dose and ultra-low-dose protocols can be used, such as:

- Renal colic
- Plasmacytoma status
- Repeated chest CT scans in patients with cystic fibrosis
- Lung cancer screening
- Monitoring of isolated incidental findings in the lungs, such as pulmonary nodules.

When applied in a rational manner, these radiation-sparing CT protocols allow for further significant dose reduction. Even a comparatively simple measure, such as correct patient positioning/centering in the CT scanner, has a direct impact on $CTDI_{vol}$ (22).

The radiologist guarantees the correct technical performance of the CT examination, is responsible for the CT radiation dose and the imaging quality and, via the justifying indication, strongly influences for

TABLE 2

Selection of clinical indications and questions for (alternative) imaging without ionizing radiation*

Anatomical region	Indication/question	Alternative imaging
Cranium	Tumors, metastases, meningeosis carcinomatosa , infectious diseases, stroke in an unclear time window, vascular malformations	MRI
Neck	Lymphadenopathy	MRI, ultrasound
	Tumors, retrotonsillar and parapharyngeal abscess, radiation planning	MRI
Chest	Cystic fibrosis in children, vascular malformations	MRI
Heart	Pericarditis/myocarditis, myocardial fibrosis	MRI
Abdomen	Tumors (especially liver cancers such as HCC and CCC), tumor staging, aortic aneurysm, inflammatory bowel disease such as Crohn's disease, cholestasis, pancreatitis	MRI
	Appendicitis, cholecystitis, cholestasis, diverticulitis, pancreatitis	Ultrasound
Spine/skeleton	Spinal tumors, epidural abscess, epidural hematoma, myelitis, vertebral body fracture, disc herniation, internal derangement of knee	MRI
	Joint effusion	Ultrasound

* Limitations: The selection is based on the authors' many years of clinical experience.
This list is by no means exhaustive and is based on common clinical questions.
CCC, cholangiocellular carcinoma; HCC, hepatocellular carcinoma; MRI, magnetic resonance imaging

which clinical question a CT study is performed. At the same time, the clinician also assumes considerable responsibility. Whether or not a CT study is to be performed is decided by the competent radiologists and the clinicians on a consensus basis. When it comes to requesting the proper imaging study in everyday clinical practice, the guidelines published by the various medical societies are just as helpful as initiatives on radiation protection by radiological societies which help to select the most appropriate examination on a case by case basis. Examples include the ACR Appropriateness Criteria, the Royal College of Radiologists' Referral Guidelines (iRefer) and the ESR iGuide of the European Society of Radiologists (24–26). A selective overview of the common clinical questions which can be addressed using alternative imaging modalities not based on ionizing radiation is provided in *Table 2*.

Furthermore, the checklist in *Box 2* provides an overview of the most important questions to be addressed prior to performing a CT scan. The clinical indication, right CT protocol and correct positioning play a major role in reducing the radiation dose, among other factors.

Radiation risk and significance of computed tomography

Radiation-related cancer only manifests years to decades after exposure and thus can only be identified with the help of statistical methods. The additional, individual relative lifetime cancer mortality risk due to ionizing radiation with whole-body exposure at a low single dose is estimated at 5% per Sievert (5). As a real-world example, one might consider a polytrauma patient after a high-impact trauma who undergoes head/neck, chest and abdominal CT scanning. This imaging study has an average mean effective dose of 19.6 mSv (*Table 1*: 4.6 mSv for a polytrauma cranial CT study and 15 mSv for a polytrauma trunk CT study, based on a national survey published by Schegerer et al. [9]). According to the linear no-threshold (LNT) model for low radiation doses, this corresponds to an additional lifetime cancer mortality risk for the polytrauma patient of about 0.0975% (5).

In this case, it is clear that the benefit of exposure significantly exceeds the risk of additional cancer mortality. Even more so when the so-called mean background risk is taken into account. The background risk—the risk to develop cancer without radiation exposure (incidence risk)—is assumed to be 43%. The lifetime risk varies both with age and sex. For a woman, the lifetime risk is about 38% compared to 47% for men. The mean background risk of cancer death without exposure to ionizing radiation (mortality risk) is reported at 23% (27, 28).

However, the argument of risks potentially associated with CT dose exposure needs to be countered by pointing out that in everyday clinical practice the benefits of computed tomography are far greater in many diagnostic areas, especially in emergency diagnosis, cardiovascular diagnosis, stroke diagnosis, and oncology. In addition, it is helpful to contrast the risks of everyday life against the (potential) carcinogenesis induced by ionizing radiation from medical applications (29). McCollough et al. summarized the lifetime risks of death from a wide variety of causes. For example, approximately 228 out of 1000 persons would die as a result of cancer, approximately 11.9 out of 1000 persons would die as a result of a car accident, approximately 0.2 out of 1000 persons would

BOX 2

Checklist

- **Strategies for reducing radiation dose in computed tomography (CT)**
  - Is CT the right imaging modality?
  - Is there a medically established indication?
  - Is there a specific question?
  - Has the right CT protocol been selected?
  - What image quality is required? Can a low-dose protocol be used?
  - How many scan series are required (e.g., arterial phase or venous phase)?
  - Is it possible to further narrow the area to be imaged?
  - Is the patient positioned in the center of the gantry? Are the arms properly positioned?
  - Have all metallic foreign material (as far as possible) been removed from the patient?
  - Does the scout view image completely cover the area to be imaged?
  - Is the patient able to lie still and follow breathing commands, if necessary? Apply further measures, if necessary!
  - Can otherwise unnecessary repeat examinations be avoided?
  - Is a dose warning or dose exceedance displayed prior to the scan? Is it possible to reduce the radiation dose by changing technical parameters (e.g., tube current or tube voltage)?

die as a result of a bicycle accident, and only approximately 0.5 out of 1000 persons would die as a result of a computed tomography scan with an effective dose of 10 mSv (as an example, a routine abdominal CT scan) (29).

Future trends

Novel photon-counting CT scanners allow immediate quantification of the radiation exposure of each individual patient scanned. In comparison to the currently used CT technology, photon-counting CT scanner provide opportunities to reduce radiation exposure, reconstruct higher resolution images, correct beam-hardening artifacts, and optimize the use of contrast agents for quantitative imaging (30).

Conclusion

Computed tomography is an essential part of everyday clinical practice, in both inpatient and outpatient settings. Being a modality characterized by a relatively high radiation exposure, computed tomography is the main contributor to the collective effective dose of the population per year, and this trend is rising. Although, in accordance with the ALARA ("as low as reasonably achievable") principle, all efforts must be directed toward achieving a reduction in CT radiation dose while maintaining adequate image quality, the benefits of CT imaging in all areas of medicine must not be disregarded. By no means should necessary CT examinations be withheld for the reason of radiation exposure, since the potential benefit of computed tomography is frequently many times greater than the potential radiation risk. Nevertheless, a careful review of the justifying indication should be performed and consideration should be given to the use of alternative imaging modalities, such as ultrasound or magnetic resonance imaging.

Conflict of interest statement
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The remaining authors declare that no conflict of interest exists.

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Questions on the article in issue 9/2023:

Radiation Exposure in Computed Tomography

cme plus+

The submission deadline is 2 March 2024. Only one answer is possible per question. Please select the answer that is most appropriate.

Question 1

How many CT studies are carried out in Germany each year?

a) 700 000
b) 2 000 000
c) 6 000 000
d) 9 000 000
e) 12 000 000

Question 2

What two types of radiation effects are distinguished in the text?

a) Apparent and inapparent
b) Cosmetic and organ damage
c) Deterministic and stochastic
d) Psychological and somatic
e) Reversible and irreversible

Question 3

Which of the following terms is mentioned in the text as a dose parameter for estimating the radiation exposure from a CT scan?

a) Radiation strength product (SSP)
b) Dose-length product (DLP)
c) Dose-length ratio (DLR)
d) Radiation length ratio (RLR)
e) Dose-length sum (DLS)

Question 4

What is the basis for establishing diagnostic reference levels?

a) Data sets of previous CT studies on patients
b) Data from test series of CT studies from the German Federal Office for Radiation Protection (BfS)
c) Data sets from CT studies on dummies
d) Data sets from CT studies on laboratory animals
e) Computer simulations by CT scanner manufacturers

Question 5

Which of the following rankings of CT studies by increasing effective dose is correct according to the publication of the Federal Office for Radiation Protection?

a) Abdomen < chest, including adrenal glands < neurocranium
b) Neurocranium < abdomen < chest, including adrenal glands
c) Chest, including adrenal glands < abdomen < neurocranium
d) Neurocranium < chest, including adrenal glands < abdomen
e) Abdomen < neurocranium < chest, including adrenal glands

Question 6

Approximately how high is the radiation exposure from cosmic radiation during a transatlantic flight (for example from Frankfurt to New York)?

a) 0.01 mSv
b) 1 mSv
c) 7.9 mSv
d) 10 mSv
e) 0.5 Sv

Question 7

Approximately how high is the effective dose from a cranial CT scan?

a) 0.05 mSv
b) 0.7 mSv
c) 1.6 mSv
d) 5.1 mSv
e) 7.9 mSv

Question 8

Approximately how high is the average lifetime risk of cancer for women and men?

a) 38% and 47%, respectively
b) 51% and 35%, respectively
c) 15% and 37%, respectively
d) 45% and 24%, respectively
e) 7% and 32%, respectively

Question 9

Which of the following techniques is mentioned in the text as a mechanism for dose reduction?

a) Vibration positioning
b) Cooling adjustment
c) Tube current modulation
d) Sluice current adjustment
e) Lead vaporization

Question 10

Approximately by what percentage did the number of CT examinations in Germany increase in the period from 2007 to 2014?

a) 5%
b) 10%
c) 25%
d) 40%
e) 70%