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PHYSICS

Local clinical diagnostic reference levels for chest and abdomen CT examinations in adults as a function of body mass index and clinical indication: a prospective multicenter study

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Abstract

Objectives To compare institutional dose levels based on clinical indication and BMI class to anatomy-based national DRLs (NDRLs) in chest and abdomen CT examinations and to assess local clinical diagnostic reference levels (LCDRLs).

Methods From February 2017 to June 2018, after protocol optimization according to clinical indication and body mass index (BMI) class (< 25; ≥ 25), 5310 abdomen and 1058 chest CT series were collected from 5 CT scanners in a Swiss multicenter group. Clinical indication–based institutional dose levels were compared to the Swiss anatomy-based NDRLs. Statistical significance was assessed ($p < 0.05$). LCDRLs were calculated as the third quartile of the median dose values for each CT scanner.

Results For chest examinations, dose metrics based on clinical indication were always below P75 NDRL for $CTDI_{vol}$ (range 3.9–6.4 vs. 7.0 mGy) and DLP (164.0–211.2 vs. 250 mGycm) in all BMI classes except for DLP in BMI ≥ 25 (248.8–255.4 vs. 250.0 mGycm). For abdomen examinations, they were significantly lower or not different than P50 NDRLs for all BMI classes (3.8–9.0 vs. 10.0 mGy and 192.9–446.8 vs. 470mGycm). The estimated LCDRLs show a drop in $CTDI_{vol}$ (21% for chest and 32% for abdomen, on average) with respect to current DRLs. When considering BMI stratification, the largest LCDRL difference within the same clinical indication is for renal tumor (4.6 mGy for BMI < 25 vs. 10.0 mGy for BMI ≥ 25; − 117%).

Conclusion The results suggest the necessity of estimating clinical indication–based DRLs, especially for abdomen examinations. Stratifying per BMI class allows further optimization of the CT doses.

Key Points

- *Our data show that clinical indication–based DRLs might be more appropriate than anatomy-based DRLs and might help in reducing large variations in dose levels for the same type of examinations.*
- *Stratifying the data per patient-size subgroups (non-overweight, overweight) allows a better optimization of CT doses and therefore the possibility to set LCDRLs based on BMI class.*
- *Institutions who are fostering continuous dose optimization and LDRLs should consider defining protocols based on clinical indication and BMI group, to achieve ALARA.*

Keywords Multidetector computed tomography · Radiometry · Health care · Clinical protocols

Hugues Brat and Federica Zanca are equal contributors.

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Abbreviations

AD	Achievable doses
BMI	Body mass index
CDRL	Clinical diagnostic reference level
CHO	Channelized Hotelling observer
CT	Computed tomography
CTDI	Computed tomography dose index
DLP	Dose length product
DRL	Diagnostic reference level
Dw	Water-equivalent diameter
EUCLID	European study on clinical DRLs
G3R	Groupe 3R
ICRP	International Commission on Radiological Protection
LCDRL	Local clinical diagnostic reference level
LDRL	Local diagnostic reference level
MDCT	Multidetector CT scanner
NDRL	National diagnostic reference level

Introduction

The International Commission on Radiological Protection (ICRP) first introduced the term "diagnostic reference level" (DRL) in 1996 in publication 73 [1]. A recent report updated the recommendations on DRLs in medical imaging [2] and clarified issues related to definitions of terms. According to this ICRP report, national DRLs (NDRLs, representative of an entire country) and local DRLs (LDRLs, representative of a few healthcare facilities in a local area) are calculated as the third quartile of the median dose values of each CT modality. LDRLs consider faster local optimization processes and are anatomy-based, like NDRLs. The same report also addresses the importance of clinical DRLs (CDRLs) to define more specific dose levels according to the needed image quality for a specific clinical indication. For example, the same DRL for CT of the chest is applied to a work-up for pulmonary embolism, lung cancer, or even coronary calcium scoring, which require different image quality levels, and should have different DRLs, in line with the ALARA principle. A few national radiation protection authorities (Finland, Germany, Denmark, Norway, and the UK) have already recognized the importance on working towards establishing CDRLs.

The European Society of Radiology has recently started a European prospective study to develop a set of CDRLs based on clinical indication, to limit large variations in dose levels for the same type of examinations.

Also, the American College of Radiology tried to go one step further in the definition of DRLs, benchmarking patient doses at a national level according to patient size (achievable dose according to water-equivalent diameter) as a help in optimizing CT protocols [3].

Within this context and considering that clinical DRLs, local DRLs, and appropriate image quality are a cornerstone of ESR's policy, we initiated a multicenter prospective study to compare dose metrics based on clinical indication to NDRLs and to contribute to the assessment of local clinical DRLs (LCDRLs), driven by the appropriate image quality and while considering patient body mass index (BMI).

Material and methods

Study preparation: design of optimized clinical indication–based protocols

Prior to this study, adult (> 16 years) CT examinations obtained from five CT scanners (Ingenuity, Philips Medical Systems) of five centers of the Swiss Groupe 3R (3R, Réseau Radiologique Romand) were prospectively collected through a dose monitoring system (DoseWatch®, GE Healthcare) from April to June 2015. This baseline data indicated a large variability across protocols in terms of nomenclature and exposure settings.

Consequently, a harmonization phase (phase I) was implemented during the period June 2015–January 2016. Senior radiologists defined a clinical indication–based protocol map. In order to investigate the influence of patient size, the BMI of 25 was chosen as a threshold to distinguish non-overweight (BMI < 25) from overweight (BMI ≥ 25) patients. As a result, two acquisition protocols (according to the BMI class) were determined for each clinical indication.

In parallel, acquisition and reconstruction parameters (Table 1) were also harmonized among all CT scanners, per clinical indication. Iterative reconstruction algorithm iDose level 3 (abdomen) or 4 (chest) remained unchanged during the study. Automatic exposure control was used.

Protocols' $CTDI_{vol}$ was not optimized at this stage but just adapted to remain close to values enabling a dose metric like the Swiss P25 NDRL [4] for BMI < 25 patients and to the P75 NDRL for BMI ≥ 25 patients. Subsequently, each protocol was mapped into the dose monitoring system to the RadLex playbook [5].

An optimization phase (phase II) lasted from January 2016 to January 2017, based on a 12% step-wise mAs reduction for all protocols. In parallel, phantom tests were performed to identify the lower dose limit for low-contrast liver lesions by a task-based quantification of image quality [6]. For both phases I and II, image quality was assessed by 22 radiologists (10–31 years of experience) using European image quality guidelines (adapted, binary task, "0" = non-diagnostic image; "1" = diagnostic image) [7] and through an electronic image quality voting button in the dose tracking software, used by the radiologists during their routine work through a contextual call process configured in the PACS system. After 50 examinations of the same indication without negative voting ("0"), an additional 12% of dose

Table 1 CT acquisition and reconstruction parameters

Anatomical region	Protocol name	Detector configuration (mm)	Rotation time (s)	Pitch	kVp BMI < 25	kVp BMI ≥ 25	mAs max BMI < 25	mAs max BMI ≥ 25	Reconstruction algorithm/ filter (soft, hard)	Slice reconstruction thickness (mm)	Reconstruction interval (mm)
Chest	Emphysema	64 × 0.625	0.4	0.891	100	100	120	194	iDose level 4 /B, YB	0.9	0.45
Chest	Pulmonary embolism	64 × 0.625	0.4	0.891	100	100	134	217	iDose level. 4 /B, YB	0.9	0.45
Chest	Pneumonia	64 × 0.625	0.4	0.891	100	100	120	194	iDose level 4 /B, YB	0.9	0.45
Abdomen	Appendicitis	64 × 0.625	0.4	0.984	100	120	150	143	iDose level 3 /B, YB	0.9	0.45
Abdomen	CT colonography	64 × 0.625	0.4	1.172	120	120	64	102	iDose level 3 /B	0.9	0.45
Abdomen	Diverticulitis	64 × 0.625	0.4	0.984	100	120	150	143	iDose level 3 /B	0.9	0.45
Abdomen	Kidney stones	64 × 0.625	0.4	0.984	100	120	150	143	iDose level 3 /B	0.9	0.45
Abdomen	Liver tumor	64 × 0.625	0.4	0.984	100	120	150	143	iDose level 3 /B, YB	0.9	0.45
Abdomen	Pancreas tumor	64 × 0.625	0.4	0.984	100	120	150	143	iDose level 3 /B, YB	0.9	0.45
Abdomen	Renal tumor	64 × 0.625	0.4	0.984	100	120	150	143	iDose level 3 /B	0.9	0.45
Abdomen	Renal infection	64 × 0.625	0.4	0.984	100	120	150	143	iDose level 3 /B	0.9	0.45

reduction was applied. In case of 3 negative voting's for one type of protocol, each confirmed by a second reader, dose was increased back by 12% to reach previously accepted dose level, representing the "right dose for the right diagnosis."

Study data collection

In the period February 2017–June 2018, a third phase of the study was performed to collect dose metrics and compare them to NDRLs as well as to assess local clinical diagnostic reference levels for CT (Appendix: Dates of the study phases). The following data were automatically retrieved using DoseWatch® and for each series: (1) DLP, (2) $CTDI_{vol}$, (3) protocol name, (4) protocol scan parameters, (5) anatomical region, (6) center name, (7) RadLex coding, (8) patient age and (9) gender, and (10) date of scan. Short scans obtained to determine the peak time for contrast injection were excluded as well as scout acquisitions. Use of collected CT data was approved by the Institutional Review Board (Medical Ethics Committee).

Statistical analyses

Minimum, maximum, median, 25th percentile (P25), and 75th percentile (P75) values were calculated for $CTDI_{vol}$ and DLP quantities for each clinical indication and anatomical region for the following:

- Compare clinical indication–based institutional dose levels to the national P50 and P75 DRLs [8]. Clinical indication–based institutional dose levels were calculated as the median values of the distribution of all facilities' DRL quantities, as suggested in the ICRP publication 135 [2] (Fig. 1).
- Estimate LCDRLs, calculated as the 75th percentile (P75) of the distribution of the medians of distributions of the DRL quantity of each facility (Fig. 1).

In the rest of this manuscript, the 50th percentile of the NDRL is defined as P50 NDRL and the national diagnostic reference level as P75 NDRL. Comparison of our institutional dose data to the P50 NDRL was also performed to assist in optimizing image quality and patient dose.

The Mann–Whitney tests were used to assess statistically significant differences among two unpaired groups, and the Wilcoxon test was used to compare one group to a hypothetical value, using the statistical software Prism 7 (GraphPad). A p value < 0.05 was considered statistically significant. To assess the skewness of the BMI distribution, a Kolmogorov–Smirnov test was performed for each clinical indication.

Results

Data collected

Seventy percent (70%) of all indications, represented by the 11 most recurrent clinical indications for chest and abdomen

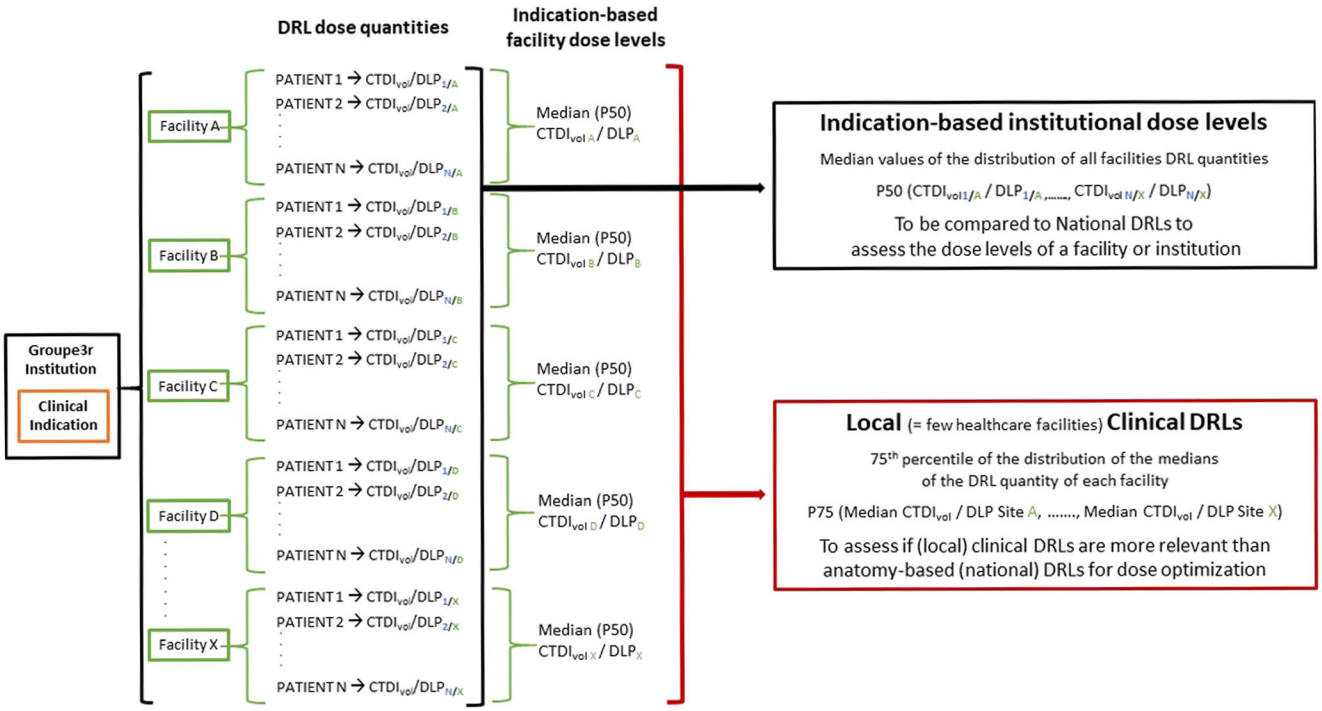

Fig. 1 Schematic overview of the methodology used to estimate clinical indication–based institutional dose levels and LCDRLs

Table 2 Study data per protocol and stratified per BMI

Anatomical region	Protocol name	Number of series per BMI class	
		BMI < 25 (%)	BMI ≥ 25 (%)
Chest (16.6%)	Emphysema	147 (2.3)	144 (2.3)
	Pulmonary embolism	165 (2.6)	255 (4.0)
	Pneumonia	178 (2.8)	169 (2.6)
Abdomen (83.4%)	Appendicitis	249 (3.9)	248 (3.9)
	CT colonography	73 (1.1)	92 (1.4)
	Diverticulitis	541 (8.5)	720 (11.3)
	Kidney stones	501 (7.9)	630 (9.9)
	Liver tumor	318 (5)	481 (7.6)
	Pancreas tumor	262 (4.1)	287 (4.5)
	Renal tumor	250 (3.9)	330 (5.2)
	Renal infection	150 (2.4)	178 (2.8)
Total number of series		6368 (100)	

% of the series in each table cell normalized to the total number of series is reported between brackets

examinations (Table 2), were evaluated. In total, 6368 diagnostic chest and abdomen CT series were collected; 53.5% of the patients were female and 46.5% male. Mean age of the patients was 59.7 years (range 16–101). Five thousand three hundred ten (83.4%) were CT of the abdomen, 44.1% with BMI < 25 and 55.9% with BMI ≥ 25; 1058 (16.6%) were CT of the chest, 46.3% with BMI < 25 and 53.7% with BMI ≥ 25. Examinations were i.v. contrast enhanced, except for emphysema, pneumonia, CT colonography, and kidney stone protocols.

Comparison of indication-based institutional dose levels to NDRLs

Comparison of the institutional median dose quantities based on clinical indication to NDRLs is reported in Tables 3 and 4. Values are shown per clinical indication and BMI class. BMI class named "ALL" indicates that the data are pooled together with respect to the BMI stratification; "all BMI classes" indicates instead each one of the BMI classes (ALL, < 25 and > 25, separately).

The median $CTDI_{vol}$ of all chest examination indications was statistically significantly lower than the P75 NDRL for all BMI classes (Table 3). The median $CTDI_{vol}$ was also significantly lower than the P50 NDRL for all BMI classes except for the emphysema BMI ≥ 25 class, for which it was not significantly different, and for the pneumonia and pulmonary embolism BMI ≥ 25 class, for which it was significantly higher.

The median DLP of all chest indications was statistically significantly lower than the P75 NDRL for all BMI classes, except for BMI ≥ 25 pneumonia and pulmonary embolism indications, for which it was higher (Table 4). The median DLP of all chest indications was also significantly lower than the P50 NDRL for the BMI < 25 class only.

For abdomen examinations, the median $CTDI_{vol}$ for all clinical indications and BMI classes was significantly lower than the P75 and P50 NDRLs, except for renal infection BMI ≥ 25, for which it was not significantly different from the P50 NDRL (Table 3).

The median DLP per clinical indication for abdomen examinations was significantly lower than the P75 and P50 NDRLs for all clinical indications and BMI classes, except for appendicitis, diverticulitis, and renal infection BMI ≥ 25, for which it was not significantly different from the P50 NDRL (Table 4).

Figures 2 (chest) and 3 (abdomen) show the box-plot of $CTDI_{vol}$ (left) and DLP (right) metrics grouped per clinical indication and stratified per BMI class. The Kolmogorov–Smirnov test indicated that the BMI distribution in the BMI ≥ 25 class was skewed to the right for each clinical indication, with a skewness value ranging from 0.4 to 0.7 per chest examinations and from 0.6 to 1.1 per abdominal examinations, with long tails of BMI values larger than 30.

Assessment of local clinical DRLs per indication

The calculated LCDRLs per $CTDI_{vol}$ and DLP are reported in Table 5.

For chest examinations, LCDRLs are lower than or equal to P50/P75 NDRLs for the $CTDI_{vol}$ metric (range 4.1–6.0 mGy vs. 6/7 mGy) and for the DLP metric (169.4–227 vs. 210/250 mGycm) in the ALL BMI and BMI < 25 classes; for BMI ≥ 25 patients, they are higher than P75 NDRLs for the $CTDI_{vol}$ metric (range 7.1–7.9 mGy vs. 6/7 mGy) and for the DLP metric (267.3–321.8 vs. 210/250 mGycm).

If we consider the ALL BMI category only, as currently done for the DRL definition, an average $CTDI_{vol}$ drop with respect to P75 NDRLs of 21% is observed (range 14% for

Table 3 Institutional median $CDTI_{vol}$ per clinical indication and BMI class, compared to P50 and P75 NDRLs

Anatomical region	Clinical indication	BMI class	Median $CTDI_{vol}$ (mGy)	*p* value to P50 (6 mGy)	*p* value to P75 (7 mGy)
Chest	Emphysema	ALL	*4.9*°^	< 0.0001*	< 0.0001*
		< 25	*4.3*°^	< 0.0001*	< 0.0001*
		≥ 25	*5.8*^	0.17	< 0.0001*
	Pneumonia	ALL	*4.8*°^	< 0.0001*	< 0.0001*
		< 25	*3.9*°^	< 0.0001*	< 0.0001*
		≥ 25	*6.2*^	0.01* (higher)	< 0.0001*
	Pulmonary embolism	ALL	*5.1*°^	< 0.0001*	< 0.0001*
		< 25	*4.1*°^	< 0.0001*	< 0.0001*
		≥ 25	*6.4*^	0.0005* (higher)	< 0.0001*
Anatomical region	Clinical indication	BMI class	Median $CTDI_{vol}$ (mGy)	*p* value to P50 (10 mGy)	*p* value to P75 (11 mGy)
Abdomen	Appendicitis	ALL	*6.7*°^	< 0.001*	< 0.0001*
		< 25	*5.1*°^	< 0.001*	< 0.0001*
		≥ 25	*8.7*°^	< 0.001*	< 0.0001*
	CT colonography	ALL	*4.9*°^	< 0.001*	< 0.0001*
		< 25	*3.8*°^	< 0.001*	< 0.0001*
		≥ 25	*5.5*°^	< 0.001*	< 0.0001*
	Diverticulitis	ALL	*7.3*°^	< 0.001*	< 0.0001*
		< 25	*5.7*°^	0.0045*	< 0.0001*
		≥ 25	*9.0*°^	< 0.0001*	< 0.0001*
	Kidney stones	ALL	*6.8*°^	< 0.001*	< 0.0001*
		< 25	*5.3*°^	< 0.001*	< 0.0001*
		≥ 25	*8.6*°^	< 0.001*	< 0.0001*
	Liver tumor	ALL	*6.9*°^	< 0.001*	< 0.0001*
		< 25	*5.1*°^	< 0.001*	< 0.0001*
		≥ 25	*8.4*°^	< 0.001*	< 0.0001*
	Pancreas tumor	ALL	*6.9*°^	< 0.001*	< 0.0001*
		< 25	*5.3*°^	< 0.001*	< 0.0001*
		≥25	*8.7*°^	< 0.001*	< 0.0001*
	Renal infection	ALL	*7.5*°^	< 0.001*	< 0.0001*
		< 25	*5.8*°^	< 0.001*	< 0.0001*
		≥ 25	*8.9*^	0.27	< 0.0001*
	Renal tumor	ALL	*6.6*°^	< 0.0001*	< 0.0001*
		< 25	*5.1*°^	< 0.001*	< 0.0001*
		≥ 25	*8.4*°^	< 0.001*	< 0.0001*

*$p < 0.05$ (significant); ^Significantly lower than the P75 NDRL; °Significantly lower than the P50 NDRL

emphysema to 30% for pulmonary embolism), when stratifying per clinical indication. This suggests that already proposing DRLs based on clinical indication would reduce the dose metric values used for dosimetry purposes.

The DRLs could be further optimized when considering the BMI class; indeed, the largest difference within the same clinical indication is for pneumonia (7.9 mGy for BMI ≥ 25 vs. 4.5 mGy for BMI < 25; − 75%). Similar results are observed for other clinical indications.

For abdomen clinical indications and BMI < 25 class, LCDRLs were below P50/P75 NDRLs (4.6–7.0 mGy vs. 10/11 mGy and 226.7–273.4 mGycm vs. 470/540 mGycm). For BMI ≥ 25, the LCDRLs for $CTDI_{vol}$ were below the P75 NDRL for all indications and above P50 NDRL for almost all indications (7.1–10.6 mGy vs. 10/11 mGy). For the same class, the LCDRL for DLP was lower than P50/P75 NDRLs (383.7–465.5 mGycm vs. 470/540 mGycm).

Again, if we consider the ALL BMI category only, an average $CTDI_{vol}$ drop with respect to P75 NDRLs of 32% is observed (range − 27% for diverticulitis to − 40% for CT colonography).

With respect to BMI stratification when considering LCDRLs, the largest difference is for renal tumor (10.0 mGy for BMI ≥ 25 vs. 4.6 mGy for BMI < 25; − 117%). Again, similar results are observed for other clinical indications.

Table 4 Institutional median DLP per clinical indication and BMI class, compared to P50 and P75 NDRLs

Anatomical region	Clinical indication	BMI class	Median DLP (mGycm)	*p* value to P50 (210 mGycm)	*p* value to P75 (250 mGycm)
Chest	Emphysema	ALL	211.2^	0.02* (higher)	< 0.0001*
		< 25	184.5°^	0.0053*	< 0.0001*
		≥ 25	248.8^	< 0.0001* (higher)	< 0.0001*
	Pneumonia	ALL	194.0^	0.4	< 0.0001*
		< 25	164.0°^	< 0.0001*	< 0.0001*
		≥ 25	255.4	< 0.0001* (higher)	< 0.0001* (higher)
	Pulmonary embolism	ALL	209.2^	0.09	< 0.0001*
		< 25	166.0°^	< 0.0001*	< 0.0001*
		≥ 25	254.1	< 0.0001* (higher)	< 0.0001* (higher)
	Clinical indication	BMI class	Median DLP (mGycm)	*p* value to P50 (470 mGycm)	*p* value to P75 (540 mGycm)
Abdomen	Appendicitis	ALL	331.9°^	< 0.0001*	< 0.0001*
		< 25	258.9°^	< 0.0001*	< 0.0001*
		≥ 25	446.8^	0.95	< 0.0001*
	CT colonography	ALL	265.2°^	< 0.0001*	< 0.0001*
		< 25	192.9°^	< 0.0001*	< 0.0001*
		≥ 25	300.0°^	< 0.0001*	< 0.0001*
	Diverticulitis	ALL	344.8°^	< 0.0001*	< 0.0001*
		< 25	261.7°^	< 0.0001*	< 0.0001*
		≥ 25	437.6^	0.06	< 0.0001*
	Kidney stones	ALL	336.5°^	< 0.0001*	< 0.0001*
		< 25	250.9°^	< 0.0001*	< 0.0001*
		≥ 25	425.9°^	< 0.0001*	< 0.0001*
	Liver tumor	ALL	279.8°^	< 0.0001*	< 0.0001*
		< 25	204.6°^	< 0.0001*	< 0.0001*
		≥ 25	349.3°^	< 0.0001*	< 0.0001*
	Pancreas tumor	ALL	283.0°^	< 0.0001*	< 0.0001*
		< 25	206.3°^	< 0.0001*	< 0.0001*
		≥ 25	372.4°^	< 0.0001*	< 0.0001*
	Renal infection	ALL	350.6°^	< 0.0001*	< 0.0001*
		< 25	258.8°^	< 0.0001*	< 0.0001*
		≥ 25	443.4^	0.5	< 0.0001*
	Renal tumor	ALL	325.4°^	< 0.0001*	< 0.0001*
		< 25	241.3°^	< 0.0001*	< 0.0001*
		≥ 25	403.5°^	< 0.0001*	< 0.0001*

*$p < 0.05$ (significant); ^Significantly lower than the P75 NDRL; °Significantly lower than the P50 NDRL

Discussion

In the first part of the study, we evaluated the impact of using clinical indication instead of anatomical region to calculate institutional dose metrics, for the purpose of benchmarking them against NDRLs. We also assessed the impact of stratifying them per BMI class.

The median $CTDI_{vol}$ and DLP of all chest and abdomen CT indication–based protocols were always significantly lower than the achievable (P50) and acceptable (P75) NDRLs, except for the BMI ≥ 25 class (Tables 3 and 4). This result is not surprising considering that currently, the DRLs are based on a set of heterogeneous examinations for the same anatomical region but with very different settings of acquisition parameters, and therefore dose. Stratifying per clinical indications allows to reduce the variability in terms of dose metrics.

The patient size subgroup analysis revealed, however, that for the BMI ≥ 25 category, even the acceptable dose level of P75 might be a challenge, especially for chest examinations for which $CTDI_{vol}$ and DLP were significantly higher than the P75 NDRL. The stratification per BMI is one of the unique contributions of this work in the assessment of size-based and clinical indication–based DRLs. While the impact of patient size on radiation dose is well established, national DRLs have

Table 5 Local CDRLs for chest and abdomen protocols, stratified per BMI class

Anatomical region	Protocol name	Local CDRLs $CTDI_{vol}$ (mGy)			Local CDRLs DLP (mGycm)		
		All BMI	BMI < 25	BMI ≥ 25	All BMI	BMI < 25	BMI ≥ 25
Chest	Emphysema	6.0	4.9	7.1	227	209.6	321.8
	Pulmonary embolism	4.9	4.1	7.1	207	169.4	267.3
	Pneumonia	5.6	4.5	7.9	223	184.1	293.0
Abdomen	Appendicitis	7.4	6.9	10.6	353	270.5	465.5
	CT colonography	6.6	4.7	7.1	322	250.4	406.5
	Diverticulitis	8.0	6.1	10.1	360.6	273.4	448.0
	Kidney stones	6.8	5.5	9.8	339.5	254.4	447
	Liver tumor	7.3	6.0	10.5	289.4	227.3	398.8
	Pancreas tumor	7.1	5.4	8.7	304.5	233.8	383.7
	Renal tumor	8.8	4.6	10.0	354.7	226.7	432.2
	Renal infection	7.9	7.0	9.8	316.3	244.6	411.4

previously typically provided one single value for an anatomical region, as it is the case in Switzerland. These are based on a standard-size phantom representing an "average" patient. DRLs based on clinical indication and patient size will allow facilities to optimize protocols and avoid unnecessary radiation exposure to the patient while ensuring a diagnostic image quality.

In terms of dose levels, we surprisingly observed quite high $CTDI_{vol}$ and DLP values for kidney stones ($CTDI_{vol}$ of 6.8 mGy and DLP of 336.5 mGycm for ALL BMI). This might be explained by the fact that for BMI > 30, the $CTDI_{vol}$ increases substantially (7.4 mGy for a BMI = 30 and 18.3 mGy for a BMI = 47). The BMI distribution of this clinical indication was skewed to the right (skewness 0.8), impacting the dose distribution. The result of the abdomen examinations reinforces the message that the BMI < 25 class might require different (lower) DRLs than the BMI ≥ 25 class.

The second part of the study aimed at proposing LCDRLs for the evaluated clinical indications (Table 5), in order to reduce large variations in dose levels for the same type of examination. Both chest and abdominal examinations, considering DRLs based on clinical indication, show a drop in $CTDI_{vol}$ (21% for chest and 32% for abdomen, on average) with respect to DRLs based on anatomical region.

As discussed above, stratifying per BMI class has also a strong impact on dose levels. For chest examinations, the $CTDI_{vol}$ and DLP metrics for the BMI ≥ 25 class were higher than the P75 and P50 NDRLs, respectively. This confirms that subgroups based on BMI class might allow a better CT dose optimization. For chest overweight patients, for example, a higher P75 DRL level should be proposed.

For abdomen examinations, LCDRLs ranged from 4.6 mGy for renal tumor to 7 mGy for renal infection for BMI < 25 class and from 7.1 mGy for CT colonography to 10.6 mGy for appendicitis for BMI ≥ 25 class, indicating a stronger impact of the clinical indications than on chest exams. Except for a few clinical indications (appendicitis, diverticulitis, liver), abdominal LCDRLs were lower than P50 and P75 NDRLs for all BMI classes.

When comparing our results to the literature, several studies have been published on the establishment of national DRLs [9–19], all focusing on anatomical region. A recurrent conclusion is that the proposed DRLs were lower than previously published national values. Besides, DRLs for adults have been confined to a representative standard patient, defined as the 75th percentile of the mean doses of a sample of patients close to the "standard" size (typically 70 kg). However, larger fractions of patients are currently non-standard, as it can be observed from our data, where overweight patients are not outliers but represent > 50% of the population (Table 2). Among published studies investigating local DRLs [20–25], only one addressed CDRLs for adult examinations in CT [24], showing an average drop of 20% in respect to earlier DRLs based on anatomical region. Reported value for selected clinical indications was comparable or higher than the ones reported in our study. However, the authors included only patients with a weight between 60 and 90 kg, and they did not harmonize protocols among scanners as we did in our study.

Kanal et al [3] investigated the definition of diagnostic reference levels (DRLs) and achievable doses (ADs) for the 10 most common adult CT examinations in the USA as a function of patient size. Patient size was defined as the water-equivalent diameter (Dw), and DRLs have been proposed in function of patient size. However, the DRLs did not account for clinical indication and no diagnostic image quality has been assessed. Klosterkemper et al [26] analyzed the institutional chest and abdominopelvic CT dose data in relation to these DRLs based on Dw, to detect patient-size subgroups in which CT dose can be optimized. This study revealed a wide variability of $CTDI_{vol}$ across patient groups

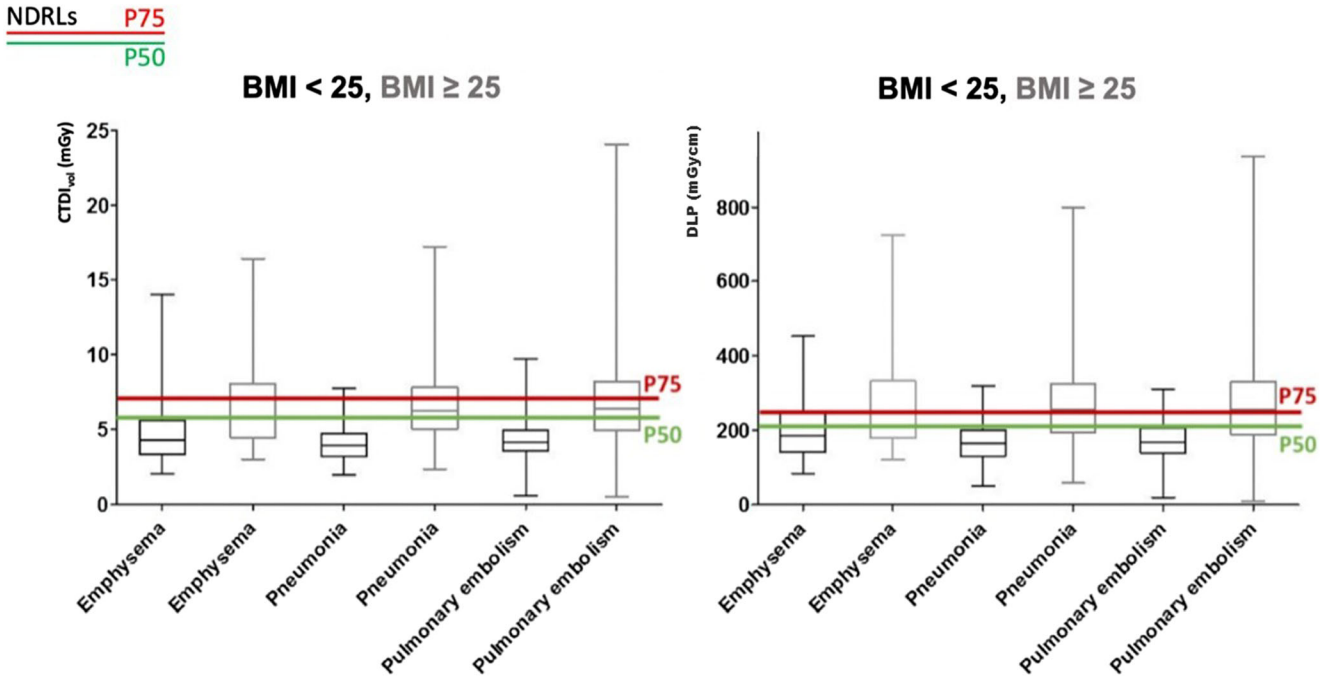

Fig. 2 Box-plot of $CTDI_{vol}$ and DLP stratified per BMI class for chest clinical indication–based protocols. Black color indicates BMI < 25 and gray color BMI ≥ 25. NDRL P50 (green line) and P75 (red line) are illustrated

with increased patient size. This is also confirmed by our study where we showed that different BMI classes imply different dose levels and that variability of dose metrics is especially high for patient with BMI ≥ 25 (Figs. 2 and 3). Boere et al [27] also showed that size-dependent LDRLs are of additional value in determining the appropriate radiation dose for individual patients undergoing CTA performed before and after endovascular aortic repair and proposed a method for determining size-dependent LDRLs, supporting our statement of defining LCDRLs based on clinical indication and patient size.

Compared to all the abovementioned studies, to the best of our knowledge, our study is the only one addressing clinical indication and patient size, while collecting data from

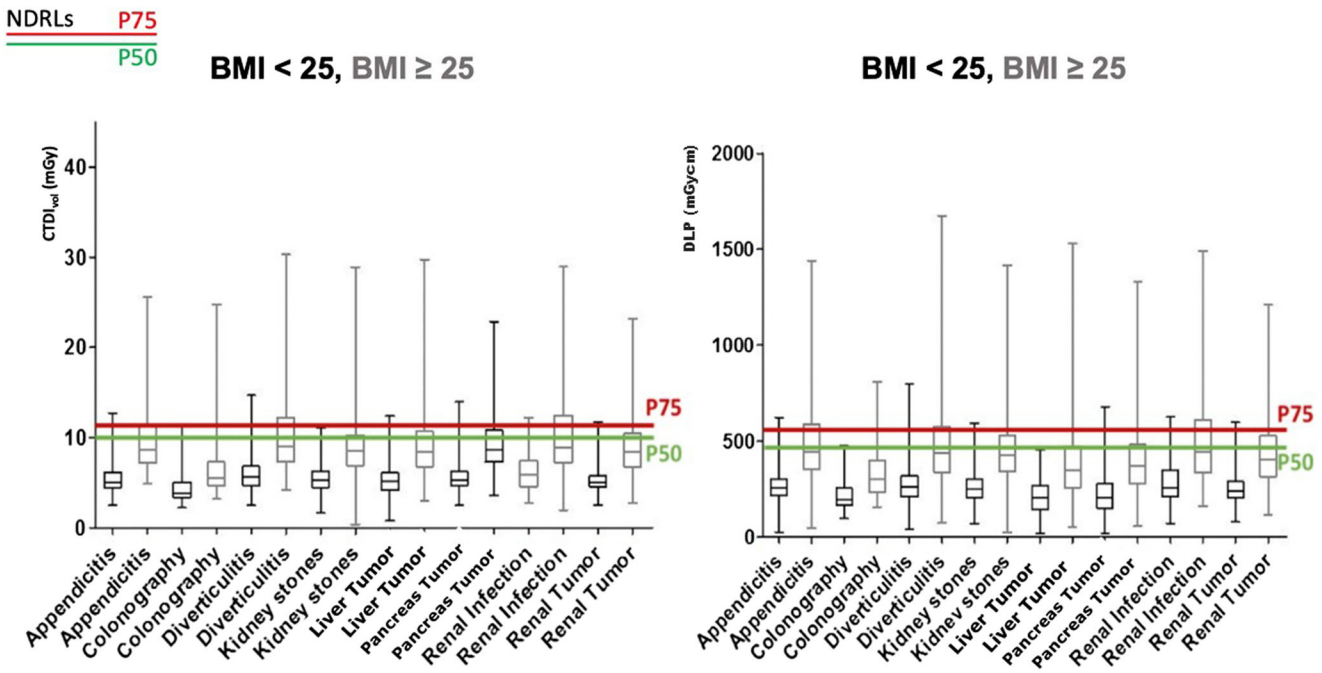

Fig. 3 Box-plot of $CTDI_{vol}$ and DLP stratified per BMI class for abdomen clinical indication–based protocols. Black color indicates BMI < 25 and gray color BMI ≥ 25. NDRL P50 (green line) and P75 (red line) are illustrated

harmonized and optimized protocols linked to a prospective diagnostic image quality evaluation. Most dose surveys for DRLs have assumed acceptable image quality rather than confirming and documenting it as in our study. It needed an automatic dose tracking system and an image quality evaluation tool integrated in the clinical workflow. The optimization process was also a strong collaboration between radiologists, medical physicists, and industry and remains a continuous process, as shown by the results of our kidney protocol.

Our study has also several limitations: (1) we collected data from Philips scanners which were not of last generation. In that respect, the assessed CDRLs could be slightly different from other vendors or more high-end scanners. (2) We did not address a large scale of BMI classes, but focused for workflow reasons only on non-overweight vs. overweight. Refining this scale could define more CDRLS, especially for the obese group (BMI > 30), as shown by the ACR [3] and this study. (3) Some of our protocols might not be completely optimized, like the kidney protocol, for example, with a possible impact on the proposed CDRLs. (4) Adults only have been addressed. Using this methodology to define clinical DRLs in pediatric patients could also have a strong impact on dosimetry optimization.

In conclusion, this study suggests the necessity of estimating DRLs based on clinical indication, especially for abdomen exams. In addition, stratifying per BMI class allows a further optimization of the CT doses and the setting of BMI-based CDRLs. Institutions who are fostering continuous dose optimization and LDRLs should consider defining protocols based on clinical indication and BMI class, to achieve ALARA.

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Compliance with ethical standards

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Federica Zanca was a former employee of GE Healthcare.

Stephane Montandon is a Philips employee.

Statistics and biometry No complex statistical methods were necessary for this paper.

Informed consent A written informed consent is submitted to every patient upon admission in Groupe 3r stating, among others, possible use of anonymized patient data for research purposes. The patient is free to oppose this use and listed as such. Specific written informed consent was therefore waived by the Institutional Review Board.

Ethical approval Institutional Review Board approval was obtained.

Methodology

- Prospective
- Observational
- Multicenter study

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