Cloud-Based CT Dose Monitoring using the DICOM-Structured Report: Fully Automated Analysis in Regard to National Diagnostic Reference Levels

Cloud-basiertes Monitoring von CT-Dosisdaten mit Hilfe des DICOM-Structured Report: Analyse im Hinblick auf nationale Referenzwerte

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Zusammenfassung

Ziel: Ziel dieser Studie war die Implementierung eines Cloud-basierten CT-Dosismonitorings basierend auf dem DICOM-Structured Report (DICOM-SR) zur automatischen Überwachung der Dosisexposition im Hinblick auf die nationalen diagnostischen Referenzwerte (DRW).

Material und Methoden: Zur automatischen Erfassung und Überwachung der CT-Dosisdaten wurde eine neuartige, in Kooperation mitentwickelte Software basierend auf dem DICOM-SR eingesetzt. Der DICOM-SR aller CT-Untersuchungen unserer Einrichtung zwischen 09/2011 und 03/2015 wurde automatisch anonymisiert und an einen Cloud-Server verschickt. Die Daten wurden automatisch im Hinblick auf die Körperregion, das Patientenalter und den korrespondierenden DRW für den volumetrischen Computertomografie-Dosis-Index ($CTDI_{vol}$) sowie für das Dosis-Längen-Produkt (DLP) analysiert.

Ergebnisse: Datensätze von 36 523 CT-Untersuchungen (131 527 Scanserien) von drei verschiedenen CT-Geräten und einem PET-CT wurden analysiert. Insgesamt betrug der mittlere $CTDI_{vol}$ 51,3 % und das mittlere DLP 52,8 % der nationalen DRW. Bezogen auf die nationalen DRW betrugen $CTDI_{vol}$ und DLP für die Abdomen-CT 43,8 % und 43,1 % (n = 10 590), für die Schädel-CT 66,6 % und 69,6 % (n = 16 098) und für die Thorax-CT 37,8 % and 44,0 % (n = 10 387). Insgesamt überschritten 1,9 % der CT-Untersuchungen den $CTDI_{vol}$ und 2,9 % der Untersuchungen das DLP der nationalen DRW. Zwischen unterschiedlichen CT-Protokollen, die dem gleichen nationalen DRW zugeordnet wurden, variierte die Strahlenexposition um bis zu 50 %.

Schlussfolgerung: Das implementierte, Cloud-basierte CT-Dosismonitoring basierend auf dem DICOM-SR ermöglicht eine automatische, umfassende Benchmarkanalyse im Hinblick auf die nationalen DRW. Insgesamt betrug die Dosisexposi-

Abstract

Purpose: To implement automated CT dose data monitoring using the DICOM-Structured Report (DICOM-SR) in order to monitor dose-related CT data in regard to national diagnostic reference levels (DRLs).

Materials and Methods: We used a novel in-house co-developed software tool based on the DICOM-SR to automatically monitor dose-related data from CT examinations. The DICOM-SR for each CT examination performed between 09/2011 and 03/2015 was automatically anonymized and sent from the CT scanners to a cloud server. Data was automatically analyzed in accordance with body region, patient age and corresponding DRL for volumetric computed tomography dose index ($CTDI_{vol}$) and dose length product (DLP).

Results: Data of 36 523 examinations (131 527 scan series) performed on three different CT scanners and one PET/CT were analyzed. The overall mean $CTDI_{vol}$ and DLP were 51.3 % and 52.8 % of the national DRLs, respectively. $CTDI_{vol}$ and DLP reached 43.8 % and 43.1 % for abdominal CT (n = 10 590), 66.6 % and 69.6 % for cranial CT (n = 16 098) and 37.8 % and 44.0 % for chest CT (n = 10 387) of the compared national DRLs, respectively. Overall, the $CTDI_{vol}$ exceeded national DRLs in 1.9 % of the examinations, while the DLP exceeded national DRLs in 2.9 % of the examinations. Between different CT protocols of the same body region, radiation exposure varied up to 50 % of the DRLs.

Conclusion: The implemented cloud-based CT dose monitoring based on the DICOM-SR enables automated benchmarking in regard to national DRLs. Overall the local dose exposure from CT reached approximately 50 % of these DRLs indicating that DRL actualization as well as protocol-specific DRLs are desirable. The cloud-based approach enables multi-center dose monitoring and offers great potential to further optimize radiation exposure in radiological departments.

tion der CT ungefähr 50 % der DRW bei deutlicher Variabilität zwischen den unterschiedlichen CT-Protokollen. Dies deutet darauf hin, dass eine Aktualisierung der DRW sowie die Implementierung von Protokoll-spezifischen DRW wünschenswert ist. Der Cloud-basierte Ansatz ermöglicht ein Multicenter Dosismonitoring und bietet großes Potential, die Strahlenexposition der CT in radiologischen Abteilungen weiter zu optimieren.

Kernaussagen:

- Die neu entwickelte, cloud-basierte Software nutzt den DICOM-Structured-Report und ermöglicht ein umfassendes CT-Dosismonitoring.
- Die Software ermöglicht eine automatische Auswertung der Dosisdaten im Hinblick auf nationale Referenzwerte.
- Die ermittelte Dosisexposition durch CT-Untersuchungen in dieser Studie lag bei ungefähr 50 % der nationalen Referenzwerte.
- Der Cloud-basierte Ansatz bietet großes Potential für ein Multicenter Dosismonitoring.

Key Points:

- The newly developed software based on the DICOM-Structured Report enables large-scale cloud-based CT dose monitoring
- The implemented software solution enables automated benchmarking in regard to national DRLs
- The local radiation exposure from CT reached approximately 50 % of the national DRLs
- The cloud-based approach offers great potential for multi-center dose analysis.

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Introduction

Besides dose optimization for every single CT scan, dose monitoring as part of quality assurance in modern radiology has gained ever more importance [1]. To evaluate CT radiation exposure, diagnostic reference levels (DRLs) for diagnostic and interventional radiology examinations have been published in many countries [1 – 3]. In CT, these DRLs are usually provided for different body regions such as "head" and "chest" or for specific protocols such as "lung-embolism" or "renal colic" [1, 4].

Systematic analysis of dose-related CT data in regard to the DRLs is an important aspect of quality assurance but requires comprehensive data collection. Different methods to monitor CT dose data have been introduced. Optical character recognition (OCR) can be used to read the dose data from the so-called "patient protocol", which is stored as an image in the Picture Achieving and Communication System (PACS) [5]. Alternatively, the DICOM header can be used to gain these dose-related data from CT [6]. Modern CT scanners provide the Digital Imaging and Communication in Medicine-Structured Report (DICOM-SR) which supplies important dose parameters and allows for straightforward systematic dose monitoring [7, 8]. Recently, different local dose monitoring software solutions have been made commercially available [1, 5, 9] and initial studies reported great potential for dose optimization [1].

To our knowledge, implementation of a dedicated, cloud-based software device for automated benchmarking of CT dose data with respect to DRLs, which enables dose optimization beyond local analysis, has not been reported so far. Therefore, the aim of this study was to implement automated cloud-based dose monitoring which enables surveillance of CT dose exposure in regard to national DRLs.

Methods

Data acquisition

This retrospective study was approved by the local ethics committee.

The DICOM-SR was automatically created by all institutional CT scanners for every examination. The DICOM-SR was then automatically sent to a local gateway server for anonymization and further processing. Anonymization was performed with a self- developed software device, which is part of the novel in-house co-developed software tool DoseIntelligence™ (DoseIntelligence™, Pulmokard GmbH, Herdecke, Germany). The anonymized DICOM-SR datasets were automatically transferred to a cloud server via an encrypted connection and a database was used to store the data on the server (**Fig. 1**).

A cloud-based approach was used because it offers great potential for multicenter dose monitoring and potentially enables dose optimization beyond local environments due to comparison of local data with dose data from other cloud participants or cloud-based DRLs.

National diagnostic reference levels (DRLs)

German national DRLs for CT are provided for different body regions for $CTDI_{vol}$ and DLP. Reference levels are defined by the Federal Office of Radiation Protection according to the 3 rd quartiles of the mean patient exposition evaluated in a large collective. While a CT examination can consist of several scan series (e. g. non-contrast, arterial, venous phase), the reference parameters are defined for every single scan series. There are different DRLs for children (according to their age group) and for adults. The most important national DRLs are listed in **Table 1**.

Protocol matching

In order to compare our dose-related CT data to national DRLs, firm protocol matching is necessary. As the large number of different CT scan protocols in our institution surpasses by far the limited amount of different DRLs based on body regions, various scan protocols have to be assigned to the same reference parameter [4]. In our study, this protocol matching to body regions was performed manually by one radiologist (J.B). Each protocol was assigned to one of the body regions for which national DRLs are provided. If a series could not be matched to a DRL (for example the scout images, any phantom scan or examinations lacking national DRLs like "neck CT"), they were marked as "not to be taken into account".

Comparison of dose-related data to DRLs

$CTDI_{vol}$ and DLP of every scan series were automatically analyzed and compared to the national DRLs (the ratio being expressed in percent) and values were stored in the database. The correspond-

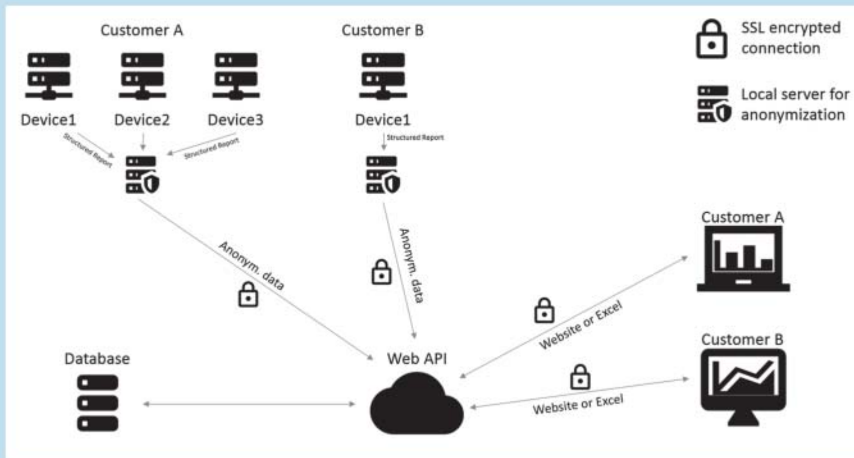

Fig. 1 Structure of automated cloud-based dose monitoring.

Abb. 1 Aufbau des automatischen, Cloud-basierten Dosismonitorings.

Table 1 National DRLs for the six most common body regions [4].

Tab. 1 Die nationalen DRWs für die sechs wichtigsten Untersuchungsregionen [4].

body region	DRL $CTDI_{vol}$ (mGy)	DRL DLP (mGy*cm)
cranial	65	950
chest	12	400
upper abdomen	20	450
abdomen	20	900
pelvis	20	450
lumbar spine (bone)	16	500

The provided $CTDI_{vol}$ values are supposed to be used for orientation.

ing body region for every protocol as well as patient age was automatically considered to assess the correct DRL.

Analysis in regard to body mass index (BMI)

Patient height and weight were manually recorded by the technician prior to the CT study and added to the DICOM-SR via the CT scanner interface. For further data analysis, BMI was calculated automatically and patients were divided into different groups: Underweight: BMI < 18 kg/m²; normal weight: 18 – 25 kg/m²; overweight: 25 – 30 kg/m², obesity I°: 30 – 35 kg/m², obesity II°: 35 – 40 kg/m²; obesity III°: > 40 kg/m².

Data analysis

Data analysis was performed with a novel in-house co-developed software tool (DoseIntelligence™, Pulmokard GmbH, Herdecke, Germany) and the commercially available Excel 2013™ including Powerpivot and Powerview (Microsoft, Redmond, WA, USA). Only protocols with at least 40 examinations were analyzed in detail.

Results

Examinations and Patients

Overall, the DICOM-SRs of n = 36 523 CT examinations (n = 131 527 scan series) were stored in the database at the time of this retrospective analysis. Examinations were performed on three different CT scanners (CT1: Somatom Definition AS+; CT2: Somatom Definition Flash; CT3: Somatom Definition AS with sliding gantry, Siemens, Healthcare Sector, Forchheim, Germany) and one PET-CT (Biograph mCT, Siemens, Healthcare Sector, Forchheim, Germany) between 09/2011 and 05/2015.

In total, 90 622 scan series were marked as "not to be taken into account". These included 18 594 scan series, which could not be matched to a DRL at the time of the analysis, and had to be excluded, e. g. neck CT and CT of extremities. Scout images are accounted for as independent scan series by the dose monitoring software. The remaining 72 073 scan series, which had to be excluded, contained scout images and phantom measurements for research and consistency check. Therefore, overall 41 036 scan series were ultimately analyzed in this study. The most frequent examinations were performed for cranial CT (n = 16 098), abdominal CT (n = 10 590), chest CT (n = 10 387), upper abdomen (n = 2909), mid-face (Sinusitis, n = 505), pelvis (n = 427) and lumbar spine (n = 119).

Comparison of dose-related data to DRLs

The radiation exposure of all included scan series corresponded to 51.3 % of the national DRL for $CTDI_{vol}$ and 52.8 % of the national DRL for DLP. Specific values for the different body regions are shown in **Table 2**.

Overall, 1.9 % (n = 763) of scan series exceeded the national DRLs for $CTDI_{vol}$ and 2.9 % (n = 1208) of scan series exceeded the reference DLP.

Dose variation of protocols matched to one body region

There was a high variation in radiation exposure for different scan protocols matched to the same body region. The highest difference in DLP between two protocols with the same DRL was found for two different abdominal CT protocols ($CTDI_{vol}$ / DLP: 2.76 mGy / 126.9 mGycm (13.8 % / 14.1 % of the DRL) compared to 10.3 mGy / 478.8 mGycm (51.6 % / 53.2 % of the DRL); **Table 3**). The highest difference between two protocols with the same DRL on the same CT scanner was found for two chest CT protocols ($CTDI_{vol}$ / DLP: 4.48 mGy / 148.4 mGycm (37.4 % / 37.1 % of the DRL) compared to 7.32 mGy / 270.4 mGycm, (61.0 % / 67.6 % of the DRL), CT3).

Analysis in regard to body mass index (BMI)

BMI was recorded for 13 321 out of 41 036 patients (32.5 %) (**Fig. 2**). There was a continuous increase in the mean $CTDI_{vol}$ and DLP according to the BMI group (underweight: $CTDI_{vol}$: 34.3 % / DLP: 35.8 % to obesity III°: $CTDI_{vol}$: 66.9 % / DLP 73.3 %). National DRLs were exceeded increasingly more often according to the BMI group (unknown: 3.48 %, underweight: 1.11 %, normal

Table 2 Overview of dose data for the different body regions compared to the corresponding national DRLs.

Tab. 2 Übersicht über die CT-Dosisdaten der verschiedenen Körperregionen.

region	series	mean age	mean $CTDI_{vol}$	$\%CTDI_{vol}$	mean DLP	%DLP	%exceeding DLP	%exceeding $CTDI_{vol}$
abdominal	10 590	60.84	8.74	43.83	386.82	43.14	3.92	3.11
pelvis	427	63.84	9.72	49.07	307.70	69.28	17.80	10.30
mid-face	505	48.60	5.02	55.78	65.90	66.05	7.33	4.55
cranial CT	16 098	63.85	43.01	66.58	656.13	69.64	1.13	0.35
lumbar spine (ax.)	1	53.00	8.80	20.95	35.83	14.33	0.00	0.00
lumbar spine (bone)	119	62.38	11.66	73.46	282.69	57.19	11.76	17.65
upper abdomen	2909	62.66	8.03	40.14	197.67	43.94	0.38	1.48
chest	10 387	59.88	4.49	37.83	173.86	44.03	4.55	2.37
overall	41 036	61.79	21.03	51.25	420.07	52.84	2.94	1.86

Absolute numbers as well as the percentage of national DRLs are shown. Furthermore, the percentage of examinations exceeding the DRLs is shown. Mean age in years; $CTDI_{vol}$: Volumetric Computed Tomography Dose Index (mGy); DLP: Dose Length Product (mGy*cm); Percentage of examinations exceeding the national DRLs [4]. Series: n; mean age in years; mean $CTDI_{vol}$ in mGy; mean DLP in mGycm; lumbar spine (ax): axial CT for the discs.
Die Werte sind sowohl absolut, als auch in Prozent des entsprechenden DRW angegeben. Zusätzlich ist der prozentuale Anteil der Untersuchungen angegeben, welcher die DRW überschreitet.

Table 3 Protocols with the lowest and highest radiation exposure per body region.

Tab. 3 Dargestellt sind die Protokolle mit der jeweils niedrigsten und höchsten Strahlenexposition einer Körperregion.

body region	protocol 1 (low)	mean $CTDI_{vol}$/DLP	$\%CTDI_{vol}$/%DLP	protocol 2 (high)	mean $CTDI_{vol}$/DLP	$\%CTDI_{vol}$/%DLP
abdomen	urolithiasis (n = 218)	2.76/126.9	13.8/14.1	abdomen venous (n = 955)	10.3/478.8	51.6/53.2
upper abdomen	upper abdomen non-contrast (n = 67)	2.91/60.2	14.6/13.4	liver late phase (n = 51)	8.9/198.0	44.5/44.0
chest	chest arterial (n = 5137)	3.6/115.5	30.6/29.8	chest incl. liver (n = 397)	7.7/353.2	64.1/88.3
pelvis	pelvis (n = 244)	9.8/269.6	49.0/60.4	pelvis venous (n = 42)	8.9/301.6	43.6/68.6
cranial	head (n = 137)	35.6/614.7	54.7/64.4	3 D dataset for surgical navigation (n = 115)	49.0/1000.4	75.3/105.3

Only protocols with n > 40 examinations were included. Absolute values as well as relative values in comparison to the national DRLs are provided.
Es wurden nur Protokolle mit mehr als 40 Untersuchungen ausgewertet. Angegeben sind sowohl die Absolutwerte für $CTDI_{vol}$ und DLP sowie die prozentualen Werte bezogen auf den entsprechenden DRW.

weight: 0.93 %, overweight 1.42 %, obesity I°: 2.74 %, obesity II°: 3.52 %, obesity III°: 16.8 %) (**Fig. 3**).

Comparison of the different CT scanners

CT3 had a considerably higher mean radiation exposure compared to the other two CT scanners ($CTDI_{vol}$/DLP: 68.5 %/69.8 % compared to 47.2 %/48.9 % and 41.6 %/42.7 %, respectively) (**Fig. 4**). The difference between the CT scanners varied according to the body region examined. The dose exposure per scanner for the three most frequently examined body regions (cranial CT, chest CT, abdominal CT) is shown in **Fig. 5**.

Discussion

In the study presented here we used a novel cloud-based software device for monitoring dose-related CT data of a tertiary care radiological department in order to benchmark CT radiation exposure to national DRLs. In this retrospective large-scale analysis of a 3.75-year interval consisting of more than 35 000 CT examinations, national DRLs were not systematically exceeded for any body region. The mean radiation exposure in clinical practice was only approximately 50 % of the national DRLs. A marked variation in radiation exposure between different scan protocols of the same body region (and therefore related to the same DRL) was found.

The radiation exposure between CT3 and the other two CT scanners included in this study differed remarkably. This is most likely the result of CT3 being the only CT scanner without an iterative reconstruction technique. The difference in radiation exposure in this study is in accordance with previous studies, which reported a significant reduction of radiation exposure in CT due to the use of iterative reconstruction instead of filtered back projection [10, 11].

National DRLs for CT examinations have been reported for many countries, e. g. for Ireland [2], Germany [4], the United Kingdom [12], Canada [1], Portugal [13], Switzerland [14] and the US [15]. Mostly these DRLs are defined for examinations of a certain body region, while only very few DRLs are given for specific CT protocols [1]. The national DRLs of different countries vary distinctly from each other, for example there is a DLP range from 787 mGycm to 1305 mGycm for cranial CT [12, 16], 371 – 1051 mGycm for chest CT [3, 16] and 329 – 1306 mGycm for abdominal CT [3, 16]. The German DRLs used for analysis in this study do not differ markedly from the center span of other reported DRLs.

Our results demonstrated a remarkable variation in the radiation dose applied by different CT protocols, which are all in clinical use to examine the same body region depending on the clinical issue

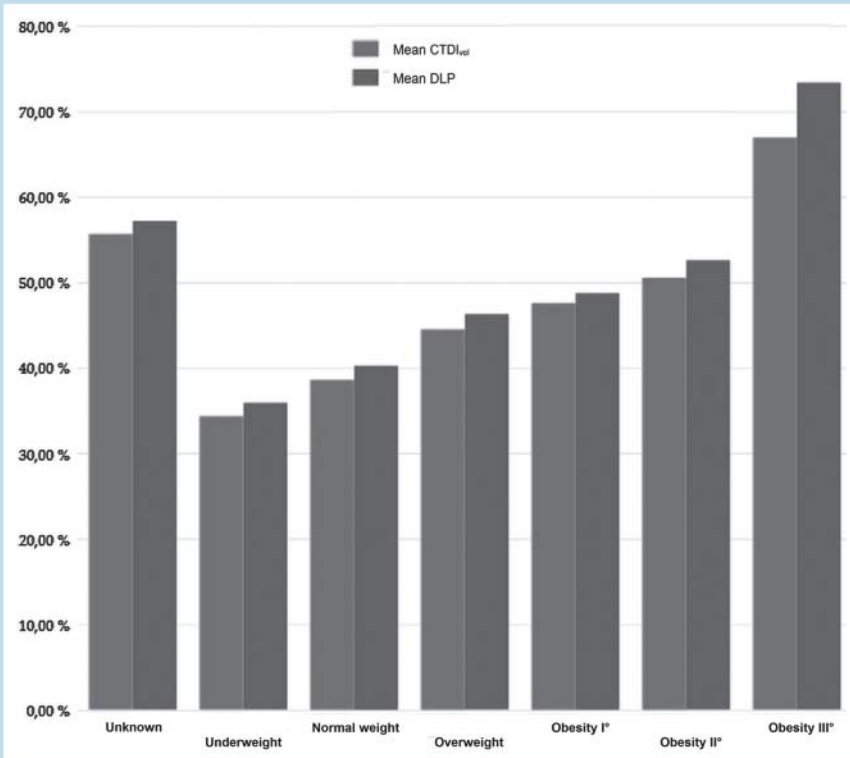

Fig. 2 $CTDI_{vol}$ and DLP as percentage of the national DRL for the different BMI groups.

Abb. 2 Dargestellt sind der $CTDI_{vol}$ und das DLP (in % des jeweiligen DRW) für die verschiedenen BMI-Gruppen.

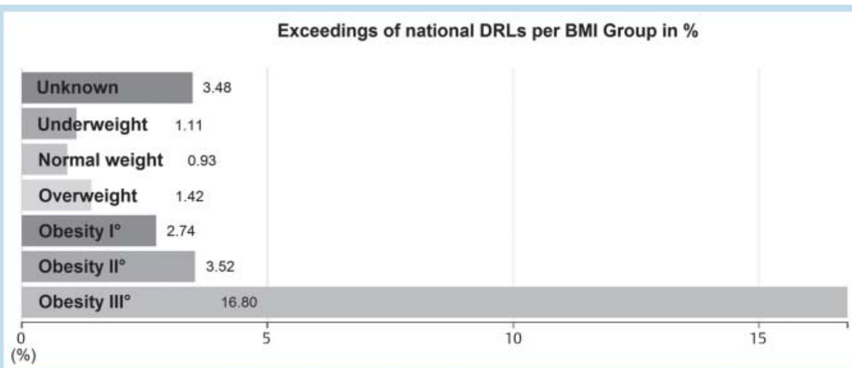

Fig. 3 Exceeding of national DRLs according to patients' BMI group.

Abb. 3 Prozentualer Anteil der Überschreitungen der nationalen DRW für die verschiedenen BMI-Gruppen.

(for abdominal CT, for example, we use a low-dose non-contrast protocol to detect ureteral concrements while our protocol for tumor staging includes a standard dose arterial and venous phase). Of course, these protocols differ essentially regarding radiation dose. Our results are in good accordance with prior studies, which introduced protocol-specific DRLs, for example for "renal colic" or "lung embolism" [1, 2, 17]. Current national DRLs in Germany, however, do not reflect the variety of CT protocols used in the clinical routine today. Therefore, more sophisticated DRLs are desirable and could help to further optimize radiation exposure from CT.

We found an increase in CT radiation exposure according to the BMI. National or international DRLs are traditionally reported for normal-sized patients (e. g. 60 – 80 kg) and do not take patient constitution into account [2, 4, 8]. Initial studies reported local DRLs based on size-specific dose estimates (SSDEs) [18]. To our knowledge, SSDEs have not been implemented in any national DRLs but according to our results, adaption of DRLs to a patient's constitution seems very reasonable.

Today, national DRLs are mostly based on surveys completed by different participating CT sites. Most commonly, the 75th percentile is calculated to account for the national DRL [2, 4]. The accuracy of this method depends on the accuracy of the participants' data and on the number of included examinations. Foley et al. used data that included at least ten average-sized patients for each CT examination [2]. This small group size might not reflect the real dose exposure for the corresponding CT examination. Recently, Taylor et al. reported a high variability for DLP in CT dose surveys depending on the protocol and patient weight [19]. Even when including 50 patients per protocol, a 95 % confidence interval lower than 10 % of the median (CI95 %/med< 10 %) was not reached for most protocols. Furthermore, for abdominal CT, n = 420 and for cervical spine n = 900 examinations were needed to reach the CI95 %/med< 10 % [19]. Only a few studies reported implementation of local DRLs based on systematic dose monitoring [1]. Besides the larger sample size when including all CT examinations in DRL assessment, the lack of manual processing with potential risk for selection bias helps to improve accuracy

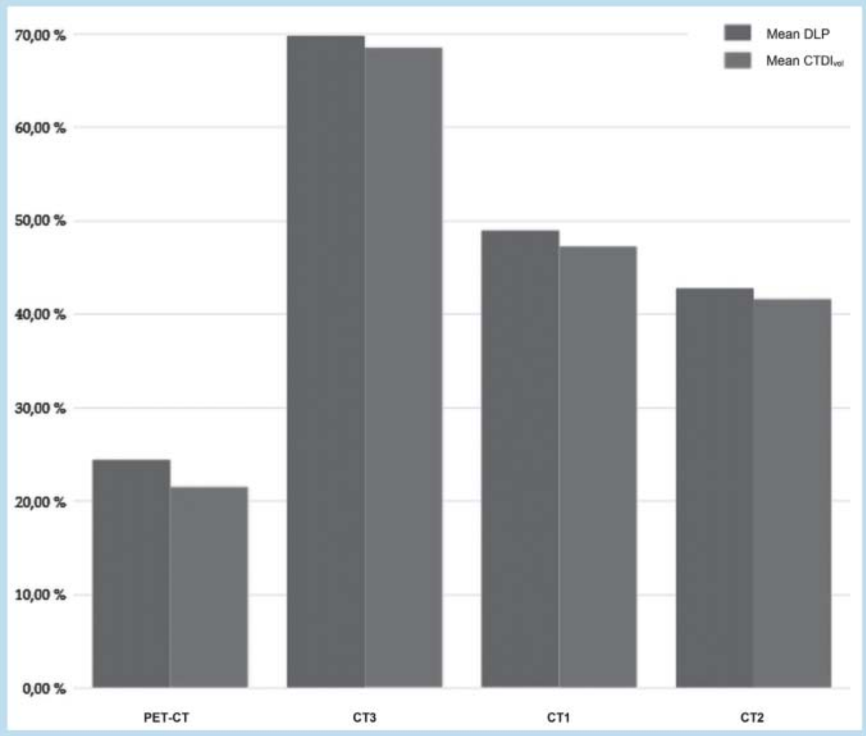

Fig. 4 $CTDI_{vol}$ and DLP in percentage of the national DRLs for the different scanners included in this study.

Abb. 4 Dargestellt sind der $CTDI_{vol}$ und das DLP (in % des jeweiligen DRW) für die unterschiedlichen CT-Geräte.

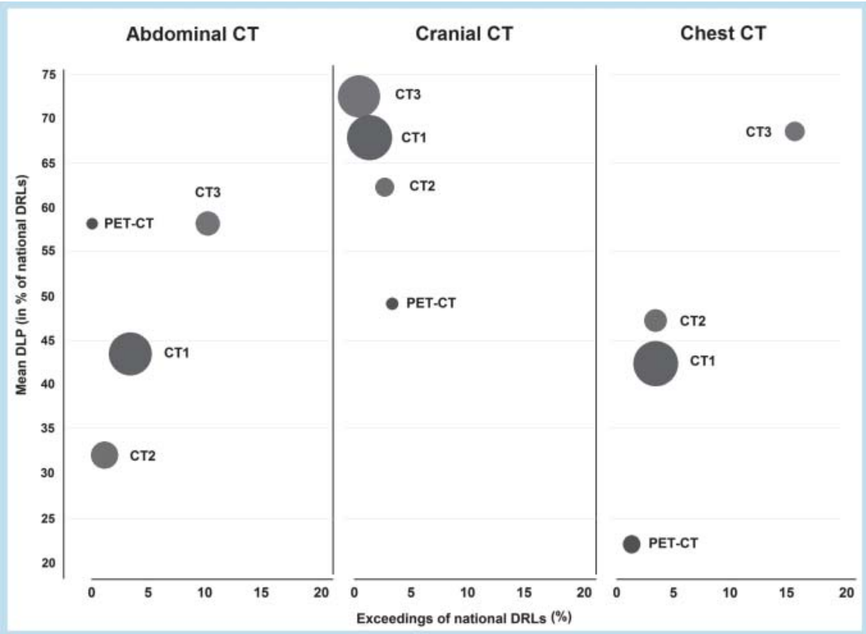

Fig. 5 DLP for the different CT scanners for abdominal CT, cranial CT and chest CT. DLP is shown in percentage of the national DRL (y-axis). The percentage of examinations exceeding DRLs is shown on the x-axis. The size of the dots equals the number of examinations displayed.

Abb. 5 Detaillierte Auswertung der Körperregionen Abdomen, Schädel und Thorax: Dargestellt sind das DLP (in % des DRW, y-Achse) und der Prozentsatz der DRW-Überschreitungen (x-Achse) für die verschiedenen CT-Geräte.

even further. Large-scale analysis of dose-related CT data, as presented here, and particularly cloud-based multicenter dose monitoring, which is possible with the presented software tool, allow for implementation of more accurate and more specific DRLs and therefore help to reduce radiation exposure from CT in the future.
Our study has limitations. This study reports initial single-center results. Single-center dose monitoring in regard to national DRLs only allows for limited dose analysis because no improvement may be performed if radiation exposure for a specific protocol is below the corresponding DRL. Nevertheless, the introduced cloud-based approach enables multicenter dose monitoring which may enable benchmarking with cloud-based reference levels from similar departments, CT scanners and protocols and can help to optimize radiation exposure in CT beyond analysis concerning national or local DRLs.
For some body regions and various CT protocols, no national DRLs have been reported so far, e. g. CT of the neck, cervical CT angiography, whole body CT (PET-CT, skeletal CT for myeloma survey or aortic CT angiography). Therefore, our results cannot be compared to national DRLs for these protocols and we did not include these protocols in our study. Patient weight and height were assessed by statements of the patient or provided patient data, not by our own

measurements. This might have led to an inaccuracy of the data, which cannot be evaluated further. We did not evaluate additional dose reduction techniques like iterative reconstruction or automated tube current modulation. The data provided about these techniques in the DICOM-RDSR are limited and therefore it was not included in our study.

In conclusion, we implemented cloud-based CT dose monitoring to automatically compare CT radiation exposure to national DRLs. Overall, the local dose exposure from CT was approximately 50 % of these DRLs and showed a large variability between different CT protocols matched to the same DRL, indicating that DRL actualization and protocol-specific DRLs are desirable. The cloud-based approach may help to implement more accurate and more specific DRLs in the future by multicenter analysis and thus lead to further optimization of radiation exposure in CT.

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