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PATIENT DOSES IN CT EXAMINATIONS IN SWITZERLAND: IMPLEMENTATION OF NATIONAL DIAGNOSTIC REFERENCE LEVELS

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Diagnostic reference levels (DRLs) were established for 21 indication-based CT examinations for adults in Switzerland. One hundred and seventy-nine of 225 computed tomography (CT) scanners operated in hospitals and private radiology institutes were audited on-site and patient doses were collected. For each CT scanner, a correction factor was calculated expressing the deviation of the measured weighted computed tomography dose index (CTDI) to the nominal weighted CTDI as displayed on the workstation. Patient doses were corrected by this factor providing a realistic basis for establishing national DRLs. Results showed large variations in doses between different radiology departments in Switzerland, especially for examinations of the petrous bone, pelvis, lower limbs and heart. This indicates that the concept of DRLs has not yet been correctly applied for CT examinations in clinical routine. A close collaboration of all stakeholders is mandatory to assure an effective radiation protection of patients. On-site audits will be intensified to further establish the concept of DRLs in Switzerland.

INTRODUCTION

Since its first introduction in the 1970s, computed tomography (CT) has been established as one of the most important imaging modalities in diagnostic radiology worldwide. Due to short examination times, user friendliness and high diagnostic yield, CT represents more and more the method of choice in clinical routine. This situation is reflected by a distinct increase in the frequency of CT examinations performed over the last few years. In Switzerland, from 1998 to 2003, the number of CT examinations in diagnostic radiology has increased by almost 70 %[1]. The current practice indicates that this trend will continue in the future.

Compared with conventional X-ray imaging techniques, CT involves much larger radiation doses delivered to the patient. For example, the average effective dose of a CT scan of the abdomen or chest is more than 10 times or even 100 times larger than that of a conventional X-ray examination, respectively[2]. While technical advances of state-of-the-art multidetector rows CT (MDCT) scanners have improved the radiation efficiency[3], simultaneously a significant increase in patient doses has been observed due to unjustified and inappropriate application of the more and more complex scan techniques[4]. Today, the contribution of CT to the medical exposure of the Swiss population is estimated to be 50 % of the collective dose, which is of similar order to neighboring countries[1]. Assuming that the linear non-threshold model for radiation-induced cancer risk is valid also in the low dose range (<100 mSv), the excessive and often unjustified application of CT results in a significant increase of the overall cancer risk of the population[5–7].

In medicine there are no legal dose limits for patients when exposing them to ionising radiation. However, medical X-ray examinations must fulfill the two basic principles of radiation protection, i.e. justification (provide more good than harm to the patient) and optimisation (following the ALARA principle 'as low as reasonably achievable'), as first proposed by the International Commission on Radiological Protection (ICRP) in 1996[8]. One powerful tool for optimisation represents the concept of diagnostic reference levels (DRLs), which has been implemented in the Swiss legislation[9]. Article 37a of the Radiological Protection Ordinance specifies that patient doses must be recorded and regularly compared with corresponding DRLs and that radiological procedures must be justified if the DRLs are exceeded. In practice, DRLs are derived by determining the 75th percentile of the distribution of a defined dosimetric quantity for routine conditions. DRLs are specific to a country or region assessing the local radiological practice and should be periodically updated. The application of the concept of DRLs helps the radiologists and radiographers to identify and optimise those imaging protocols, which provide unusually high patient doses.

The aim of this work was to establish national DRLs for the two dosimetric quantities in

CT: volume computed tomography dose index ($CTDI_{vol}$) and dose length product (DLP), of the most frequently performed indication-based CT examinations of adults in Switzerland. On-site audits were carried out and patient doses were collected for CT scanners installed and operated in Swiss hospitals and private radiology institutes.

METHODS

Audits

This work started at the beginning of the year 2007. On-site audits of Swiss hospitals and private radiology institutes operating a CT scanner in diagnostic radiology were carried out. The audit protocol consisted of (1) the assessment of constructional and operational radiation protection issues as well as the quality assurance program; (2) dose measurements; and (3) collection of patient dose data. Hospitals were categorised as university hospitals (UH), cantonal hospitals (CH) and regional hospitals (RH) depending on the number of available patient beds.

Dose measurements

Dose measurements for the determination of weighted CTDI ($CTDI^{head}_{w,measured}$) were performed using a CT head dose phantom together with an X-ray multimeter (Barracuda, RTI Electronics, Mölndal, Sweden) and a pencil-shaped ionisation chamber (DCT10 RS, RTI Electronics, Mölndal, Sweden) with an active length of 10 cm. Both the X-ray multimeter and the pencil-shaped ionisation chamber are calibrated at regular intervals by a calibration laboratory (Institute of Radiation Physics, University Hospital Center and University of Lausanne, Switzerland), which is accredited by the Swiss Federal Office of Metrology. The head phantom is made of solid acrylic and had a thickness of 15 cm and a diameter of 16 cm. For the placement of the ionisation chamber, five probe holes are provided, one in the centre and four around the perimeter, each of them 90° apart and 1 cm from the edge.

Measurements were done by placing the head phantom at the isocentre of the CT scanner and applying one axial slice of a clinical head protocol in sequential scan mode. The beam collimation was set to 1 cm. In total, measurements were repeated five times with identical scan parameters and the ionisation chamber in one of the five probe holes while the others were plugged by acrylic rods. $CTDI^{head}_{w,measured}$ was calculated according to

$$CTDI^{head}_{w,measured} = \frac{1}{3} \cdot CTDI^{head}_{centre} + \frac{2}{3} \cdot CTDI^{head}_{periphery}, \quad (1)$$

where $CTDI^{head}_{centre}$ represents the measured dose in the centre of the head phantom and $CTDI^{head}_{periphery}$ the mean of the four measured doses in the periphery. A correction factor f describing the deviation of $CTDI^{head}_{w,measured}$ to the nominal $CTDI_w$ as displayed on the workstation ($CTDI^{head}_{w,nominal}$) was defined and calculated according to the following equation:

$$f = 1 + \frac{(CTDI^{head}_{w,measured} - CTDI^{head}_{w,nominal})}{CTDI^{head}_{w,nominal}}. \quad (2)$$

Since the dose was measured for one axial slice only (i.e. pitch=1), $CTDI_w$ equals $CTDI_{vol}$.

Patient doses

Patient doses ($CTDI_{vol}$ and DLP) were collected for 21 predefined indication-based CT protocols for adults (Table 1) with already existing DRLs. These previous DRLs were adapted partly from a national survey performed in 2004[10] and partly from recommendations of the European Commission[11].

During on-site audits, radiologists or radiographers operating locally the CT scanner were instructed to select those protocols from Table 1, which were most frequently applied at their radiology department. For each of the selected protocols, the patient database was searched for one representative average-sized patient (excluding cancer patients) and the $CTDI_{vol}$ and DLP per acquisition were recorded, i.e. for an examination consisting of a native phase followed by a contrast agent phase two $CTDI_{vol}$ and DLP values were collected. Patients with following body dimensions were defined as average sized: women: height = 160–170 cm, weight = 60–70 kg; men: height = 175–185 cm, weight = 75–85 kg. To account for differences between nominal and measured doses, the acquired $CTDI_{vol}$ and DLP values of the selected CT protocols were multiplied by the correction factor f:

$$CTDI_{vol,corrected} = CTDI_{vol} \cdot f. \quad (3)$$

$$DLP_{corrected} = DLP \cdot f. \quad (4)$$

The correction factor f was applied to adjust patient doses of all selected CT protocols (head and body protocols), although it was derived from one single measurement using a head phantom only. This approach was based on the assumption that the correction factor represents a scanner-specific measure that is identical for measurements using a head and an abdominal phantom/protocol, respectively. Since both the measured and the nominal CTDI change similarly as a function of volume, this assumption seems to be valid. In addition to doses, the following scan parameters were recorded for each selected

Table 1. Indication-based CT protocols with previous DRLs for $CTDI_{vol}$ and DLP for adults adapted partly from a national survey in 2004 and partly from recommendations of the European Commission.

Protocol	Indication	$CTDI_{vol}$ (mGy)	DLP (mGy·cm)
Skull/brain	Metastases, abscess	60	1000
Brain (vascular)	Bleeding, arteriovenous malformation, aneurysm	80	1000
Sinus	Traumata, sinusitis	30	450
Petrous bone	Traumata, cholesteatoma	30	150
Cervical spine	Adenopathy, abscess	30	600
Neck	Angiography, vascular dissections	30	600
Shoulder	Traumata, arthrography	30	450
Thorax	Infiltration, adenopathy	10	350
Thorax (vascular)	Angiography, pulmonary embolism	15	450
Thorax/upper abdomen	Pulmonary carcinoma, metastases	15	600
Upper abdomen	Liver, spleen, pancreas	15	300
Upper abdomen (vascular)	Vascular pathology	20	400
Abdomen/pelvis	Emergency, abscess	15	700
Abdomen/pelvis (vascular)	Angiography	20	650
Pelvis	Bones, traumata, malformations	10	200
Pelvis (vascular)	Angiography	15	300
Thorax/abdomen/pelvis	Traumata, multiple injuries	20	1100
Lumbar spine	Traumata, fractures	—	—
Lower limbs	Angiography	10	700
Heart (cardiovascular)	Chest pain, cardiac insufficiency	50	1000
Heart	Calcium scoring	10	150

patient: tube voltage, tube current, pitch, scan length and the use of automatic tube current modulation.

Data analysis

Statistical analysis was performed using the software package SPSS 13.0 for Windows. Results for the correction factor f are presented and expressed as median (interquartile range). Correlations between patient doses ($CTDI_{vol,\ corrected}$ and $DLP_{corrected}$) and scan parameters (tube current, pitch and scan length) were statistically tested by linear regression analysis. To account for the skewed distributions, independent variables were logarithmically transformed. A P-value of <0.05 was considered to be statistically significant.

RESULTS

Audits

By the end of the year 2009, about 80 % (179 of 225) of all CT scanners operated in diagnostic radiology in Switzerland were audited (Figure 1). Results demonstrate an even data distribution over different categories of hospitals. Since the beginning of this work 3 y ago, 33 CT scanners have been replaced by scanners of newer type series (7 in UH, 4 in CH, 13 in RH and 9 in private radiology institutes (RI)). All of the replaced scanners were audited and provided additional data for statistical analysis.

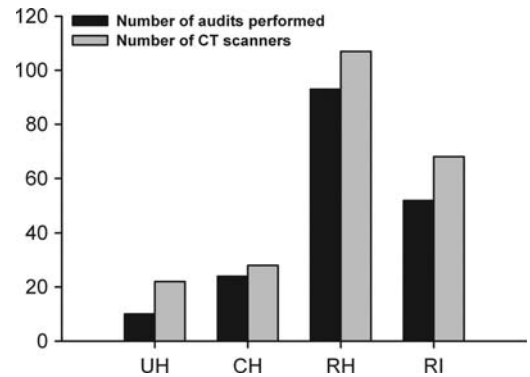

Figure 1. Number of audits performed (black bars) and total number of CT scanners (grey bars) operated in university hospitals (UH), cantonal hospitals (CH), regional hospitals (RH) and private radiology institutes (RI) in Switzerland.

Sixteen and 64 MDCT scanners are most frequently operated in hospitals and private institutes (Figure 2). Each CT scanner was manufactured by one of the four major CT companies (Siemens: 66 CT scanners, General Electric: 45 CT scanners, Philips: 41 CT scanners and Toshiba: 27 CT scanners).

Dose measurements

Dose could not be measured for 13 CT scanners either due to malfunctioning of the scanner or the

measurement device, missing display of $CTDI_{vol}$ or by lack of knowledge of the radiologists or radiographers on how to select one single axial slice. Seven correction factors lay outside the tolerance limit, which ranges between −0.2 and 0.2 as defined in the directive of the Federal Office of Public Health (FOPH) on CT quality assurance[12]. These data were not included in the statistical analysis. For the 159 valid dose measurements, the median correction factor f was calculated to be 0.95 (0.998–0.907). More than 75 % of the correction factors were less than 1 implying that for corresponding CT scanners applied patient doses were lower than patient doses as displayed on the workstation.

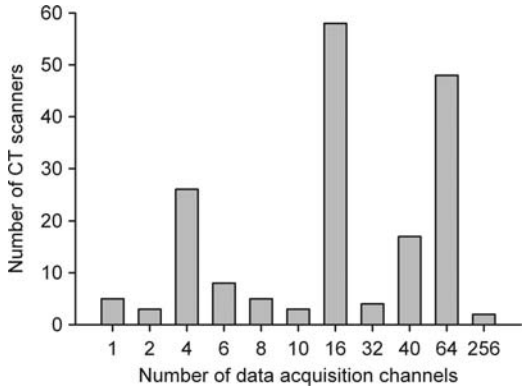

Figure 2. Number of CT scanners for different detector array configurations. Sixteen and 64 multidetector row CT scanners are most commonly used.

Patient doses

Results of the statistical analysis of the $CTDI_{vol,\ corrected}$ and $DLP_{corrected}$ distributions are presented in Tables 2 and 3, respectively. The sample size of the patient doses was sufficiently high for statistical analysis. The most frequently applied CT protocols represented standard examinations of the skull/brain, thorax and abdomen/pelvis as well as examinations of the sinus.

The 75th percentiles of the $CTDI_{vol,\ corrected}$ and $DLP_{corrected}$ distributions of the survey presented here were close to the previous DRLs, which were partly derived from a survey in 2004 and recommendations of the European Commission. However, for a few examinations such as petrous bone, pelvis, lower limbs and heart (cardiovascular), significant deviations were observed. This is illustrated in more detail in Figure 3 showing the underlying dose distributions.

For the petrous bone and the heart, dose distributions are spread over a wide range indicating different practices and application of CT protocols of the various radiological departments. In contrast, the dose distributions for pelvis and the $CTDI_{vol,\ corrected}$ distribution for lower limbs is right skewed as would be theoretically expected. The $DLP_{corrected}$ distribution for lower limbs, however, is extremely broad

Table 2. Parameters derived from descriptive statistics of the $CTDI_{vol,\ corrected}$ distribution for the 21 indication-based CT protocols for adults.

Protocol	Sample size	25th percentile (mGy)	Median (mGy)	75th percentile (mGy)
Skull/brain	203	47	58	69
Brain (vascular)	52	39	57	65
Sinus	143	12	18	25
Petrous bone	45	36	50	74
Cervical spine	93	14	19	28
Neck	41	12	15	21
Shoulder	60	14	20	34
Thorax	120	7	10	13
Thorax (vascular)	146	8	12	15
Thorax/upper abdomen	88	8	13	16
Upper abdomen	64	9	12	16
Upper abdomen (vascular)	45	9	12	15
Abdomen/pelvis	188	10	11	14
Abdomen/pelvis (vascular)	41	11	13	18
Pelvis	82	10	15	20
Pelvis (vascular)	33	10	12	22
Thorax/abdomen/pelvis	111	9	13	16
Lumbar spine	23	16	23	30
Lower limbs	29	8	13	17
Heart (cardiovascular)	26	27	39	65
Heart	14	4	8	11

Table 3. Parameters derived from descriptive statistics of the $DLP_{corrected}$ distribution for the 21 indication-based CT protocols for adults.

Protocol	Sample size	25th percentile (mGy·cm)	Median (mGy·cm)	75th percentile (mGy·cm)
Skull/brain	187	643	867	1083
Brain (vascular)	47	547	860	1134
Sinus	131	157	252	359
Petrous bone	39	252	370	539
Cervical spine	87	270	459	605
Neck	38	342	462	547
Shoulder	53	259	386	551
Thorax	108	233	338	424
Thorax (vascular)	137	243	353	467
Thorax/upper abdomen	84	306	449	623
Upper abdomen	53	219	367	468
Upper abdomen (vascular)	42	231	411	569
Abdomen/pelvis	176	351	497	633
Abdomen/pelvis (vascular)	37	470	607	734
Pelvis	74	277	381	490
Pelvis (vascular)	28	299	429	574
Thorax/abdomen/pelvis	109	383	702	1012
Lumbar spine	20	282	494	896
Lower limbs	26	484	695	1420
Heart (cardiovascular)	23	485	763	1222
Heart	13	52	122	423

because of the large variation in scan lengths ranging from 40 to 150 cm.

Based on the results in Tables 2 and 3 and Figure 3, national DRLs were defined for Switzerland (Table 4). These DRLs will be published in a directive by the FOPH in the beginning of 2010 to pursue the effort of dose optimisation. In addition to the DRLs, also the 25th percentiles of the dose distributions (target values) are shown in Table 4.

Scan parameters (tube voltage, tube current, pitch, scan length and use of automatic tube current modulation) of CT protocols are summarised in Table 5. Although nearly identical tube voltage was used for all protocols, tube current showed significant differences. The highest tube current was applied for examinations of the skull/brain and the cardiovascular system of the heart and was more than three times as high as the tube current for examinations of the sinus. Forty-seven per cent of all skull/brain and brain CTs were performed in sequential acquisition mode. For examinations of the head in helical acquisition mode, the pitch was smaller than for examinations of the thorax, abdomen and pelvis. Depending on the anatomical region, median scan lengths showed huge variations ranging from a minimum of 11 cm for the sinus to a maximum of 115 cm for the lower limbs. Unlike for examinations of the head, automatic tube current modulation was frequently switched on.

$DLP_{corrected}$ correlated with both scan length ($R^2 = 0.34$, $P < 0.001$) and $CTDI_{vol,\ corrected}$ ($R^2 = 0.06$, $P < 0.001$). This is expected from theory since DLP is defined as CTDI times scan length. From Figure 4a and b, it is obvious that the longer the scan length and the higher $CTDI_{vol,\ corrected}$, the higher $DLP_{corrected}$. Interestingly, the slope of the regression line in Figure 4a is around twice as large as that in Figure 4b. This implies that $DLP_{corrected}$ is more (positively) influenced by $CTDI_{vol,\ correlated}$ than by the scan length. $CTDI_{vol,\ corrected}$ demonstrated also a significant correlation with the tube current ($R^2 = 0.22$, $P < 0.001$) and pitch ($R^2 = 0.14$, $P < 0.001$). The slopes of both regression lines are similar but with opposite sign as illustrated in Figure 4c and d.

DISCUSSION

In this work, national DRLs in CT were established for 21 indication-based CT examinations of adults in Switzerland. This is the first time DRLs fully base on a nationwide survey on CT doses since previous DRLs were adapted partly from a small survey and partly from recommendations of the European Commission. A unique feature of the data presented here is the manner in which it was collected. While most of the countries use questionnaires or web-based databases for analysis[13–15], patient doses during on-site audits were collected. Thereby, each radiology department operating a CT scanner in diagnostics was assured to participate in the survey that provided a solid basis for the assessment of the national radiological practice. Moreover, incorrect data acquisition could be eliminated since data were

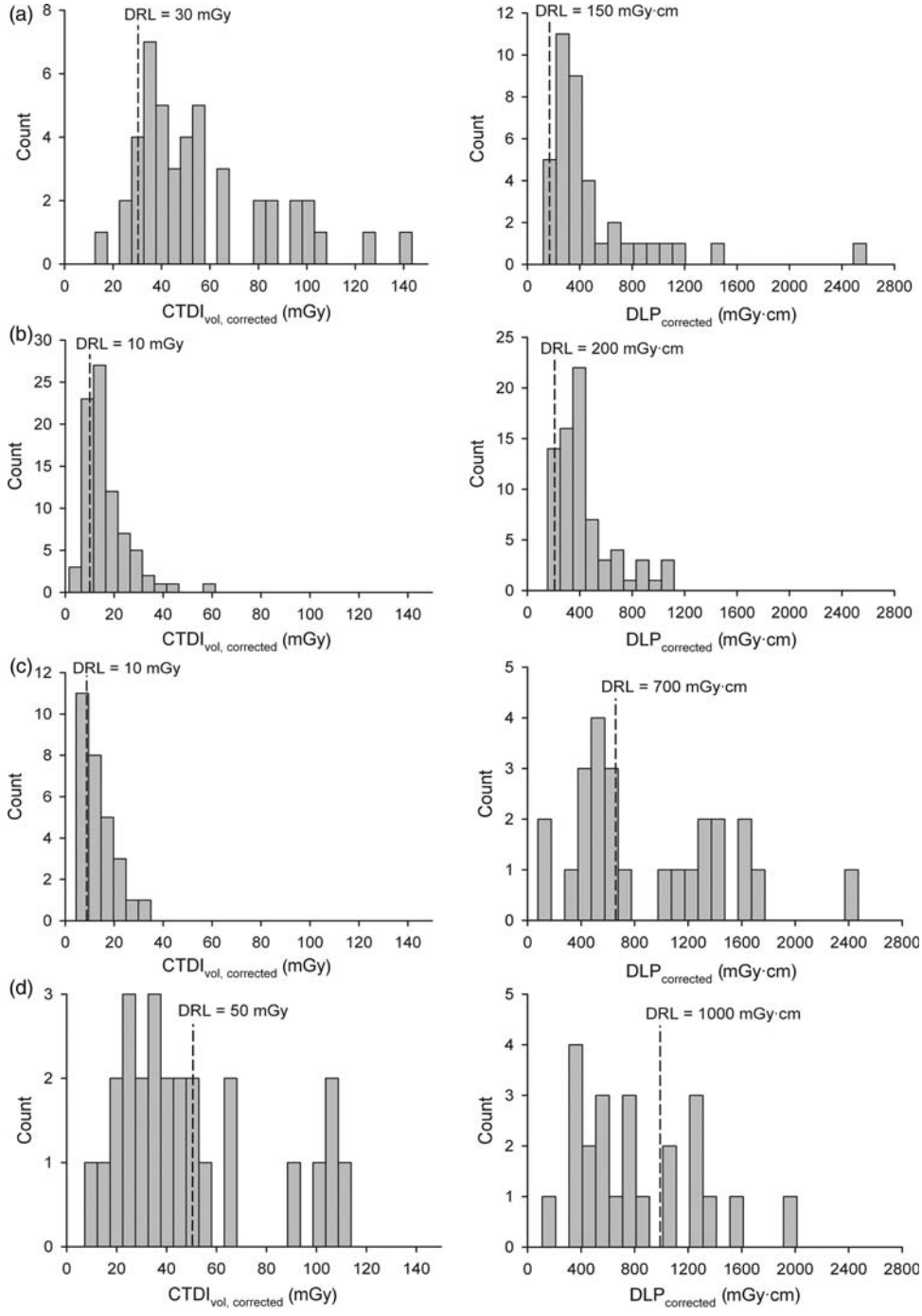

Figure 3. Dose distributions of $CTDI_{vol,\ corrected}$ (left row) and $DLP_{corrected}$ (right row) for examinations of the petrous bone (**a**), pelvis (**b**), lower limbs (**c**) and heart (**d**). Corresponding DRLs are indicated by a dashed line.

Table 4. National DRLs (75th percentiles) and target values (25th percentiles) for $CTDI_{vol}$ and DLP for adults in Switzerland based on a nationwide survey performed in 2007–2010.

Protocol	DRL		Target value	
	$CTDI_{vol}$ (mGy)	DLP (mGy·cm)	$CTDI_{vol}$ (mGy)	DLP (mGy·cm)
Skull/brain	65	1000	45	600
Brain (vascular)	65	1000	45	600
Sinus	25	350	10	150
Petrous bone	50	250	35	200
Cervical spine	30	600	15	250
Neck	20	500	10	350
Shoulder	30	500	15	250
Thorax	10	400	5	250
Thorax (vascular)	15	450	10	250
Thorax/upper abdomen	15	600	10	300
Upper abdomen	15	400	10	200
Upper abdomen (vascular)	15	500	10	250
Abdomen/pelvis	15	650	10	350
Abdomen/pelvis (vascular)	15	650	10	500
Pelvis	20	500	10	300
Pelvis (vascular)	20	500	10	300
Thorax/abdomen/pelvis	15	1000	10	700
Lumbar spine	30	850	15	300
Lower limbs	15	1000	10	700
Heart (cardiovascular)	50	1000	30	500
Heart	10	150	5	50

collected locally. Obviously, a good communication between the medical staff and the auditors represents a necessary prerequisite. These audits had the further advantage that the current practice could be discussed with the radiologists and radiographers and serious deficiencies (e.g. the use of standard clinical 'high-dose' CT protocols for the scout scan and the application of too large scan ranges also covering anatomical regions that are not relevant for the clinical indication) could be corrected instantly.

A limitation of the study was the restricted time duration of the audit. During audits CT scanners were blocked and clinical routine work was interrupted. Thus, only dose of one representative standard patient for the most frequently performed CT examinations could be collected. However, as illustrated in Tables 2 and 3, the sample size was sufficiently large for derivation of national DRLs. This was particularly true for standard examinations of the skull/brain, thorax and abdomen/pelvis, which are most commonly performed in Switzerland and most probably also worldwide. In contrast, cardiovascular examinations provided less data since only a few centres in Switzerland are specialised and appropriately equipped for cardiac radiology. Another limitation of this study was the qualitative definition of an average-sized ('standard') patient. The most correct way for assessing the patient size would have been to determine the cross-sectional area of the imaged anatomical region. However, audit time was limited and the calculation of the cross-sectional area was not feasible. Therefore, the assessment of an average size was based on the body dimensions of the patient (height and weight). For each selected patient, the scan parameters were in accordance with the standard settings confirming the appropriate definition of an average-sized patient by the local medical staff.

One part of the audit consisted of measuring the weighted CTDI of a standard clinical head protocol. In Switzerland, CTDI measurements are part of the quality assurance programme and are normally carried out by the technician of the CT manufacturer. As required by the Swiss legislation, these measurements must be performed at regular intervals and result must be documented. In this work, however, CTDI was measured in order to determine the deviation from the nominal weighted CTDI as displayed on the workstation. According to the Swiss legislation, displayed CTDI values must lay within a tolerance limit of ± 20 % of the measured CTDI values. For many CT scanners, deviations up to -20 % were observed. Legal requirements are fulfilled; however, 'real' patient doses are thereby significantly underestimated. This is critical when estimating effective doses and thus the radiation-induced cancer risk. The application of the correction factors allows the radiologists and radiographers to estimate effective doses based on 'real' CTDI and DLP values and to correctly apply

Table 5. Scan parameters of CT protocols for adults presented as median (interquartile range). The tube current is expressed in milliampere per second per tube rotation.

Protocol	Tube voltage (kV)	Tube current (mAs per rotation)	Pitch	Scan length (cm)	Tube current modulation (%)
Skull/brain	120 (120–130)	320 (250–350)	0.75 (0.56–1.0)	15 (13–16)	27
Brain (vascular)	120 (120–120)	270 (200–350)	0.78 (0.6–0.95)	16 (11–22)	34
Sinus	120 (120–120)	100 (60–150)	0.75 (0.56–0.9)	11 (10–12)	18
Petrous bone	120 (120–120)	202 (150–339)	0.63 (0.5–0.8)	6 (4–10)	10
Cervical spine	120 (120–130)	187 (150–250)	0.85 (0.63–1.0)	18 (16–23)	72
Neck	120 (120–120)	165 (125–220)	0.94 (0.83–1.2)	25 (18–28)	82
Shoulder	120 (120–140)	186 (150–296)	0.7 (0.56–0.9)	14 (11–20)	68
Thorax	120 (120–120)	120 (100–200)	1.2 (0.98–1.38)	32 (30–35)	78
Thorax (vascular)	120 (120–120)	136 (100–200)	1.13 (0.94–1.39)	30 (28–33)	81
Thorax/upper abdomen	120 (120–120)	150 (110–200)	1.18 (0.98–1.38)	38 (30–44)	80
Upper abdomen	120 (120–120)	163 (146–204)	1.17 (0.9–1.38)	25 (21–31)	69
Upper abdomen (vascular)	120 (120–120)	155 (115–221)	0.96 (0.89–1.2)	26 (23–37)	81
Abdomen/pelvis	120 (120–120)	165 (126–224)	1.07 (0.93–1.38)	41 (38–45)	83
Abdomen/pelvis (vascular)	120 (120–120)	191 (149–232)	1.17 (0.99–1.36)	41 (38–45)	74
Pelvis	120 (120–130)	180 (120–220)	0.96 (0.79–1.16)	25 (20–30)	63
Pelvis (vascular)	120 (120–120)	163 (150–238)	0.9 (0.79–1.18)	25 (21–38)	82
Thorax/abdomen/pelvis	120 (120–120)	177 (107–214)	1.15 (0.98–1.38)	60 (51–67)	84
Lumbar spine	120 (120–138)	264 (221–300)	0.69 (0.56–0.9)	21 (15–27)	68
Lower limbs	120 (120–120)	190 (92–236)	0.94 (0.79–1.14)	115 (92–125)	62
Heart (cardiovascular)	120 (120–120)	380 (263–800)	0.2 (0.2–0.2)	14 (12–18)	72
Heart	120 (120–120)	180 (68–256)	0.2 (0.19–1.0)	13 (12–16)	69

In case of modulated tube current, the mean overall slices were calculated and used for analysis. Percentages in the last column express how often the automatic tube current modulation was switched on if available.

national DRLs. The approach presented here was based on the assumption that the correction factor was a characteristic measure for each CT scanner and did not change for different CT protocols. However, multiple measurements and averaging would be mandatory to increase the accuracy of correcting appropriately patient doses. For a couple of CT scanners, CTDI could not be measured because radiographers did not know how to select one single axial slice. This lack of knowledge might be one possible explanation for the inappropriate use of CT. More training of the radiographers and the collaboration with medical physicists is necessary for an appropriate use of the more and more complex CT scan sequences.

Based on the 75th percentiles of the analysed patient dose distributions, Swiss DRLs were established as shown in Table 4. In addition, the 25th percentiles defined as target values are also presented. Target values should demonstrate that optimisation does not end just below the DRLs but is further possible. Most of the established DRLs are similar or slightly smaller than previous DRLs, which were partly derived from a national survey 6 y ago and recommendations of the European Commission with a few exceptions (petrous bone, pelvis, lower limbs and heart). For the petrous bone and the heart, doses showed an extremely broad distribution (Figure 3a and d). The doses varied by up to a factor of 10. This is mainly caused by different clinical practices of the radiology departments. A DRL of 50 mGy was defined for $CTDI_{vol}$ of both examinations and of 250 mGy·cm for DLP of the petrous bone assuming a typical scan length of 5 cm. For the pelvis and lower limbs, the theoretically expected right-skewed dose distributions were accounted for by increasing the DRLs for $CTDI_{vol}$ to 20 and 15 mGy, respectively, and to 500 mGy·cm for DLP of the pelvis. The typical scan length for lower limbs was assumed to be 70 cm resulting in a DRL of 1000 mGy·cm for DLP. Surprisingly, vascular protocols of the brain, thorax, abdomen and pelvis provided similar or slightly larger DRLs compared with the non-vascular protocols. This is in contrast to findings from literature showing similar image quality in terms of contrast-to-noise ratio for

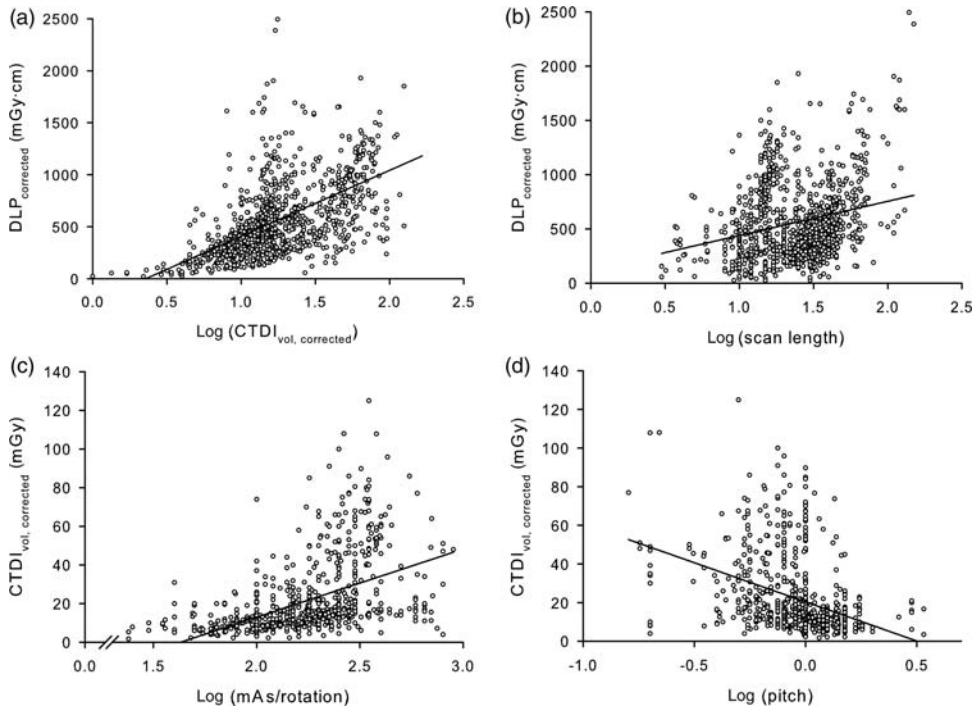

Figure 4. Scatter plots of $DLP_{corrected}$ vs. logarithmically transformed $CTDI_{vol,\ corrected}$ (**a**) and scan length (**b**) as well as $CTDI_{vol,\ corrected}$ vs. logarithmically transformed tube current (**c**) and pitch (**d**). Data points are presented by open circles and the regression curve by a solid line.

reduced tube voltages of 80–100 kV and thus reduced doses compared with standard settings of 120 kV[16, 17]. Statistical analysis for lumbar spine CT resulted in a DRL of 30 mGy for $CTDI_{vol}$ and 850 mGy·cm for DLP, indicating a scan length of almost 30 cm. This means that the entire lumbar spine (including the five lumbar vertebral bodies) is routinely scanned, although an average number of three bodies would be clinically sufficient for the diagnosis of lower back pain with sciatica.

Above findings indicate that there is still a large optimisation potential of diagnostic CT examinations for adults in Switzerland. The reasons are diverse: some radiological departments are not aware of the concept of DRLs; radiologists or radiographers are not willing to optimise their CT protocols due to lack of time or interest; radiologists are practising defensive medicine. This demonstrates the need for periodic re-audits at short-time intervals and the consequent justification of CT examinations, which provide unusually high patient doses. In addition, this year the FOPH will launch a project to introduce clinical audits in Switzerland in order to further reduce patient doses. Clinical audits allow to identify and eliminate unjustified radiological procedures and to optimise the justified ones.

In most of the European countries, national DRLs for adults have been introduced and established based on nationwide surveys[15, 18–20]. For the most frequently performed CT examinations of the head, thorax and abdomen, differences between DRLs of Switzerland and other European countries are very small. The largest differences for DRLs of the CTDI are found between Switzerland and Germany (thorax: 15 vs. 22 mGy, abdomen: 15 vs. 24 mGy) and for DRLs of the DLP between Switzerland and Denmark (thorax: 450 vs. 700 mGy·cm, abdomen: 650 vs. 800 mGy·cm). In general, Swiss DRLs are similar or slightly smaller than DRLs of other European countries and even significantly reduced when comparing to DRLs as proposed by the European Commission[21].

In this work, patient doses of children were also collected. However, since in Switzerland only a few centres are specialised in paediatric radiology, the amount of acquired data did not allow a statistically significant analysis. Germany established national DRLs for paediatric CT examinations based on a nationwide survey in 2005–06[22]. Results of the work have shown that patient doses for children were similar to German DRLs (data not presented). As a consequence,

Switzerland fully adopts German DRLs for the national practice[23].

In addition to patient doses also fundamental CT scan parameters (tube voltage, tube current, pitch, scan length and use of automatic tube current modulation) were concurrently recorded. These parameters were shown to have a major influence on radiation dose[24]. The effect of tube voltage and the use of automatic tube current modulation could not be statistically tested. For almost every CT examination, a tube voltage of 120 kV was applied (Table 5). In order to test the influence of the automatic tube current modulation doses should have been recorded for the same patient and examination, while the modulation algorithm was switched on and off, respectively. This, however, was never the case since only one dose value was assessed for one specific examination. Tube current, pitch and scan length showed a strong correlation with dose. The scan length presents that parameter which can be most easily modified by the radiologist or radiographer. Depending on the indication, the scan length must always be restricted to the region of interest to avoid unnecessary exposure that provides no additional information. The modification of tube current and pitch is more sophisticated since most of the modern CT scanners do not allow changing these parameters separately. Often they are coupled and while changing one of them also the other gets modified. This makes it difficult to estimate their effect on image quality. Thus, those CT protocol parameters should not be modified.

CONCLUSION

In this work, national DRLs for $CTDI_{vol}$ and DLP of 21 indication-based CT protocols for adults were established in Switzerland based on local audits and taking into account the differences between measured doses and doses as displayed on the workstations. Results showed that most of these DRLs are similar or slightly smaller than previous DRLs, which were partly derived from a national survey in 2004 and recommendations of the European Commission. However, for examinations of the petrous bone, pelvis and lower limbs, DRLs were increased by a factor ranging between 1.5 and 2. The observed broad dose distributions indicate that the concept of DRLs has not yet been fully understood and implemented in clinical routine. Further efforts are required to reduce patient doses. These include (1) periodical re-audits, (2) the establishment of a consulting service free of charge that provide expert advice to radiologists on CT protocol optimisation and (3) the introduction of clinical audits to identify and eliminate unjustified CT examinations.

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