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Derivation of new diagnostic reference levels for neuro-paediatric computed tomography examinations in Switzerland

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Abstract

Purpose. Definition of new national diagnostic reference levels (DRLs) for volume computed tomography dose index ($CTDI_{vol}$) and dose length product (DLP) for neuro-paediatric CT examinations depending on the medical indication. *Methods*. Paediatric cranial CT data sets acquired between January 2013 and December 2016 were retrospectively collected between July 2016 and March 2017 from eight of the largest university and cantonal hospitals that perform most of the neuro-paediatric CTs in Switzerland. A consensus review of $CTDI_{vol}$ and DLP was undertaken for three defined anatomical regions: brain, facial bone, and petrous bone, each with and without contrast medium application. All indications for cranial CT imaging in paediatrics were assigned to one of these three regions. Descriptive statistical analysis of the distribution of the median values for $CTDI_{vol}$ and DLP yielded values in the minimum, maximum, 25th percentile (1st quartile), median (2nd quartile), and 75th percentile (3rd quartile). New DRLs for neuro-paediatric CT examinations in Switzerland were based on the 75th percentiles of the distributions of the median values of all eight centres. Where appropriate, values were rounded such that the DRLs increase or at least remain constant as the age of the patient increases. *Results.* Our results revealed DRLs for $CTDI_{vol}$ and DLP up to 20% lower than the DRLs used so far in Switzerland and elsewhere in Europe. *Conclusions.* This study provides Swiss neuro-paediatric CT DRL values to establish optimum conditions for paediatric cranial CT examinations. Periodic national updates of DRLs, following international comparisons, are essential.

Keywords: radiation protection, radiation monitoring, CT, neuro-paediatrics, DRL, $CTDI_{vol}$, DLP

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

Abbreviations

CM	contrast medium
CT	computed tomography
CTDIvol	volume computed tomography dose index
DLP	dose length product
DRL	diagnostic reference level
FOPH	Federal Office of Public Health
MRI	magnetic resonance imaging
SL	scan length

1. Introduction

Exposure of children to ionising radiation during computed tomography (CT) examinations is a cause for concern. Most neuro-paediatric CT examinations take place in emergency situations, and a five-fold increase in frequency in the United States was documented from 1995–2008 [1]. This corresponds to a compound annual growth rate of 13.2% of paediatric emergency department visits that included a CT and a doubling time of approximately 5.6 years [1]. In 2008, CT was performed in 1.7 million of a total of 27.9 million paediatric visits to the emergency department [1]. Owing to its widespread availability, paediatric CT imaging is frequently used to enable correct diagnosis in the outpatient setting, e.g. for trauma and craniofacial surgery patients, who may undergo multiple head CTs during preoperative treatment and follow-up. Craniofacial paediatric CT imaging is commonly used for diagnostic evaluation, operative planning, and outcome analysis, despite increasing controversy regarding radiation exposure [2, 3]. The general increase of paediatric CT can be attributed to the availability of fast helical and multi-detector scanning, reducing the need for sedation and allowing the examination of younger, sicker, and uncooperative children.

Many university and regional hospitals in Switzerland use low-dose CT protocols, which partly limit the diagnostic value in regard to the clinical indication and necessity of repetition [4]. Low-dose CT protocols reduce the amount of ionising radiation exposure for paediatric patients but image quality and diagnostic utility are often significantly compromised.

Particularly in neurosurgical practice, children often require multiple brain CTs for some conditions e.g. hydrocephalus, intracranial haemorrhage, postoperative evaluation, and intracranial infectious fluid collections. Neurosurgeons are looking for very specific information on the CT images, in terms of the pathology and anatomical position; a decreased image quality may not be adequate. MRI—the imaging method of choice for children in most clinical circumstances—is not available in every hospital at all times.

In 2012, Pearce *et al* published a retrospective epidemiological study on the relationship between paediatric head CTs and increased risk of developing brain cancer and leukaemia. The authors reported that CT scans in children resulting in cumulative doses of about 50 mGy, could almost triple the risk of leukaemia, whereas doses of about 60 mGy might triple the risk of brain cancer [5]. Mathews *et al* reviewed a large cohort study of 680 000 children in Australia who underwent a CT examination between 1985 and 2005; a 24% higher cancer incidence in exposed than in non-exposed children was observed [6]. In 2013, the United Nations Scientific Committee on the Effects of Atomic Radiation considered the effects of radiation exposure on children and concluded that for a given radiation dose, children are generally at more risk of tumour induction than adults [7]. This emphasises that the estimates of lifetime cancer risk for those exposed as children might be a factor of two to three times higher than estimates for a population exposed at all ages [7].

These studies, together with the 'as low as reasonably achievable' (ALARA) concept in radiation protection, triggered worldwide awareness of the need for justification of paediatric CT examinations and optimisation of doses [8]. This led the International Commission on Radiological Protection (ICRP) to introduce the concept of diagnostic reference levels (DRLs) [9]. The objective was to suggest radiation dose levels for CTs under defined conditions in standard patients [10]. DRLs are not dose limits for individual patient examinations, rather they are used to identify those situations in which, for a specific radiological procedure, unusually high or low doses necessitate optimisation actions [10–13]. In recent years, DRLs have proved to be a valuable tool to reduce large differences in CT radiation doses between different radiological facilities. However, since the DRL is defined as the 75th percentile of the dose distribution, there is still a large potential to achieve further dose optimisation [10].

Paediatric CTs in small- and medium-sized hospitals are obviously performed much less often than adult CTs. The medical staff lack relevant experience and the use of the paediatric CT protocols is not optimised [14–19]. It is important to pay particular attention to paediatric CTs, because children are much more sensitive to ionising radiation than adults [16, 17]. Reliable CT scanning in a safe and effective manner is challenging in children because body size must be more carefully considered, patient cooperation and understanding is often limited or absent, and there is a lower tolerance for CT protocol errors in paediatrics [16, 17].

The purpose of our retrospective multicentre study was to define new national DRLs for volume computed tomography dose index ($CTDI_{vol}$) and dose length product (DLP) of the most frequently performed neuro-paediatric CT examinations in Switzerland. These new DRLs are aimed to serve as an initial benchmark and provide guidance for the optimised application of CT protocols in neuroradiology departments in Swiss hospitals performing paediatric CTs. The strength, value, and originality of our study is that we propose DRLs for medical indications. The DRLs of other European countries were used for comparison.

2. Materials and methods

According to the Swiss radiation protection legislation (Radiological Protection Ordinance, Article 34, paragraph 2 [20]), the radiation protection authority is allowed to collect and process anonymised data of radiological examinations and, for this reason, no ethical approval was required for this study.

2.1. Data collection

Paediatric cranial CT data sets acquired between January 2013 and December 2016 were retrospectively collected during a 9-month period (July 2016 to March 2017) from the eight largest university and cantonal hospitals in Switzerland performing most of the neuro-paediatric CTs nationwide. The participating hospitals were the university hospitals of Geneva, Lausanne, Bern, Basel, and Zurich and the cantonal hospitals of Chur, Aarau, and Lucerne.

Anonymised dose data were collected from four Siemens CT scanners (Somatom Definition Edge), four GE CT scanners (Brightspeed 8, Discovery 750 HD, Lightspeed VCT, Revolution), three Toshiba CT scanners (Aquilion CXL, Aquilion One, Aquilion RXL), and one Philips CT scanner (Brilliance CT 64). The cantonal hospital of Aarau and the university hospital of Lausanne each provided dose data from three CT scanners; the other hospitals provided dose data from one CT scanner. In four hospitals, data were collected using commercial dose management software; in two hospitals, data were collected using data collection software developed in-house; and in two hospitals, data were manually registered in specific spreadsheets. The collected dose data were summarised in an Excel spreadsheet and sent to the project coordinator for analysis. Throughout the period of data collection, the project coordinator maintained close contact with the participating centres to provide support and clarification and give feedback when potential for increased efficiency was seen.

2.2. Patient data

The study population of children aged 0–16 years was classified into four age groups: <1.5 years, 1.5–5.5 years, 5.5–10.5 years, and 10.5–16 years. This age classification allowed the comparison of the actual Swiss practice in neuro-paediatric CT to the earlier practice in Switzerland and in other countries.

For each child, we gathered the following data: 1. age; 2. date of the CT; 3. indication for the CT; 4. exposure data, $CTDI_{vol,}$ and DLP, as well as approximated scan length (SL) calculated by dividing the DLP by the $CTDI_{vol}$; 5. number of scans (if scans were repeated; e.g. because of lack of patient cooperation or excessive motion). The values used for the $CTDI_{vol}$ and DLP were the displayed values. Differences between the displayed and measured $CTDI_{vol}$ were in conformity with Swiss legal requirements (limit of $\pm 20\%$).

2.3. CT indications

A consensus review between the study coordinator, the local physicists collecting the data sets and the responsible person of the radiation protection authority of the $CTDI_{vol}$ and DLP was undertaken for the following three anatomical regions: brain, facial bone, and petrous bone; each with and without contrast medium (CM) application. All indications for cranial CT imaging were assigned to one of these regions. The medical indications for these defined anatomical regions, each with and without CM, are summarised in table 1.

All paediatric neuro CTs analysed were indicated after explicit consultation with the clinician and were of sufficient diagnostic image quality with regard to the clinical question. None of the scans were acquired only for study purposes.

Table 1. Indications for cranial CT imaging in paediatrics assigned to the three anatomic subgroups: brain, facial bone, and petrous bone, with and without CM.

Anatomical region	Medical indication
Brain without CM application	• brain trauma • child abuse • evaluation of ventricular width (e.g. in patients with suspected shunt dysfunction) • localisation of brain pressure probes • preoperative determination of extent of craniosynostosis • dysmorphia of the skull • detection and evaluation of calcifications (e.g. in syndromes such as Sturge–Weber)
Brain with CM application	• in complicated mastoiditis to rule out intracranial complications like sinus vein thrombosis, intracranial abscess, or Bezold's abscess • central and anterior skull base tumours (e.g. fibrous dysplasia, ossifying fibroma, ecchordis physalliphora) • for staging of systemic diseases like Langerhans histiocytosis or mastocytosis with multifocal brain manifestations
Facial bone without CM application	• midface trauma (fracture evaluation) including the paranasal sinus, nose, and orbit • choanal atresia and stenosis of piriform aperture • polyposis nasi, Morbus Widal, and evaluation of uncomplicated sinusitis • dentogenic pathologies (e.g. periradicular cysts) • for foreign body localisation after midface trauma or in case of ingestion • juvenile temporomandibular arthropathy
Facial bone with CM application	• complicated sinusitis • acute and chronic osteomyelitis of midface and anterior skull, as well as recurrent infections (e.g. recurrent multifocal osteomyelitis in children) • osteonecrosis (e.g. radiogenic induced) • suspected nasal, paranasal, or orbital tumours • tumour-like lesions and temporomandibular joint tumours (e.g. chondromatosis)
Petrous bone without CM application	• congenital anomalies of the temporal bone, middle ear cavity, and inner ear

Table 1. (Continued.)

Anatomical region	Medical indication
	• for postoperative cochlear implant location, or localisation of hearing aids
Petrous bone with CM application	• in complicated mastoiditis to rule out periauricular complications like Bezold's abscess • posterior skull base tumours (e.g. fibrous dysplasia, ossifying fibroma) • staging of systemic diseases like Langerhans histiocytosis or mastocytosis with focal posterior skull base manifestation • acute or chronic osteomyelitis, as well as recurrent infections of posterior skull base

2.4. Patient data analysis

The data acquired were analysed per centre, and stratified according to age group and anatomical region; with and without CM. If more than one CT scan had to be acquired for a patient, e.g. if the patient had moved or needed several follow-up CT scans; each was evaluated separately.

For each age group, anatomic region, and hospital, median values for $CTDI_{vol}$ and DLP were calculated. Descriptive statistical analysis of the resulting distributions of the median values yielded values for minimum, maximum, 25th percentile (1st quartile), median (2nd quartile), and 75th percentile (3rd quartile). In accordance with the recommendations of the ICRP [9], national DRLs were defined as the 75th percentiles of the dose distributions.

The results for brain CTs were compared with the currently valid DRLs in Switzerland [11], from *L'Institut de Radioprotection et de Sûreté Nucléaire* (IRSN) France 2009 [21], the American Association of Physicists in Medicine (AAPM) [22], and the European Guidelines on DRLs for Paediatric Imaging [23]. For the international comparison of the anatomic region of facial bone we used the available valid DRLs from Switzerland [11] and the IRSN France [21] and, for petrous bone, DRLs from the IRSN France [21], which were the only ones available. Our literature search did not yield other comparable DRLs for the anatomic regions of facial bone and petrous bone; in our experience the second and third most frequently CT-examined anatomic regions in children. Note that the survey from *L'Institut de Radioprotection et de Sûreté Nucléaire* (IRSN) France 2009 does not document DRLs for children older than 10 years [21].

Data were reviewed and processed by an experienced medical physicist, and an independent quality assurance check of the processed data was performed. If necessary, clarification from the project coordinator was requested. At the end of our study each of the participating centres received a copy of their recorded data to verify whether the data were correct and if any comments needed to be added.

2.5. Statistical analysis

The statistical analysis was performed using R software version 3.3.3 (R: a language and environment for statistical computing, R Foundation for Statistical Computing, Vienna, Austria). The statistical significance of differences between the different age groups for each anatomical localisation was tested with Kruskalv–Wallis (significance level $p = 0.05$).

3. Results

In total, 1645 (100%) paediatric neuro CTs were recorded and retrospectively analysed: 1172 (71.2%) brain CTs without CM application; 127 (7.7%) brain CTs with CM application; 206 (12.5%) facial bone CTs without CM application; 14 (0.9%) facial bone CTs with CM application, 125 (7.6%) petrous bone CTs without CM application, and 1 (0.1%) petrous bone CT with CM application. The total frequencies of all types of examinations are given in table 2.

The number of CTs with CM application was very low; dose data for CTs with and without CM application for the three anatomic regions (results in the appendix) were pooled for further analysis. For most of the studies with CM application the same CT protocol with the same scanning parameters were used as for native CT studies. In table 3, the 75th percentiles of the distribution of the median values of all eight centres for $CTDI_{vol}$ and DLP are presented for the three anatomic regions. The values for $CTDI_{vol}$ and DLP recorded for each centre separately are documented in the appendix.

The comparison of the 75th percentiles of the distribution of the median values of all eight centres for $CTDI_{vol}$ and DLP for brain CTs to the currently valid DRLs in Switzerland [11], from IRSN France [21], the AAPM [22], and the European Guidelines on DRLs for Paediatric Imaging [23] revealed from 10% up to 40% lower values; compare figures 1(a) and (b). The international comparison of the anatomic regions, facial bone, and petrous bone, with the available valid DRLs for facial bone from Switzerland [11] and the IRSN France [21] and with the available DRLs from the IRSN France [21] for petrous bone, also revealed decreases in the 75th percentiles from 5%–70% in comparison to the currently valid values as shown in figures 2(a) and (b) and 3(a) and (b).

For $CTDI_{vol}$, there was a significant difference between the age classes for the brain ($p < 0.001$) and the facial bone ($p < 0.05$), but not for the petrous bone ($p = 0.24$). Concerning the DLP value, significant differences between age classes were found for the brain ($p < 0.001$), the facial bone ($p = 0.01$), and the petrous bone ($p = 0.02$).

In contrast, the SL for the three anatomical regions was higher than the currently valid values in Switzerland [11], as well as those from IRSN France [21], the AAPM [22], and the European Guidelines on DRLs for Paediatric Imaging [23] (see appendix).

In our large cohort of CTs, no wide variations in dose were found between the participating hospitals (compare appendix).

New DRLs for neuro-paediatric CT examinations in Switzerland were based on the 75th percentiles of the distributions of the median values of all eight centres. Where appropriate, values were rounded such that the DRLs increase, or at least remain constant, as the age of the patient increases. From our point of view such rounding of the values is practical for hospitals acquiring paediatric CTs. Table 3 shows the rounded values that were obtained taking the standard deviations into consideration. The new proposed DRLs for the three anatomic regions—brain, facial bone, and petrous bone—are presented in table 3 and figures 4(a) and (b).

Table 2. Total frequencies of all types of examinations at all eight participating centres.

Centres	Brain without CM	Brain with CM	Facial bone without CM	Facial bone with CM	Petrous bone without CM	Petrous bone with CM	Total number of CTs	Total % of CTs
A	149	16	34	4	23	1	**227**	**14**
B	130	31	18	2	17	0	**198**	**12**
C	17	0	5	1	3	0	**26**	**2**
D	38	0	4	1	9	0	**52**	**3**
E	28	11	2	1	9	0	**51**	**3**
F	39	10	29	3	21	0	**102**	**6**
H	309	25	47	0	0	0	**381**	**23**
I	462	34	67	3	43	0	**609**	**37**
Total number of CTs	1172	127	206	14	125	1	**1645**	—
Total % of CTs	71.2%	7.7%	12.5%	0.9%	7.6%	0.1%	—	**100**

Table 3. New proposed rounded DRLs (75th percentiles) as well as target values (median values) for $CTDI_{vol}$ and DLP for neuro-paediatric CT examinations, age-related and separated according to the three anatomic regions: brain, facial bone, and petrous bone. For $CTDI_{vol}$ compare figure 4(a) and for DLP compare figure 4(b).

Anatomical region	Patient's age [years]	DRLs (75th percentile) $CTDI_{vol}$ [mGy]	DRLs (75th percentile) DLP [mGy.cm]	Target value (median) $CTDI_{vol}$ [mGy]	Target value (median) DLP [mGy.cm]
Brain without and with CM	<1.5	25	350	20	300
	1.5–5.5	30	420	24	390
	5.5–10.5	35	540	30	490
	>10.5	40	670	36	610
Facial bone without and with CM	<1.5	10	120	7	90
	1.5–5.5	10	120	7	90
	5.5–10.5	15	170	7	110
	>10.5	15	200	10	140
Petrous bone without and with CM	<1.5	20	110	17	95
	1.5–5.5	30	200	20	110
	5.5–10.5	30	200	20	150
	>10.5	30	200	20	150

4. Discussion

Following our study, we established new age-related DRLs for $CTDI_{vol}$ and DLP for the most frequently performed neuro-paediatric CT examinations in Switzerland. Our results with new DRLs for $CTDI_{vol}$ and DLP were up to 20% lower than the DRLs so far used in Switzerland, as well as in other European countries (figures 1–3), confirm the importance of regular re-assessment of the radiological practice; at least every 3 to (maximum) 5 years. As a consequence of our study, new national DRLs were established in Switzerland for $CTDI_{vol}$ and DLP for paediatric patients in four defined age groups (<1.5 years, 1.5–5.5 years, 5.5–10.5 years, and 10.5–16 years) for the three main anatomic regions—brain, facial bone, and petrous bone.

DRLs are considered to be dynamic values that are reviewed periodically [24]. DRLs for indication-based CTs in Switzerland were established for adults in 2010 [25]. The results showed large variations in doses between different radiology departments in Switzerland, especially for examinations of the petrous bone, pelvis, lower limbs, and heart, indicating that the concept of DRLs was not being correctly applied for CTs in clinical routine in Switzerland.

A dose optimisation process should be triggered resulting in a lower radiation dose, especially in children. By repeatedly implementing such reviews, the global radiation dose is expected to decrease over a (short) period of time [15, 25–29].

As our study demonstrated, a multidisciplinary collaboration between different centres is essential when developing and implementing dose-optimised CT protocols beyond institutional single-centre boundaries. As shown, each participating centre provided a different amount of CT data depending on the hospital's size.

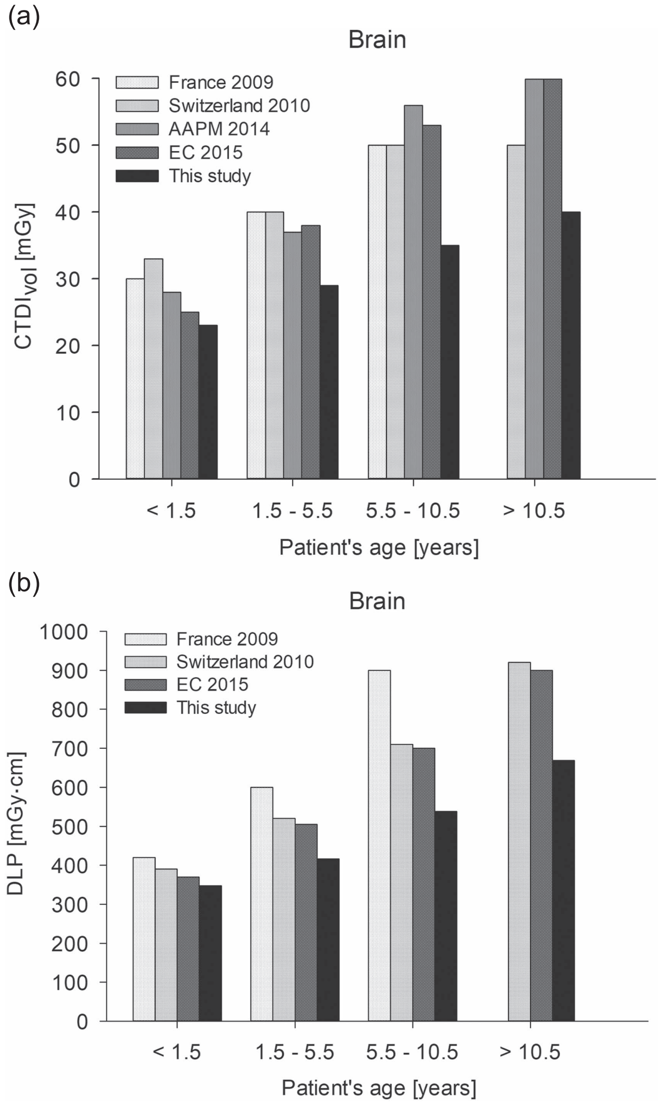

Figure 1. Comparison of the 75th percentiles for $CTDI_{vol}$ (figure 1(a)) and DLP (figure 1(b)) for brain CT scans (black bars) compared to the currently valid DRLs in Switzerland from 2010 and in France from 2009 as well as to the DRLs published by the AAPM in 2014 and by the European Commission in 2015.

Since there was no statistically significant difference between dose data with and without CM application for the three defined anatomic regions and the number of CTs with CM was very low, the dose data were pooled for analysis. This decision was supported by the data evaluation, which revealed that for most of the studies with CM the same CT protocol was used with the same scanning parameters as for native CT studies. The pooling increased the statistical power and led to more reliable results.

The routine use of dose management software during CT scanning might also have an influence on the results. Centres using commercial or in-house developed dose management

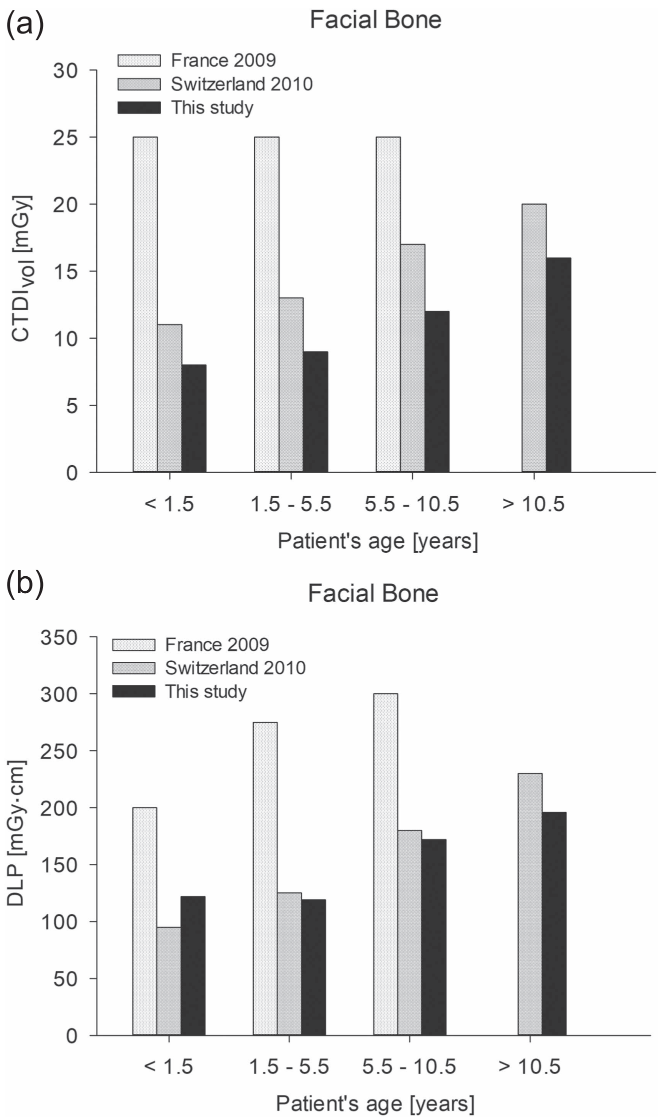

Figure 2. Comparison of the 75th percentiles for $CTDI_{vol}$ (figure 2(a)) and DLP (figure 2(b)) for facial bone CT scans (black bars) compared to the currently valid DRLs in Switzerland from 2010 and in France from 2009.

software provided more data than centres collecting dose data manually. The new Swiss DRLs for $CTDI_{vol}$ and DLP are much lower than the current Swiss DRLs and the DRLs of other European countries, indicating the use of dose-optimised CT protocols. Nevertheless, SLs were slightly higher than current values and the DRLs of other European countries suggesting a non-optimised radiological practice. The scan range chosen was too conservative and emphasises the need for continuation of efforts towards the optimisation of CT protocols.

Radiation dose must not be the only criterion considered when choosing the appropriate imaging modality for children. Some of the indications listed in table 1 could be examined

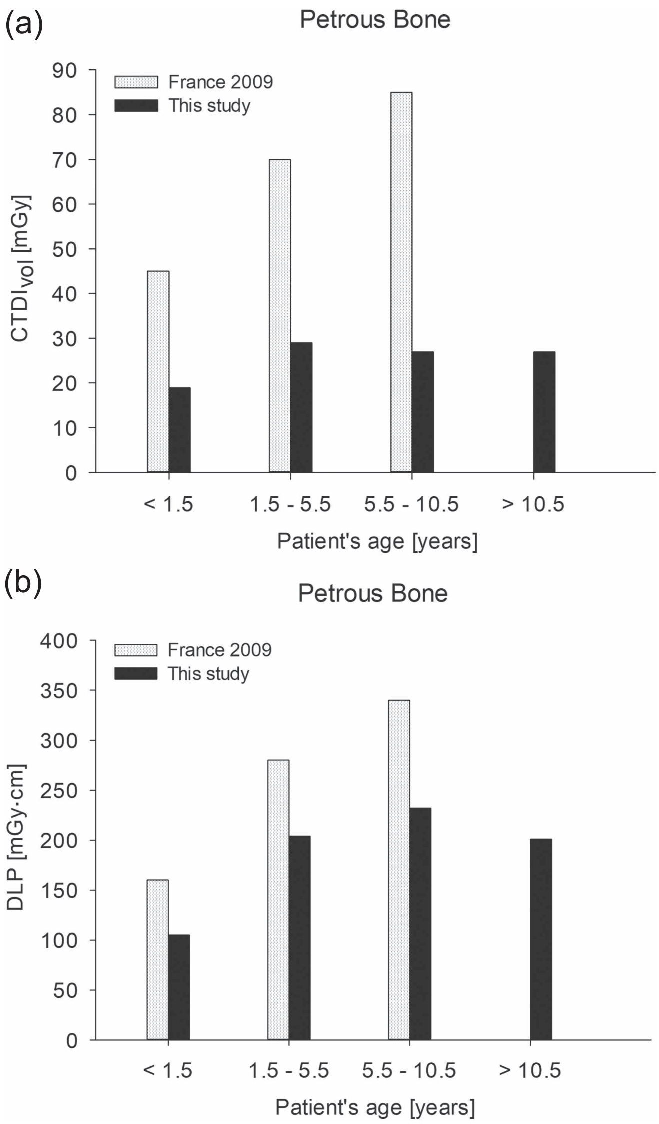

Figure 3. Comparison of the 75th percentiles for $CTDI_{vol}$ (figure 3(a)) and DLP (figure 3(b)) for petrous bone CT scans (black bars) compared to the currently valid DRLs in France from 2009.

adequately with MRI. But MRI is not always practical or preferable: particularly in acute trauma patients needing rapid treatment, CT is the preferred modality. Therefore, it is important to have CT protocols in place that minimise radiation dose without sacrificing diagnostic accuracy. Unfortunately, in practice, DRLs have not changed significantly over time [24]. Even though DRLs are currently the best tools for dose optimisation, the concept of DRLs only seems to work slowly. The DRL values set by different countries for brain CT examinations in children have changed little in recent years; several countries published

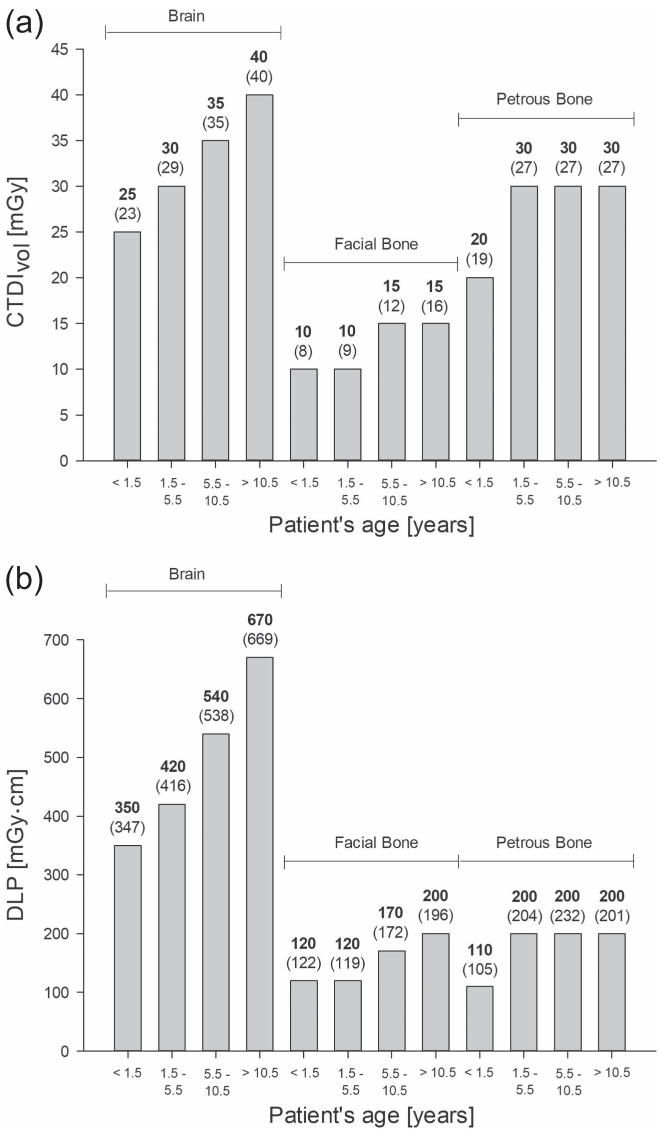

Figure 4. The proposed new rounded DRLs (grey bars) based on the 75th percentiles (in brackets) for $CTDI_{vol}$ (figure 4(a)) and DLP (figure 4(b)) for neuro-paediatric CT examinations; age-related and separated according to the three anatomic regions: brain, facial bone, and petrous bone.

current DRLs (2010–2014) that are equal to or even higher than the initial paediatric DRLs [24]. Although the ALARA principle is now more than 35 years old [30], and was introduced in paediatric imaging more than 10 years ago [8], it seems that there is still work to be done on dose optimisation in paediatric brain CT scans. This is highlighted by our current results with DRLs for $CTDI_{vol}$ and DLP up to 20% lower than the DRLs so far used in Switzerland as in other European countries.

There is no doubt that such regular data collection and re-evaluation is time and resource consuming, but since the Swiss legislation demands the implementation of DRLs and since dose management systems are increasingly installed in radiology departments allowing automatic data collection, this will facilitate such an endeavour.

A major element of that process of optimisation is a national and international consensus on the DRLs to avoid wide variations and minimise radiation risk and long-term complications in children. We recommend a time frame of 3 to a maximum of 5 years. In the future, it would be worthwhile to suggest DRLs for sub-specific cranial CT indications that might have different image quality requirements.

5. Limitations

The number of paediatric cranial CTs performed in Switzerland is limited. There are relatively few paediatric patients owing the small population and low number of university, cantonal, and regional hospitals compared to other European countries.

The small amount of dose data inevitably results in decreased statistical accuracy. However, since one of the aims of this study was to harmonise the CT practice across Switzerland, all available data was included for analysis.

We are also aware that the different methods of data collection in the eight hospitals—using commercial dose management software; in-house developed data collection or manual data registration in specific spreadsheets—might have an influence on the amount and correctness of collected data. Commercial dose management software accesses all dose date from the DICOM header whereas manual data collection might be biased in terms of number and accuracy.

To improve statistical accuracy, the calculation of the 75th percentile of a dose distribution should be based on at least 20 data sets, as recommended by the ICRP in publication 135 on DRLs in medical imaging [9]. However, since the number of neuro-paediatric CT scans in Switzerland is limited, several hospitals provided fewer than 20 data sets for specific examinations (see table 2). If these data were to be omitted from the analysis, DRLs would be based on data from only a few hospitals and would not reflect the overall CT practice across Switzerland. Therefore, in order to harmonise the CT practice across Switzerland, we decided to include all data in our analysis, being fully aware that the statistical accuracy was decreased.

Image quality of the CT scans was assessed in a qualitative manner by the clinicians depending on the clinical indication. Image quality was considered to be sufficient if it allowed an accurate diagnosis. No quantitative image quality assessment (e.g. by calculating the signal-to-noise ratio or using model observers) was performed, since this would have gone beyond the scope of this study.

6. Conclusion

This article reports results from a national dose survey of neuro-paediatric CT examinations (1645 data sets were analysed) in eight participating university and cantonal hospitals in Switzerland. The results of the DRLs for $CTDI_{vol}$ and DLP were up to 20% lower than the DRLs so far used in Switzerland and other European countries, indicating that regular national and international updates of DRLs are essential. With respect to the rapidly evolving technology allowing a lower exposure to radiation while maintaining a high image quality sufficient for a correct diagnosis, periodic updates of regional and international DRLs at least every 3 to a maximum of 5 years are indispensable to establish optimum conditions for paediatric brain CTs.

Acknowledgements

We would like to thank the eight participating hospitals; the university hospitals of Geneva, Lausanne, Bern, Basel, and Zurich and the cantonal hospitals of Chur, Aarau, and Lucerne for providing the neuro-paediatric CT data sets.

Appendix

A. Median values for $CTDI_{vol}$, DLP, and SL from all eight centres for CT of the brain with and without primary CM application separated by age group.

Table A.1. Paediatric Patients aged <1.5 years, brain CT without CM application.

	Center:	A	B	C	D	E	F	H	I	*All data*	DRL 75
CTDI [mGy]	Min	17	6	13	17	5	6	12	1	1	
	25th percentile	18	16	13	20	10	8	14	1	13	
	Median	30	23	13	20	13	20	16	16	16	**21**
	75th percentile	31	26	13	22	13	24	19	16	19	
	Max	32	30	13	26	21	26	27	29	32	
DLP [mGy.cm]	Min	241	18	207	255	108	66	31	25	18	
	25th percentile	292	202	209	307	151	134	205	30	163	
	Median	474	314	211	321	186	299	245	182	229	**316**
	75th percentile	530	361	212	339	201	365	273	231	290	
	Max	723	416	214	395	417	483	390	628	723	
Scan length [cm]	Median	16	14	16	15	16	15	15	14	15	**16**
number of exams		26	38	2	10	5	11	64	107	263	

Table A.2. Paediatric patients aged <1.5 years, brain CT with CM application.

	Center:	A	B	C	D	E	F	H	I	*All data*	DRL 75
CTDI [mGy]	Min	32	22	n	n	n	22	14	16	12	
	25th percentile	32	25	n	n	n	22	14	16	16	
	Median	32	26	n	n	n	22	14	16	20	**26**
	75th percentile	32	26	n	n	n	22	14	16	26	
	Max	32	27	n	n	n	22	14	16	32	
DLP [mGy.cm]	Min	321	120	n	n	n	347	181	136	22	
	25th percentile	366	630	n	n	n	347	190	189	197	
	Median	410	679	n	n	n	347	199	197	236	**410**
	75th percentile	455	816	n	n	n	347	208	221	320	
	Max	500	943	n	n	n	347	217	251	500	
Scan length [cm]	Median	13	13	n	n	n	16	14	12	13	**14**
number of exams		2	8	0	0	0	1	2	7	20	

Table A.3. Paediatric patients aged 1.5–5.5 years, brain CT without CM application.

	Center:	A	B	C	D	E	F	H	I	*All data*	DRL 75
CTDI [mGy]	Min	18	12	16	15	6	24	16	1	1	
	25th percentile	31	28	16	20	11	25	19	19	19	
	Median	32	30	16	22	17	26	25	19	19	**27**
	75th percentile	32	30	21	24	17	27	35	19	30	
	Max	32	44	26	27	17	30	39	40	44	
DLP [mGy.cm]	Min	189	22	276	246	77	391	159	13	13	
	25th percentile	530	390	276	339	188	396	301	252	271	
	Median	577	416	276	366	300	401	435	271	312	**420**
	75th percentile	630	472	360	426	307	436	515	290	472	
	Max	803	870	443	521	314	528	932	577	932	
Scan length [cm]	Median	18	14	18	18	18	16	16	14	15	**18**
number of exams		31	44	3	19	3	4	69	118	291	

Table A.4. Paediatric patients aged 1.5–5.5 years, brain CT with CM application.

	Center:	A	B	C	D	E	F	H	I	*All data*	DRL 75
CTDI [mGy]	Min	31	16	n	n	5	25	19	14	5	
	25th percentile	31	29	n	n	11	26	19	18	19	
	Median	31	30	n	n	17	26	19	19	27	**29**
	75th percentile	32	32	n	n	18	26	31	19	31	
	Max	32	43	n	n	18	31	36	19	43	
DLP [mGy.cm]	Min	499	43	n	n	89	331	263	252	43	
	25th percentile	551	345	n	n	210	401	277	266	293	
	Median	596	416	n	n	331	409	313	271	405	**414**
	75th percentile	666	454	n	n	356	410	480	298	454	
	Max	791	529	n	n	381	446	556	382	791	
Scan length [cm]	Median	19	14	n	n	20	16	15	14	16	**18**
number of exams		4	8	0	0	3	5	6	4	30	

Table A.5. Paediatric patients aged 5.5–10.5 years, brain CT without CM application.

	Center:	A	B	C	D	E	F	H	I	*All data*	DRL 75
CTDI [mGy]	Min	29	28	4	16	6	11	4	1	1	
	25th percentile	31	30	11	21	14	26	28	33	28	
	Median	32	31	18	21	17	28	36	35	32	**33**
	75th percentile	32	35	20	23	18	31	46	36	36	
	Max	32	39	30	28	21	33	50	41	50	
DLP [mGy.cm]	Min	381	390	51	297	54	254	36	16	16	
	25th percentile	522	416	186	349	193	429	468	473	452	
	Median	594	500	285	365	262	462	550	510	511	**520**
	75th percentile	683	543	329	392	309	553	719	547	583	
	Max	923	621	533	504	385	614	983	838	983	
Scan length [cm]	Median	19	15	16	17	16	17	16	15	16	**17**
number of exams		32	12	5	7	4	17	73	114	264	

Table A.6. Paediatric patients aged 5.5–10.5 years, brain CT with CM application.

	Center:	A	B	C	D	E	F	H	I	*All data*	DRL 75
CTDI [mGy]	Min	30	29	n	n	19	27	28	19	15	
	25th percentile	31	29	n	n	20	28	28	35	28	
	Median	32	29	n	n	22	29	36	36	32	**35**
	75th percentile	32	29	n	n	27	29	48	36	36	
	Max	32	29	n	n	37	30	48	40	48	
DLP [mGy.cm]	Min	261	472	n	n	326	460	418	271	216	
	25th percentile	503	472	n	n	378	468	482	510	473	
	Median	560	472	n	n	431	476	515	546	511	**538**
	75th percentile	721	472	n	n	538	484	707	583	613	
	Max	778	472	n	n	755	491	815	659	815	
Scan length [cm]	Median	18	16	n	n	19	17	15	15	16	**18**
number of exams		8	1	0	0	4	2	7	17	39	

Table A.7. Paediatric patients aged 10.5–16 years, brain CT without CM application.

	Center:	A	B	C	D	E	F	H	I	*All data*	DRL 75
CTDI [mGy]	Min	29	23	26	19	4	23	23	1	1	
	25th percentile	31	39	26	22	8	30	36	39	31	
	Median	32	45	39	24	17	32	46	40	40	**41**
	75th percentile	32	45	39	26	20	34	50	40	41	
	Max	46	53	40	29	27	41	174	41	174	
DLP [mGy.cm]	Min	357	451	416	363	77	402	296	22	22	
	25th percentile	567	631	500	417	151	512	600	576	569	
	Median	602	676	647	471	340	541	730	617	618	**654**
	75th percentile	719	721	665	525	374	593	873	618	721	
	Max	1008	808	766	579	492	873	1122	970	1122	
Scan length [cm]	Median	20	16	17	19	19	17	17	15	16	**19**
number of exams		60	36	7	2	16	7	103	123	354	

Table A.8. Paediatric patients aged 10.5–16 years, brain CT with CM application.

	Center:	A	B	C	D	E	F	H	I	*All data*	DRL 75
CTDI [mGy]	Min	30	22	n	n	17	30	15	40	15	
	25th percentile	30	41	n	n	17	30	28	40	29	
	Median	31	45	n	n	18	30	41	40	40	**40**
	75th percentile	31	50	n	n	20	30	49	40	48	
	Max	31	58	n	n	21	30	52	41	58	
DLP [mGy.cm]	Min	536	58	n	n	270	471	306	576	58	
	25th percentile	544	570	n	n	341	475	557	586	517	
	Median	551	699	n	n	508	479	737	617	617	**678**
	75th percentile	559	721	n	n	1049	484	844	617	730	
	Max	566	808	n	n	2396	488	989	618	989	
Scan length [cm]	Median	18	16	n	n	19	16	17	15	16	**18**
number of exams		2	14	0	0	4	2	10	6	38	

B. The median value for $CTDI_{vol}$, DLP, and scan length of all eight centres for CT of the facial bone with and without primary CM application separated by age group.

Table B.1. Paediatric patients aged <1.5 years, facial bone CT without CM application.

	Center:	A	B	C	D	E	F	H	I	*All data*	DRL 75
CTDI [mGy]	Min	7	6	n	n	13	3	n	3	3	
	25th percentile	7	6	n	n	13	4	n	3	5	
	Median	7	7	n	n	13	6	n	6	7	**7**
	75th percentile	7	9	n	n	13	8	n	8	8	
	Max	7	11	n	n	13	8	n	8	13	
DLP [mGy.cm]	Min	139	71	n	n	200	31	n	41	31	
	25th percentile	139	79	n	n	200	36	n	55	52	
	Median	139	87	n	n	200	41	n	75	87	**139**
	75th percentile	139	95	n	n	200	56	n	108	121	
	Max	139	102	n	n	200	92	n	159	200	
Scan length [cm]	Median	19	19	n	n	16	10	n	15	12	**19**
number of exams		1	3	0	0	1	4	0	4	13	

Table B.2. Paediatric patients aged <1.5 years, facial bone CT with CM application.

	Center:	A	B	C	D	E	F	H	I	*All data*	DRL 75
CTDI [mGy]	Min	11	n	n	2	n	3	n	8	2	
	25th percentile	11	n	n	2	n	3	n	8	3	
	Median	11	n	n	2	n	3	n	8	6	**9**
	75th percentile	11	n	n	2	n	3	n	8	9	
	Max	11	n	n	2	n	3	n	8	11	
DLP [mGy.cm]	Min	122	n	n	19	n	39	n	99	19	
	25th percentile	122	n	n	19	n	39	n	99	34	
	Median	122	n	n	19	n	39	n	99	69	**105**
	75th percentile	122	n	n	19	n	39	n	99	105	
	Max	122	n	n	19	n	39	n	99	122	
Scan length [cm]	Median	11	n	n	10	n	12	n	12	11	**12**
number of exams		1	0	0	1	0	1	0	1	4	

Table B.3. Paediatric patients aged 1.5–5.5 years, facial bone CT without CM application.

	Center:	A	B	C	D	E	F	H	I	*All data*	DRL 75
CTDI [mGy]	Min	1	5	n	2	5	4	4	6	1	
	25th percentile	7	6	n	2	5	4	4	6	4	
	Median	16	9	n	2	5	4	5	6	6	**7**
	75th percentile	16	12	n	2	5	4	10	8	11	
	Max	18	13	n	2	5	4	36	11	36	
DLP [mGy.cm]	Min	15	78	n	16	85	34	38	86	15	
	25th percentile	95	81	n	17	85	34	45	90	71	
	Median	176	119	n	18	85	34	69	106	86	**113**
	75th percentile	210	162	n	19	85	34	150	108	164	
	Max	258	176	n	20	85	34	809	138	809	
Scan length [cm]	Median	13	14	n	9	16	9	15	14	14	**15**
number of exams		7	4	0	2	1	1	7	9	31	

Table B.4. Paediatric patients aged 1.5–5.5 years, facial bone CT with CM application.

	Center:	A	B	C	D	E	F	H	I	*All data*	DRL 75
CTDI [mGy]	Min	14	n	n	n	5	n	n	n	5	
	25th percentile	14	n	n	n	5	n	n	n	9	
	Median	14	n	n	n	5	n	n	n	14	**12**
	75th percentile	14	n	n	n	5	n	n	n	22	
	Max	14	n	n	n	5	n	n	n	29	
DLP [mGy.cm]	Min	205	n	n	n	68	n	n	n	68	
	25th percentile	205	n	n	n	68	n	n	n	136	
	Median	205	n	n	n	68	n	n	n	205	**171**
	75th percentile	205	n	n	n	68	n	n	n	471	
	Max	205	n	n	n	68	n	n	n	736	
Scan length [cm]	Median	15	n	n	n	14	n	n	n	15	**15**
number of exams		1	0	0	0	1	0	0	0	2	

Table B.5. Paediatric patients aged 5.5–10.5 years, facial bone CT without CM application.

	Center:	A	B	C	D	E	F	H	I	*All data*	DRL 75
CTDI [mGy]	Min	1	11	1	2	n	4	4	6	1	
	25th percentile	11	17	2	2	n	4	4	8	4	
	Median	15	23	2	2	n	4	5	8	8	**11**
	75th percentile	17	28	2	2	n	5	15	8	14	
	Max	27	34	2	2	n	12	48	16	48	
DLP [mGy.cm]	Min	13	134	22	32	n	48	36	75	13	
	25th percentile	118	273	25	32	n	56	51	109	58	
	Median	172	412	29	32	n	60	62	138	123	**155**
	75th percentile	230	551	32	32	n	66	184	155	163	
	Max	274	690	35	32	n	96	983	300	983	
Scan length [cm]	Median	11	16	16	14	n	14	12	16	14	**16**
number of exams		12	2	2	1	0	8	15	17	57	

Table B.6. Paediatric patients aged 5.5–10.5 years, facial bone CT with CM application.

	Center:	A	B	C	D	E	F	H	I	*All data*	DRL 75
CTDI [mGy]	Min	13	n	n	n	n	3	n	10	3	
	25th percentile	13	n	n	n	n	4	n	10	5	
	Median	13	n	n	n	n	4	n	10	10	**12**
	75th percentile	13	n	n	n	n	4	n	10	13	
	Max	13	n	n	n	n	5	n	10	16	
DLP [mGy.cm]	Min	170	n	n	n	n	65	n	182	65	
	25th percentile	170	n	n	n	n	70	n	182	86	
	Median	170	n	n	n	n	76	n	182	170	**176**
	75th percentile	170	n	n	n	n	81	n	182	182	
	Max	170	n	n	n	n	86	n	182	247	
Scan length [cm]	Median	13	n	n	n	n	20	n	18	15	**19**
number of exams		1	1	0	0	0	2	0	1	5	

Table B.7. Paediatric patients aged 10.5–16 years, facial bone CT without CM application.

	Center:	A	B	C	D	E	F	H	I	*All data*	DRL 75
CTDI [mGy]	Min	1	6	2	2	n	4	4	6	1	
	25th percentile	1	11	2	2	n	5	7	8	5	
	Median	14	11	2	2	n	5	27	8	8	**13**
	75th percentile	19	14	2	2	n	5	28	8	12	
	Max	28	15	2	2	n	12	38	16	38	
DLP [mGy.cm]	Min	18	75	30	24	n	56	56	77	18	
	25th percentile	21	153	35	24	n	66	135	117	76	
	Median	155	195	40	24	n	74	268	128	129	**175**
	75th percentile	225	216	40	24	n	81	452	138	209	
	Max	329	302	41	24	n	309	763	270	763	
Scan length [cm]	Median	13	17	17	12	n	15	16	16	15	**17**
number of exams		14	9	3	1	0	16	25	37	105	

Table B.8. Paediatric patients aged 10.5–16 years, facial bone CT with CM application.

	Center:	A	B	C	D	E	F	H	I	*All data*	DRL 75
CTDI [mGy]	Min	17	n	5	n	n	n	n	40	5	
	25th percentile	17	n	5	n	n	n	n	40	16	
	Median	17	n	5	n	n	n	n	40	18	**28**
	75th percentile	17	n	5	n	n	n	n	40	19	
	Max	17	n	5	n	n	n	n	40	40	
DLP [mGy.cm]	Min	197	n	70	n	n	n	n	617	79	
	25th percentile	197	n	70	n	n	n	n	617	262	
	Median	197	n	70	n	n	n	n	617	332	**407**
	75th percentile	197	n	70	n	n	n	n	617	404	
	Max	197	n	70	n	n	n	n	617	810	
Scan length [cm]	Median	12	n	15	n	n	n	n	16	18	**15**
number of exams		1	0	1	0	0	0	0	1	3	

C. The median value for $CTDI_{vol}$, DLP, and scan length of all eight centres for CT of the petrous bone with and without primary CM application separated by age group.

Table C.1. Paediatric patients aged <1.5 years, petrous bone CT without CM application.

	Center:	A	B	C	D	E	F	H	I	*All data*	DRL 75
CTDI [mGy]	Min	17	26	n	n	13	17	n	11	11	
	25th percentile	17	28	n	n	13	18	n	11	13	
	Median	17	29	n	n	13	19	n	11	17	**19**
	75th percentile	17	31	n	n	13	20	n	11	26	
	Max	17	32	n	n	13	21	n	13	35	
DLP [mGy.cm]	Min	105	163	n	n	70	76	n	62	62	
	25th percentile	105	170	n	n	70	86	n	84	85	
	Median	105	177	n	n	70	95	n	85	114	**105**
	75th percentile	114	184	n	n	70	105	n	102	179	
	Max	122	191	n	n	70	114	n	179	240	
Scan length [cm]	Median	6	6	n	n	5	5	n	8	6	**6**
number of exams		3	2	0	0	1	2	0	5	13	

Paediatric patients aged <1.5 years, petrous bone CT with CM application: No such examinations were recorded at any of the participating centres.

Table C.2. Paediatric patients aged 1.5–5.5 years, petrous bone CT without CM application.

	Center:	A	B	C	D	E	F	H	I	*All data*	DRL 75
CTDI [mGy]	Min	17	27	1	44	17	14	n	3	1	
	25th percentile	17	35	1	44	17	18	n	11	11	
	Median	17	36	1	44	17	21	n	11	18	**29**
	75th percentile	19	40	1	44	17	23	n	11	35	
	Max	21	54	1	44	17	24	n	16	54	
DLP [mGy.cm]	Min	118	162	12	186	88	98	n	43	12	
	25th percentile	133	218	12	269	88	104	n	67	88	
	Median	147	260	12	352	88	110	n	79	114	**204**
	75th percentile	165	265	12	393	88	142	n	89	222	
	Max	182	378	12	435	88	228	n	106	435	
Scan length [cm]	Median	7	7	9	8	5	7	n	7	7	**7**
number of exams		3	6	1	3	1	7	0	11	32	

Paediatric patients aged 1.5–5.5 years, petrous bone CT with CM application: No such examinations were recorded at any of the participating centres.

Table C.3. Paediatric patients aged 5.5–10.5 years, petrous bone CT without CM application.

	Center:	A	B	C	D	E	F	H	I	*All data*	DRL 75
CTDI [mGy]	Min	17	43	1	44	16	16	n	15	1	
	25th percentile	21	43	1	44	17	18	n	15	15	
	Median	21	43	1	44	17	22	n	15	18	**32**
	75th percentile	21	43	1	44	17	23	n	15	40	
	Max	21	43	1	44	18	26	n	16	54	
DLP [mGy.cm]	Min	131	291	10	261	74	106	n	93	10	
	25th percentile	163	291	10	274	101	121	n	106	107	
	Median	171	291	10	293	102	125	n	115	131	**231**
	75th percentile	188	291	11	300	106	141	n	124	264	
	Max	201	291	11	386	112	170	n	209	397	
Scan length [cm]	Median	8	7	7	7	6	7	n	8	7	**7**
number of exams		6	1	2	6	6	7	0	16	44	

Table C.4. Paediatric patients aged 5.5–10.5 years, petrous bone with CM application.

	Center:	A	B	C	D	E	F	H	I	*All data*	DRL 75
CTDI [mGy]	Min	21	n	n	n	n	n	n	n	21	
	25th percentile	21	n	n	n	n	n	n	n	21	
	Median	21	n	n	n	n	n	n	n	21	**21**
	75th percentile	21	n	n	n	n	n	n	n	21	
	Max	21	n	n	n	n	n	n	n	21	
DLP [mGy.cm]	Min	212	n	n	n	n	n	n	n	212	
	25th percentile	212	n	n	n	n	n	n	n	212	
	Median	212	n	n	n	n	n	n	n	212	**212**
	75th percentile	212	n	n	n	n	n	n	n	212	
	Max	212	n	n	n	n	n	n	n	212	
Scan length [cm]	Median	10	n	n	n	n	n	n	n	10	**10**
number of exams		1	0	0	0	0	0	0	0	1	

Table C.5. Paediatric patients aged 10.5–16 years, petrous bone CT without CM application.

	Center:	A	B	C	D	E	F	H	I	*All data*	DRL 75
CTDI [mGy]	Min	21	35	n	n	20	16	n	8	8	
	25th percentile	21	51	n	n	20	18	n	15	15	
	Median	21	54	n	n	20	27	n	15	21	**27**
	75th percentile	21	54	n	n	20	27	n	15	28	
	Max	21	54	n	n	20	28	n	16	54	
DLP [mGy.cm]	Min	131	162	n	n	123	116	n	70	70	
	25th percentile	185	325	n	n	123	134	n	102	131	
	Median	201	365	n	n	123	147	n	117	180	**201**
	75th percentile	212	430	n	n	123	172	n	132	228	
	Max	238	450	n	n	123	196	n	184	450	
Scan length [cm]	Median	9	8	n	n	6	7	n	8	8	**8**
number of exams		11	8	0	0	1	5	0	11	36	

Paediatric patients aged 10.5–16 years, petrous bone with CM application: No such examinations were recorded at any of the participating centres.

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