Development of size-specific institutional diagnostic reference levels for computed tomography protocols in neck imaging

Andrea Steuwe, Christoph Thomas, Bastian Kraus, Oliver Thomas Bethge, Joel Aissa, Yan Klosterkemper, Gerald Antoch and Johannes Boos

University Düsseldorf, Medical Faculty, Department of Diagnostic and Interventional Radiology, D-40225 Düsseldorf, Germany

E-mail: johannesboos@gmx.de

Received 25 July 2019, revised 25 September 2019
Accepted for publication 11 October 2019
Published 11 December 2019

Abstract

Purpose: To develop size-specific institutional diagnostic reference levels (DRLs) for computed tomography (CT) protocols used in neck CT imaging (cervical spine CT, cervical CT angiography (CTA) and cervical staging CT) and to compare institutional to national DRLs. Materials and methods: Cervical CT examinations (spine, n = 609; CTA, n = 505 and staging CT, n = 184) performed between 01/2016 and 06/2017 were included in this retrospective study. For each region and examination, the volumetric CT dose index (CTDIvol) and dose-length product (DLP) were determined and binned into size bins according to patient water-equivalent diameter (dw). Linear regression analysis was performed to calculate size-specific institutional DRLs for CTDIvol and DLP, applying the 75th percentile as the upper limit for institutional DRLs. The mean institutional CTDIvol and DLP were compared to national DRLs (CTDIvol 20 mGy for cervical spine CT (DLP 300 mGycm) and cervical CTA (DLP 600 mGycm), and CTDIvol 15 mGy for cervical staging CT (DLP 330 mGycm)). Results: The mean CTDIvol and DLP (±standard deviation) were 15.2 ± 4.1 mGy and 181.5 ± 88.3 mGycm for cervical spine CT; 8.1 ± 4.3 mGy and 280.2 ± 164.3 mGycm for cervical CTA; 8.6 ± 1.9 mGy and 162.8 ± 85.0 mGycm for cervical staging CT. For all CT protocols, there was a linear increase in CTDIvol and DLP with increasing dw.

1 Author to whom any correspondence should be addressed.
For the CTDIvol, size-specific institutional DRLs increased with dw from 14 to 29 mGy for cervical spine CT, from 5 to 17 mGy for cervical CTA and from 8 to 13 mGy for cervical staging CT. For the DLP, size-specific institutional DRLs increased with dw from 130 to 510 mGycm for cervical spine CT, from 140 to 640 mGycm for cervical CTA and from 140 to 320 mGycm for cervical staging CT. Institutional DRLs were lower than national DRLs by 81% and 67% for cervical spine CT (\(dw = 17.8\) cm), 43% and 51% for cervical CTA (\(dw = 19.5\) cm) and 59% and 53% for cervical staging CT (\(dw = 18.8\) cm) for CTDIvol and DLP, respectively. Conclusion: Size-specific institutional DRLs were generated for neck CT examinations. The mean institutional CTDIvol and DLP values were well below national DRLs.

Keywords: computed tomography, neck CT imaging, diagnostic reference levels

(Some figures may appear in colour only in the online journal)

Introduction

The volumetric computed tomography dose index (CTDIvol) and dose-length product (DLP) of a computed tomography (CT) examination can be used as guidance to review the radiation application. National and institutional diagnostic reference levels (DRLs), which are used for quality assurance in radiology departments, are most commonly based on CTDIvol and DLP [1–4]. In the German radiation protection ordinance, DRLs are defined as dose indices for typical examinations employing ionising radiation, based on standardised phantoms or groups of patients with standard morphometry, while using a suitable modality and procedure for a respective examination [5]. DRLs are established as the 75th quartile of a distribution of patient doses for different users and CT scanner vendors; however, they are not ideal dose indices. Although DRLs are not fixed radiation limits, their constant and unjustified exceedance is not allowed and requires disclosure. In particular, due to the renewed German radiation protection ordinance and act, the dose indices of individual patients and of patient groups now need to be constantly evaluated and reviewed with respect to published DRLs to identify dose incidents and poor examination protocols—even if patients do not match the weight of a standardised patient (70 ± 3 kg), and even though DRLs should not be used on an individual patient basis [6, 7].

Most current national DRLs (nDRLs) have major drawbacks in their application and significance [8]. First, the CTDIvol is based on radiation exposure measurements by means of a standardised cylindrical CTDI-phantom (either with a diameter of 16 cm, representing a head, or with a diameter of 32 cm, representing a body). The cylindrical shape and the material (poly-methyl-meth-acrylate) are only a rough approximation of the human body. Second, DRLs for adults are typically provided for average-sized patients, although it is well known that the effective dose of a CT examination depends on patient characteristics, such as the body weight and height, body mass index (BMI) and patient composition [9, 10]. High dose values in small patients might go unnoticed as CTDIvol or DLP values do not exceed national DRL thresholds. Particularly for these smaller patients, size-specific DRLs are needed. Third, national DRLs are sometimes only provided for anatomic regions rather than for dedicated CT protocols, although the dose may vary notably within one anatomic region [11]. For neck CT imaging, three different protocol-specific DRLs are provided. However, for
abdominal imaging, the same DRL holds for CT examinations to diagnose a suspected kidney tumour or metastasis versus a suspected kidney stone; although the latter indication can be answered with a considerably reduced radiation exposure. The latter is reflected in the EUROSAFE imaging campaigns’ desire to implement CT protocol-specific DRLs [12]. Recently, size-dependent DRLs based on the BMI or patient diameter measurements were proposed for body regions such as the chest or abdomen [8, 13, 14]. However, dose variation among different CT protocols and patient sizes in neck CT imaging remains unknown, and dedicated institutional DRLs (iDRLs) may improve CT quality assurance.

Therefore, the aim of our study was to analyse CT dose data from different neck CT imaging protocols to generate size-specific and CT protocol-specific institutional DRLs.

Materials and methods

This retrospective study was approved by the institutional review board. All CT examinations assigned to the national DRLs for CT of the neck from the four institutional multi-detector CT scanners (Definition Flash with 128 slices, Definition AS+ with 128 slices, Definition AS with sliding gantry with 64 slices, Definition Edge with 128 slices, Siemens Healthineers, Forchheim, Germany) performed between 01/2016 and 07/2017 were included in our study (cervical spine CT, cervical CT angiography (CTA) and cervical staging CT). The scan volumes of the institutional standard CT protocols were as follows: external auditory canal to lower edge of the clavicle for cervical staging CT; cranio-cervical transition to the first thoracic vertebra (T1) for cervical spine CT; and aortic arch to crown for cervical CTA. Cervical spine CT examinations were performed without contrast enhancement (iodine), whereas contrast agents were applied during cervical staging CT (venous phase) and cervical CTA (arterial phase). Common indications for cervical spine CT examinations were trauma, radiculopathy, myelopathy or osseous metastases. Indications for cervical CTA were stroke, suspected vessel stenosis, occlusion or aneurysm. Indications for cervical staging CTs were suspected tumours in the neck region, lymph node staging or abscesses.

For the chosen CT protocols, there were 8328 examinations performed in the study interval. The exclusion parameters for this study were paediatric patients, patients with a water-equivalent diameter ($d_w < 15 \text{ cm}$ or $d_w \geq 25 \text{ cm}$, or reconstructed images with truncated field of view. After exclusion, 609 cervical spine CT examinations, 184 cervical staging CT examinations and 505 cervical CTA examinations were included in our analysis (figure 1).

CT dose monitoring and calculation of $d_w$

A dose management system (DoseIntelligence, Pulmokard, Herdecke, Germany) based on the Digital Imaging and Communications Radiation Dose Structured Report (DICOM-RDSR) was used to obtain CT dose data and technical parameters, including CTDI$_{vol}$, DLP, pitch, mean tube current–time product, tube voltage, scan length, anatomic region, CTDI-phantom size and the CT protocol [4]. Patient height and weight were automatically stored in the DICOM-RDSR at the time of the CT examination if they were available in the electronic patient records (only in 5% of the examinations). Assignment of CT protocols to body regions (which was necessary for comparison to national DRLs) was performed manually by one radiologist (J.B. with five years of experience in radiology).

The method of $d_w$ calculation by means of a previously validated self-designed algorithm and the Matlab environment (version R2015, The Mathworks, Natick, MA) was previously published [8]. In short, the algorithm first removes the CT scanner table, then identifies the
outer body circumference, and finally, calculates the $d_w$ according to the American Association of Physicists in Medicine (AAPM) guidelines [8, 15]. Truncated images were identified by analysis of pixels other than air adjacent to the outer border of the field of view [8]. Data sets with an average number of surrounding pixels other than air >100 were excluded to ensure that truncation of CT images did not influence our results [8]. For the purpose of this study, the mean $d_w$ of the scan volume was used. Subsequently, the calculated $d_w$ was stored into the institutional CT dose management system (DoseIntelligence, Pulmokard, Herdecke, Germany).

**Image acquisition and reconstruction**

CT examinations were performed in spiral mode without or with intravenous contrast material (Omnipaque, GE Healthcare, Munich, Germany) depending on the indication. Automated tube current modulation (CareDose 4D) was activated in all examinations, whereas automated tube voltage selection (CareKV, both Siemens Healthineers, Forchheim, Germany) was activated in most examinations. Images were reconstructed with a medium level of iterative reconstruction (SAFIRE™ Level 3, Siemens Healthineers, Forchheim Germany) when performed on the Somatom Definition AS+ (scanner 1), Flash (scanner 2), or Edge (scanner 3) CT scanners, and with filtered back-projection on the Somatom Definition AS (sliding gantry, scanner 4) CT scanner. CTDIvol values obtained from the dose protocol were based on the 32 cm phantom for all examinations in this study [16].

Figure 1. A flow chart of our study population according to the Standards for Reporting Diagnostic Accuracy (STARD) initiative.
Calculation of iDRLs and data analysis

For calculation of the iDRLs, patients were categorised into 1 cm $d_w$ bins (e.g. bin $d_w = 15$ cm includes all $d_w$ in between 15 cm and 16 cm). Analysis was performed per neck CT protocol separately. Linear regression was used to calculate iDRLs based on patient $d_w$. As recommended by the International Commission on Radiological Protection (ICRP), the 75th percentile of the CTDI$_{vol}$ and DLP were regarded as the upper limit of the iDRLs, and the 25th percentile was chosen as the lower limit [17].

Comparison of mean institutional CTDI$_{vol}$ and DLP for average-sized patients to nDRLs

Current German nDRLs are provided for CTDI$_{vol}$ and DLP, and are related to standardised patients (70 kg ± 3 kg) [18]. For neck CT examinations, the German DRLs are: cervical spine CT (CTDI$_{vol}$ 20 mGy, DLP 300 mGycm), cervical CTA (CTDI$_{vol}$ 20 mGy, DLP 600 mGycm) and neck CT for cervical staging (CTDI$_{vol}$ 15 mGy, DLP 330 mGycm) [18].

In addition to calculation of iDRls, mean institutional CTDI$_{vol}$ and DLP were calculated for an average-sized patient as determined by the $d_w$ for each neck CT protocol from the corresponding linear regression curves and were compared to the nDRLs. The average-sized patient by means of the $d_w$ was calculated by calculation of the mean $d_w$ over all patients for each of the three CT protocols (table 1). Subsequently, mean institutional CTDI$_{vol}$ and DLP values for the calculated $d_w$ were determined from the linear fits through the 1 cm $d_w$ bins described in the last section (solid lines in figures 2–4).

Additionally, iDRls of both the CTDI$_{vol}$ and DLP were compared to the size-specific DRLs of the American College of Radiology Dose Index Registry (ACR-DIR), which are provided for different $d_w$ groups [19]. For cervical spine CT, they range between 24 and 28 mGy for the CTDI$_{vol}$, and between 495 and 575 mGycm for the DLP. For cervical staging CT size-specific DRLs range between 18 and 19 mGy (CTDI$_{vol}$) and 509 to 560 mGycm

| TABLE 1. Patient characteristics (all values provided with mean ± standard deviation). |
|---------------------------------------------------------------|
| Cervical spine CT | Cervical CTA | Cervical staging CT | All |
| n | 609 | 505 | 184 | 1298 |
| Number of examinations per tube potential (n) | | | |
| 80 kV$_p$ | 8 | 117 | 23 | 148 |
| 100 kV$_p$ | 351 | 115 | 84 | 550 |
| 120 kV$_p$ | 249 | 273 | 77 | 599 |
| 140 kV$_p$ | 1 | 0 | 0 | 1 |
| CTDI$_{vol}$ [mGy] | 15.2 ± 4.1 | 8.1 ± 4.3 | 8.6 ± 1.9 | 11.5 ± 5.3 |
| DLP [mGycm] | 181.5 ± 88.3 | 280.2 ± 164.3 | 162.8 ± 85.0 | 217.3 ± 133.1 |
| Scan coverage [cm] | 11.7 ± 3.4 | 33.1 ± 7.1 | 18.0 ± 7.7 | 20.9 ± 11.5 |
| nDRL CTDI$_{vol}$ [mGy] | 20 | 20 | 15 | — |
| nDRL DLP [mGycm] | 300 | 600 | 330 | — |
| Age [years] | 67.6 ± 21.2 | 67.4 ± 19.6 | 63.4 ± 14.9 | 66.9 ± 19.9 |
| Mean water-equivalent diameter $d_w$ [cm] | 17.8 ± 1.7 | 19.5 ± 1.9 | 18.8 ± 2.2 | 18.6 ± 2.0 |
| CT: computed tomography; CTDI$_{vol}$: volumetric CT dose index; DLP: dose-length product; $^1$:average CTDI$_{vol}$, DLP over all patients; $^2$: based on the mean water-equivalent diameter of the scan volume; CTA: CT angiography; nDRL: national diagnostic reference level. |
Furthermore, the number of CT examinations exceeding the national DRLs and the size-specific iDRL were compared.

**Differences between the CT scanners and data analysis**

Impact of the employed CT scanner on the CTDI$_{vol}$ of each CT protocol was analyzed. All data is given as the mean ± standard deviation with range, or median values. Linear regression was performed to generate iDRLs. The institutional mean CTDI$_{vol}$ and DLP are provided with one decimal precision, whereas iDRLs are rounded to the nearest integer. Statistical analysis for comparison of the DLP, CTDI$_{vol}$, $d_w$, and scan range was performed using a student’s t-test with a significance level of $p < 0.05$. 

**Figure 2.** The iDRLs for cervical spine CT examinations. The bold line represents the linear regression for which the equation and the coefficient of determination ($R^2$) are provided. There was a strong correlation between the $d_w$ and CTDI$_{vol}$ (a, $R^2 = 0.97$) and between the $d_w$ and DLP (b, $R^2 = 0.95$). The dashed lines are the 75th (upper line) and 25th (lower line) percentile of each bin. The black square is positioned at the mean water-equivalent diameter for the cervical spine CTs.
Results

Patient characteristics and examination overview

For all included examinations \((n = 1298)\), the mean age was \(66.9 \pm 19.9\) years, mean \(d_{w}\) was \(18.6 \pm 2.0\) cm, mean \(CTDI_{vol}\) was \(11.5 \pm 5.3\) mGy and mean DLP was \(217.3 \pm 133.1\) mGycm. Weight information was only available in the electronic report in 5% of the examinations. For these patients, the mean patient weight was \(74 \pm 14\) kg. The mean \(CTDI_{vol}\) was highest for cervical spine CT examinations \((15.2 \pm 4.1\) mGy), whereas the mean DLP was highest for cervical CTA \((280.2 \pm 164.3\) mGycm). For cervical spine CT examinations, the \(d_{w}\) was the lowest \((17.8 \pm 1.7\) cm). The scan coverage was the longest for CTA \((33.1 \pm 7.1\) cm) and the shortest for cervical spine CT \((11.7 \pm 3.4\) cm). Detailed patient and protocol characteristics per examination type are provided in table 1. Differences in \(CTDI_{vol}\), DLP, \(d_{w}\) and scan coverage...
were significant between the three protocols (p = 0.4999 for the comparison of the CTDI_{vol} between cervical CTA and cervical staging CT, else p << 0.05).

**Relationship between CTDI_{vol}, DLP and d_w**

For all CT protocols, there was a linear increase in CTDI_{vol} and DLP with increasing d_w (see table 2 and figures 2–4). For the CTDI_{vol}, size-specific iDRLs increased with d_w from 14 to 29 mGy for cervical spine CT, from 5 to 17 mGy for cervical CTA and from 8 to 13 mGy for cervical staging CT. For the DLP, size-specific iDRLs increased with d_w from 130 to 510 mGycm for cervical spine CT, from 140 to 640 mGycm for cervical CTA and from 140 to 320 mGycm for cervical staging CT. The coefficient of determinations for the linear gradient were R^2_{CTDI} = 0.97 and R^2_{DLP} = 0.95 for CTDI_{vol} and DLP for the cervical spine.
Table 2. The number of patients per \( d_w \) bin with the corresponding average CTDI\textsubscript{vol} and average DLP. The \( d_w \) bins were subsequently used for calculation of size-specific iDRLs (75th quartiles), if \( n \geq 10 \).

| \( d_w \) [cm] | \( n \) | CTDI\textsubscript{vol} [mGy] | DLP [mGycm] | \( d_w \) [cm] | \( n \) | CTDI\textsubscript{vol} [mGy] | DLP [mGycm] | \( d_w \) [cm] | \( n \) | CTDI\textsubscript{vol} [mGy] | DLP [mGycm] |
|----------------|--------|-------------------------------|-------------|----------------|--------|-------------------------------|-------------|----------------|--------|-------------------------------|-------------|
| 15             | 61     | 13.0                          | 137.7       | 16             | 147    | 13.1                          | 139.2       | 17             | 180    | 14.7                          | 173.8       | 18             | 105    | 15.8                          | 196.7       |
| 16             | 147    | 13.1                          | 139.2       | 17             | 180    | 14.7                          | 173.8       | 18             | 105    | 15.8                          | 196.7       | 19             | 59     | 17.8                          | 225.0       |
| 17             | 180    | 14.7                          | 173.8       | 18             | 105    | 15.8                          | 196.7       | 19             | 59     | 17.8                          | 225.0       | 20             | 26     | 18.9                          | 270.9       |
| 18             | 105    | 15.8                          | 196.7       | 19             | 59     | 17.8                          | 225.0       | 20             | 26     | 18.9                          | 270.9       | 21             | 17     | 19.8                          | 269.2       |
| 19             | 59     | 17.8                          | 225.0       | 21             | 17     | 19.8                          | 269.2       | 21             | 17     | 19.8                          | 269.2       | 22             | 10     | 23.0                          | 347.7       |
| 20             | 26     | 18.9                          | 270.9       | 22             | 10     | 23.0                          | 347.7       | 23             | 8      | 19.2                          | 258.8       | 24             | 1       | 29.6                          | 293.3       |
| 21             | 17     | 19.8                          | 269.2       | 23             | 8      | 19.2                          | 258.8       | 24             | 1      | 29.6                          | 293.3       |
| 22             | 10     | 23.0                          | 347.7       | 24             | 1      | 29.6                          | 293.3       |                |        |                               |             |

CT: computed tomography, CTDI\textsubscript{vol}: volumetric CT dose index, CTA: CT angiography, \( d_w \): water-equivalent diameter.

Table 3. A comparison of the mean institutional CTDI\textsubscript{vol} and DLP for average-sized patients to nDRLs. Percentage of institutional CTDI\textsubscript{vol} and DLP with respect to nDRLs provided in parentheses.

| \( d_w \) [cm] | CTDI\textsubscript{vol} [mGy] | DLP [mGycm] | CTDI\textsubscript{vol} [mGy] | DLP [mGycm] | CTDI\textsubscript{vol} [mGy] | DLP [mGycm] |
|----------------|-------------------------------|-------------|-------------------------------|-------------|-------------------------------|-------------|
| 17.8           | 16.1 (81%)                    | 200.9 (67%) | 19.5                          | 8.7 (43%)   | 307.5 (51%)                   |             |
|                |                               |             | 18.8                          |             | 8.9 (59%)                     |             |

Table 4. A comparison of the 50th and 75th quartile of the CTDI\textsubscript{vol} and DLP of the current study with those published by Kanal \textit{et al} using the data of the ACR-DIR for cervical spine and cervical staging CT examinations [19].

| \( d_w \) [cm] | CTDI\textsubscript{vol} [mGy] | DLP [mGycm] | CTDI\textsubscript{vol} [mGy] | DLP [mGycm] | CTDI\textsubscript{vol} [mGy] | DLP [mGycm] |
|----------------|-------------------------------|-------------|-------------------------------|-------------|-------------------------------|-------------|
| 13–17          | 12.2                          | 126.9       | 15.3                          | 24          | 16.1                          | 200.9       |
| 17–21          | 16.0                          | 171.2       | 18.5                          | 28          | 16.1                          | 200.9       |
| 21–25          | 21.4                          | 264.6       | 24.8                          | 28          | 16.1                          | 200.9       |

CT: computed tomography, DLP: dose-length product, CTDI\textsubscript{vol}: volumetric CT dose index, \( d_w \): water-equivalent diameter.
Comparison of mean institutional CTDI\textsubscript{vol} and DLP for average-sized patients to nDRLs

The mean institutional CTDI\textsubscript{vol} and DLP for average-sized patients as determined by the \( d_w \) (calculated from each linear regression curve with the corresponding average patient \( d_w \) for each CT protocol) were 43\%–81\% lower than the nDRLs for CTDI\textsubscript{vol} and DLP, see figures 2–4 and table 3.

Comparison of iDRLs to the size-specific DRLs from the American College of Radiology Dose Index Registry (ACR-DIR)

The 50th and 75th quartile of the CTDI\textsubscript{vol} and DLP published by the ACR-DIR for staging CT (neck with contrast material) and cervical spine CT (without contrast material) were compared to the institutional 50th and 75th quartile of the CTDI\textsubscript{vol} and DLP (table 4) [19].

For cervical staging CT, the institutional 50th and 75th quartiles were 27\%–53\% lower than the ACR-DIR DRLs for CTDI\textsubscript{vol}. The differences were even larger for the DLP, ranging between 41\% and 70\%. With increasing \( d_w \), differences between dose levels of the current study and of the ACR-DIR decreased. For cervical spine CT, the institutional 50th and 75th quartiles were 20\%–36\% smaller for the \( d_w \) groups between 13 and 21 cm compared to ACR-DIR dose levels, whereas for the largest \( d_w \) group, the 50th and 75th quartiles were similar to ACR-DIR dose levels. The institutional 50th and 75th quartiles for the DLP differed considerably throughout all the \( d_w \) groups: they were 32\%–68\% lower than the ACR-DIR dose levels. Again, differences decreased with increasing \( d_w \).
Outlier analysis

There were 286 (251) examinations with CTDI<sub>vol</sub> (DLP) exceeding the size-specific iDRLs, whereas there were only 75 (74) examinations exceeding the nDRLs (see table 5 for the individual CT regions and figure 5 for cervical spine CTs). Patients with CTDI<sub>vol</sub> or DLP > iDRLs but not reaching the nDRLs had an average d<sub>W</sub> lower than the average d<sub>W</sub> of patients with CTDI<sub>vol</sub> and DLP < iDRLs. In return, patients with CTDI<sub>vol</sub> or DLP > nDRLs had an average d<sub>W</sub> higher than the average d<sub>W</sub> of the patient group with CTDI<sub>vol</sub> and DLP < iDRLs (see table 5).

Figure 5. Outlier analysis of cervical spine CT. The bold horizontal lines represent the nDRL for cervical spine CT (20 mGy, 300 mGycm). The red dots represent the examinations with CTDI<sub>vol</sub> or DLP above institutional and national DRLs. The yellow dots represent the examination below the national but above the iDRLs. The green dots represent the examinations below the national and institutional DRLs. The dashed black lines represent the d<sub>W</sub>-dependent iDRLs. Data above the grey dotted line in (a) is almost exclusively acquired on the Somatom Definition AS.
**Differences between the CT scanners**

On average, the highest average CTDI_{vol} and DLP values were obtained on scanner 4, except for cervical staging CT examinations. Please note that only filtered back-projection was available on scanner 4. For cervical staging CT, the CTDI_{vol} was highest for scanner 2. Here, all examinations were performed at 120 kVp (no automatic tube potential selection), whereas for all other scanners the tube potential varied between 80 kVp and 120 kVp for cervical staging CT examinations.

**Discussion**

In this study, a large-scale analysis of neck CT examinations was performed which included CT dose parameters and patient dw and consequently allowed for the development of size-specific and CT protocol-specific DRLs. Currently, there are three different national German DRLs provided for neck CT examinations, which are related to patient groups of standardised morphometry (70 ± 3 kg). In our study, a strong linear relationship between the dw and CTDI_{vol} and between the dw and DLP was found in all evaluated CT protocols: with increasing dw, both the CTDI_{vol} and DLP values increased linearly. The linear relationship is an expected result, since the tube current modulation depends on the density of the patient as obtained by the scout view (topogram). The graphs demonstrate that the automatic exposure control is working and reduces the exposure for small patients for an individual CT protocol. In our institution, cervical spine CT examinations resulted in the highest CTDI_{vol}, although the smallest dw were determined from these examinations. Although all protocols cover the neck region, the specific scan range is protocol-dependent, leading to differences in dw: cervical CTA covers a larger range of the shoulders, causing a high dw, whereas cervical spine CT covers the smallest range of the shoulders (see the protocol description in the materials and methods section), leading to the lowest dw. Furthermore, the scan protocol parameters of cervical spine CT included the highest reference tube current–time product compared to the other two protocols. Due to the long scan coverage, the largest average DLP was found for cervical CTA. The average CTDI_{vol} and DLP for cervical staging and CTA acquisitions were only 40%–60% of the nDRLs, whereas the CTDI_{vol} and DLP were 70%–80% of the nDRLs for cervical spine acquisitions. Since the CTDI_{vol} of cervical staging CT and cervical CTA are well below the nDRLs, these also cause low DLP values since the scan range is defined in the standard operating procedure and is fairly equal for all examinations within one protocol.

Compared to the DLP and CTDI_{vol} values published for the cervical staging and spine CT examinations by Kanal et al from the ACR-DIR, our calculated 50th and 70th quartiles were considerably lower (−20% to −70%) for all dw bins, except for CTDI_{vol} values in patients with a very large dw for cervical spine CT [19]. Here, the 50th and 70th quartiles were similar.

Our presented study and the performed analysis demonstrate the ability to perform a detailed subgroup analysis when using size-specific DRLs based on dw. Of note, Kanal et al based their calculations of dw on the localiser images (topograms). Calculations of dw based on the localiser image may slightly overestimate dw (by 4%) compared to calculations based on CT images, which is regarded as the reference standard and was performed in our study [20]. The 4% overestimation due to the calculation of dw cannot however explain the differences between the ACR-DIR data and our iDRLs (−20 to −70%). They are most likely due to differences in either scan protocol settings (used tube potential or tube current–time...
product) or chosen scan coverage. Unfortunately, the paper from Kanal et al does not provide this information [19].

As was observed in the outlier analysis, the largest percentage (12%) of examinations exceeding the national and institutional DRLs was found for cervical spine CT. Here, only acquisitions on scanner 4 resulted in CTDI$_{vol}$ values exceeding the nDRLs, whereas all acquisitions performed on scanners 1, 2 and 3 were below the nDRLs. The scan length for cervical spine CT for all dw amounts to only 12–15 cm. Hence, the increased DLP values are the result of an increased CTDI$_{vol}$, but are not due to a too large scan coverage. The increased CTDI$_{vol}$ on scanner 4 is most likely the result of the missing availability of iterative reconstruction. Iterative reconstruction allows for reduction of the radiation exposure by approximately 20%–40% while maintaining the same image quality [21–24]. Although the average CTDI$_{vol}$ was well below the nDRLs for cervical staging CT scans on scanner 2, we noticed a missing automatic tube potential selection, which resulted in a higher CTDI$_{vol}$ compared to the other scanners. Consequently, the CT protocol was modified on scanner 2 to allow for automatic tube potential.

Depending on the CT protocol, 75%–85% of all included cervical CT examinations were below nDRLs, 6%–26% of which exceeded the size-specific iDRLs, depending on the CT protocol. This comparison also includes patients, which do not match the weight of the standardised patient with 70 ± 3 kg. Our analysis demonstrated that a high dw causes the CTDI$_{vol}$ and DLP to be larger than institutional and national DRLs. For intermediate dw, the CTDI$_{vol}$ and DLP are often lower than institutional and national DRLs. The range for CTDI$_{vol}$ and DLP to be between institutional and national DRLs is small and includes only small dw (yellow dots in figures 4 and 5). These latter examinations would go unnoticed when using solely nDRLs for dose analysis. Hence, it is necessary to facilitate size-specific iDRLs, especially for patients smaller than the standardised patient is. Our results indicate that size- and protocol-specific DRLs may help to improve CT quality assurance by allowing for a more detailed analysis. The nDRLs are useful to detect systematic dose application errors but do not allow for a comprehensive analysis. Inclusion of the patients’ dw in the evaluation of CT radiation exposure increases the accuracy and reliability of institutional quality assurance, since size-specific DRLs allow us to detect dose outliers of small patients, whose dose values might still be below the nDRLs, but far from being optimal. Of note, such detailed analysis may require additional time and effort, but can be facilitated by using (semi-)automatic dose management systems [25].

In recent publications, iDRLs have been calculated by means of size-specific dose estimates (SSDEs) for several body regions [15, 19, 26]. SSDEs are calculated by multiplication of the CTDI$_{vol}$ and a patient size-specific conversion factor, which takes the patient size and attenuation into account [10, 20, 27]. Typically, a comparatively large dw results in a smaller SSDE than CTDI$_{vol}$ (conversion factor < 1), whereas patients with a comparatively small dw result in an SSDE > CTDI$_{vol}$. Very recently, the AAPM task group No. 293 has published a new report about SSDEs for head CT, following the report about SSDEs for body CT examinations [27, 28]. However, CT protocols of the neck include parts of the head and the body, and are thus neither full head nor body CT examinations. Hence, the value of the dw varies extensively if calculated from the mean dw of the scan volume or from a single image. Until now, dedicated size-specific conversion factors for neck CT examinations with instructions on the calculation of the dw have not been published by the AAPM [20].

Our study has some limitations. First, it was necessary to exclude a relatively large number of examinations. In cases of truncated images, large patients might seem to have a smaller dw than their actual dw with a proportionately high CTDI$_{vol}$. The exclusion of CT examinations resulted in a smaller number of patients. However, it seems unlikely that the
exclusion of patients with an incomplete field of view may have caused a systematic error. Second, since only CT scanners from one vendor were available in our institution, the developed DRLs might be different for other vendors, since the automatic tube current modulation varies per vendor [29–32]. Third, weight data of patients was not available for all patients in the electronic patient records (only in 5% of the patients). As a result, patient weight could not be extensively evaluated and associated with the exposure data obtained for the different protocols. This is unfortunate since the nDRLs are based on a patient weight of 70 ± 3 kg, and comparison of patient weight would have been of great interest.

Conclusion

Size-specific iDRLs were generated for cervical CT examinations based on the CTDIvol and DLP. Mean institutional CTDIvol and DLP values were well below the nDRLs. The iDRLs allow for a comprehensive analysis of CT radiation exposure with regard to the specific CT cervical protocol and the patient size.

ORCID iDs

Andrea Steuwe https://orcid.org/0000-0001-6259-5765

References

[1] Liang C R, Chen P X H, Kapur J, Ong M K L, Quek S T and Kapur S C 2017 Establishment of institutional diagnostic reference level for computed tomography with automated dose-tracking software J. Med. Radiat. Sci. 64 82–9
[2] Ghetti C, Ortenzia O, Palleri F and Sireus M 2017 Definition of local diagnostic reference levels in a radiology department using a dose tracking software Radiat. Prot. Dosimetry 175 38–45
[3] Tonkopi E, Duffly S, Abdolell M and Manos D 2017 Diagnostic reference levels and monitoring practice can help reduce patient dose from CT examinations Am. J. Roentgenol. 208 1073–81
[4] Boos J, Meineke A, Rubbert C, Heusch P, Lanzman R S, Aissa J, Antoch G and Kröpil P 2016 Cloud-based CT dose monitoring using the DICOM- structured report: fully automated analysis in regard to national diagnostic reference levels Fortschr Röntgenstr 188 288–94
[5] Bundesministerium der Justiz und für Verbraucherschutz 2018 Verordnung zum Schutz vor der schädlichen Wirkung ionisierender Strahlung (Strahlenschutzverordnung—StrlSchV)
[6] Walz M, Wucherer M and Loose R 2019 What are the implications of the new radiation protection ordinance? Radiologe 59 457–66
[7] European Commission 2018 Radiation Protection No 185 European Guidelines on Diagnostic Reference Levels for Paediatric Imaging
[8] Boos J, Thomas C, Appel E, Klosterkemper Y, Schleich C, Aissa J, Bethge O T, Antoch G and Kröpil P 2018 Institutional computed tomography diagnostic reference levels based on water-equivalent diameter and size-specific dose estimates J. Radiol. Prot. 38 536–48
[9] McLaughlin P D et al 2018 Body composition determinants of radiation dose during abdominopelvic CT Insights Imaging 9 9–16
[10] Leng S, Shiang M, Duan X, Yu L, Zhang Y and McCollough C H 2015 Size-specific dose estimates for chest, abdominal, and pelvic CT: effect of intrapatient variability in water-equivalent diameter Radiology 276 184–90
[11] Pyfieroen L, Mulkens T H, Zanca F, De Bondt T, Parizel P M and Casselman J W 2017 Benchmarking adult CT-dose levels to regional and national references using a dose-tracking software: a multicentre experience Insights Imaging 8 513–21
[12] Damilakis J, Fria G, Hierath M, Jaschke W, Repussard J, Schegerer A, Tsapaki V, Verius M and Simeonov G 2018 European Study on Clinical Diagnostic Reference Levels for X-Ray Medical
Imaging—Report and Review on Existing Clinical DRLs EC Tender Contract No ENER/2017/NUCL/SI2.759174 (Brussels: European Commission)

[13] Imai R, Miyazaki O, Horiiuchi T, Kurosawa H and Nosaka S 2015 Local diagnostic reference level based on size-specific dose estimates: assessment of pediatric abdominal/pelvic computed tomography at a Japanese national children’s hospital Pediatr. Radiol. 45 345–53

[14] Gabusi M, Riccardi L, Abiberti C, Vio S and Pausco M 2016 Radiation dose in chest CT: assessment of size-specific dose estimates based on water-equivalent correction Phys. Medica 32 393–7

[15] Boos J, Kropil P, Bethge O T, Aissa J, Schleich C, Sawicki L M, Heinzler N, Antoch G and Thomas C 2018 Accuracy of size-specific dose estimate calculation from center slice in computed tomography Radiat. Prot. Dosimetry 178 8–19

[16] Siemens Healthineers 2019 System Owner Manual—Dosimetry and Imaging Performance Report (Erlangen: Siemens Healthineers) Siemens Healthineers SOMATOM Definition AS Betreiberkurzhandbuch—Dosis- und Bildqualitäts-Report

[17] ICRP 2017 Diagnostic reference levels in medical imaging. ICRP publication 135 Ann. ICRP 46 (1–144)

[18] Bundesamt für Strahlenschutz 2016 Bekanntmachung der aktualisierten diagnostischen Referenzwerte für diagnostische und interventionelle Röntgenanwendungen. Report BAzn AT 15.07.2016 B8 (Salzgitter: Bundesamt für Strahlenschutz)

[19] Kanal K M, Butler P F, Sengupta D, Bhargavan-Chattfield M, Coombs L P and Morin R L 2017 US diagnostic reference levels and achievable doses for 10 adult CT examinations Radiology 284 120–33

[20] McCollough C et al 2014 Use of Water Equivalent Diameter for Calculating Patient Size and Size-Specific Dose Estimates (SSDE) in CT—AAPM Report No. 220 (Alexandria, VA: AAPM)

[21] Becce F, Ben Salah Y, Verdun F R, Vande Berg B C, Lecouvet F E, Meuli R and Omoumi P 2013 Computed tomography of the cervical spine: comparison of image quality between a standard-dose and a low-dose protocol using filtered back-projection and iterative reconstruction Skeletal Radiol. 42 937–45

[22] Vachha B, Brodoefel H, Wilcox C, Hackney D B and Moons G 2013 Radiation dose reduction in soft tissue neck CT using adaptivestatistical iterative reconstruction (ASIR) Eur. J. Radiol. 82 2222–6

[23] Den Harder A M, Willemink M J, De Ruiter Q M B, Schilham A M R, Krestin G P, Leiner T, De Jong P A and Budde R P J 2015 Achievable dose reduction using iterative reconstruction for chest computed tomography: a systematic review Eur. J. Radiol. 84 2307–13

[24] Kahn J, Grupp U, Kaul D, Ning G B, Lindner T and Streitparth F 2016 Computed tomography in trauma patients using iterative reconstruction: Reducing radiation exposure without loss of image quality Acta radiol. 57 362–9

[25] Parakh A, Kortesniemi M and Schindera S T 2016 CT radiation dose management: a comprehensive optimization process for improving patient safety Radiology 280 663–73

[26] Christner J A, Braun N N, Jacobsen M C, Carter R E, Kofler J M and McCollough C H 2012 Size-specific dose estimates for adult patients at CT of the torso Radiology 265 841–7

[27] Boone J M, Strauss K J, Cody D D, McCollough C H, McNitt-Gray M F, Toth T L, Goske M J and Frush D P 2011 Size-Specific Dose Estimates (SSDE) in Pediatric and Adult Body CT Examinations—AAPM Report No. 204 (Alexandria, VA: AAPM)

[28] Boone J et al 2019 Size-Specific Dose Estimate (SSDE) for Head CT—AAPM Report No. 293 (Alexandria, VA: AAPM)

[29] Papadakis A E and Damilakis J 2019 Automatic tube current modulation and tube voltage selection in pediatric computed tomography Invest. Radiol. 54 265–72

[30] Sookpeng S, Martin C J and Gentle D J 2015 Investigation of the influence of image reconstruction filter and scan parameters on operation of automatic tube current modulation systems for different CT scanners Radiat. Prot. Dosimetry 163 521–30

[31] Merzan D, Nowik P, Poludniowski G and Bujila R 2017 Evaluating the impact of scan settings on automatic tube current modulation in CT using a novel phantom Br. J. Radiol. 90 1069

[32] Martin C J and Sookpeng S 2016 Setting up computed tomography automatic tube current modulation systems J. Radiol. Prot. 36 R74–95