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ORIGINAL ARTICLE

Radiation dose from multidetector CT studies in children: results from the first Italian nationwide survey

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Abstract
Background Multidetector CT (MDCT) scanners have contributed to the widespread use of CT in paediatric imaging. However, concerns are raised for the associated radiation exposure. Very few surveys on radiation exposure from MDCT studies in children are available.
Objective The aim of this study was to outline the status of radiation exposure in children from MDCT practice in Italy.
Materials and methods In this retrospective multicentre study we asked Italian radiology units with an MDCT scanner with at least 16 slices to provide dosimetric and acquisition parameters of CT examinations in three age groups (1–5, 6–10, 11–15 years) for studies of head, chest and abdomen. The dosimetric results were reported in terms of third-quartile volumetric CT dose index ($CTDI_{vol}$) (mGy), size-specific dose estimate (SSDE) (mGy), dose length product (DLP) (mGy cm), and total DLP for multiphase studies. These results were compared with paediatric European and adult Italian published data. A multivariate analysis assessed the association of $CTDI_{vol}$ with patient characteristics and scanning modalities.
Results We collected data from 993 MDCT examinations performed at 25 centres. For age groups 1–5 years, 6–10 years and 11–15 years, the $CTDI_{vol}$, DLP and total DLP values were statistically significantly below the values observed in our analogous national survey in adults, although the difference decreased with increasing age. $CTDI_{vol}$ variability among centres was statistically significant (variance=0.07; 95% confidence interval=0.03–0.16; $P<0.001$).
Conclusions This study reviewed practice in Italian centres performing paediatric imaging with MDCT scanners. The variability of doses among centres suggests that the use of standardised CT protocols should be encouraged.

Keywords Multidetector computed tomography · Dose · Diagnostic reference level · Child

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Introduction

In the last decade the progressive improvement with MDCT scanners in both image quality and speed of studies has strengthened the role of CT in paediatric imaging. About 7% of CT studies are performed in children in the United States [1], 4.5% in Japan [2], 2% in Switzerland [3] and 1% in Germany [4], while in Italy the incidence of CT studies in children has not been determined.

Recently, it has been estimated that population radiation exposure has doubled since the early 1980s, mostly because of medical radiation. In the United States, CT accounts for 24% of total exposure and 49% of exposure from medical imaging [5]. Notwithstanding the undisputed role of CT in diagnostic imaging, new concerns about the exposure of children to radiation have been raised by two retrospective cohort studies. The first study showed that in children a cumulative dose of 50–60 mGy from CT studies might triple the risk of leukaemia and brain cancer, although the cumulative absolute risk

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remains small because these cancers are relatively rare [6]. The second study reported that an average estimated dose of 4.5 mSv from CT studies in children might cause about 1% of excess cases of lymphomas and solid cancers during a mean follow-up of 9.5 years [7].

Estimation of radiation doses from CT studies is a complex task. In children this task is more complex than in adults because body size is different according to age, so different age groups must be considered. Volumetric CT dose index ($CTDI_{vol}$) and dose length product (DLP) are the two main dose indices, which can be provided by a multidetector CT scanner in a dose report page or in a DICOM structured report at the end of the study. However, neither $CTDI_{vol}$ nor DLP is intended to be an indicator of patient dose because each refers to standard polymethyl-methacrylate (PMMA) phantoms. Recently the American Association of Physicists in Medicine (AAPM) developed the size-specific dose estimate (SSDE) as a new CT dose index that takes into account child size to improve the estimate of CT dose. SSDE is expected to provide paediatric radiologists a practical tool to better manage the radiation dose their patients receive [8].

Actually, both $CTDI_{vol}$ and DLP are routinely used for comparing exposures from different scanning protocols, for setting diagnostic reference levels (DRLs), and for dose optimisation.

DRLs allow radiology departments to compare their dose levels with regional or national standards. DRLs are defined as "dose levels in radiodiagnostic practices for typical examinations in groups of standard-size patients or standard phantoms for broadly defined groups of equipment. These levels are expected not to be exceeded for standard procedures when good and normal practice regarding diagnostic and technical performance is applied" [9, 10]. A DRL for a certain examination is commonly chosen as the third quartile of dose index distributions measured in a large population (usually national surveys). In Italy, DRLs in children have been established only for conventional radiology and nuclear medicine [11].

The aim of this study was to outline the status of child radiation exposure from MDCT practice in Italy, to compare our results with those of similar national surveys and to highlight the main CT parameters affecting dose.

This study was sponsored by Italian Society of Medical Radiology (SIRM) in collaboration with the Italian Association of Medical Physics (AIFM).

Materials and methods

Recruitment

This survey included two consecutive phases. Phase I was started in July 2010 with the aim of identifying the Italian institutions involved in paediatric MDCT with scanners with at least 16 slices. Through the Italian Society of Medical Radiology (SIRM), a total of 8,000 radiologists working in public, private and teaching hospitals were asked to answer a questionnaire by e-mail. The information collected included the main features of their MDCT scanners, the total number of MDCT examinations performed during the previous year (2009) and the number of MDCT examinations performed in children for more common clinical indications (head: trauma, haemorrhage; chest: infection, neoplasm; abdomen: infection, neoplasm, trauma). Patients were divided into three age groups (1–5 years, 6–10 years, 11–15 years) and into three anatomical regions (head, chest, abdomen). All examinations of the abdomen included the pelvis. More common clinical indications were decided in agreement with the Italian radiology department report [12], IMV (Greenbelt, MD/USA) benchmark report [13] and the experience of Galanski et al. [4].

At the end of phase I, only institutions that performed more than 200 MDCT studies per year in children and had at least a 16-slice CT scanner were included in the successive phase II. Centres with a radiology unit dedicated to children were considered paediatric-focused units as opposed to general units.

Phase II started in March 2011 and ended in November 2011. Centres identified through phase I were asked to provide detailed data on patient MDCT examinations collected retrospectively for each age group and anatomical region.

Data acquisition

The participating centres uploaded the required data to an online database. For each MDCT examination, CT scanner data (manufacturer, model and number of slices) and patient data (anonymous identification, age, gender and, if available, height and weight) were collected. Because a patient MDCT investigation may involve several scanning phases, the centres recorded CT scanning parameters for each phase (use of contrast medium, voltage in kV, fixed tube current in mA, use of automatic tube current modulation, tube rotation time, scan field of view, helical or axial scan, pitch, reconstructed slice thickness, z-axis coverage) and dosimetric data (for each acquisition, $CTDI_{vol}$ in mGy and DLP in mGy cm, and total DLP of the study). Topogram data were not available for the vast majority of examinations. Dosimetric data were acquired from the dose report of each individual CT examination. Both dosimetric and scanning parameters had been verified in each hospital by a medical physicist with phantom measurements according to the European guidelines EUR16262/1998 [14] to make sure that the displayed console dose indices ($CTDI_{vol}$ and DLP) and the measured dose indices were in agreement with a discrepancy less than 10%.

Statistical analysis

Data were verified for completeness and consistency. Missing values and outliers from the individual parameter distributions

were sought in order to identify possible mistakes. Because data were manually recorded in the datasheet, the outliers were mainly caused by mistakes in unit conversion or transcription, and these errors were immediately corrected. Integration of incomplete data or correction of inconsistent data was requested from the participating centres. At the end of this process, forms with more than one missing value or with inconsistencies not ascribable to transcription errors or mistakes in unit conversions were excluded from the analysis.

We report the dosimetric results of our survey in terms of first-quartile, second-quartile and third-quartile $CTDI_{vol}$, DLP (referring to a single CT acquisition), and total DLP (referring to a complete CT study, which can include multiple phases). To test the normality distribution of $CTDI_{vol}$, DLP and total DLP, we used the Shapiro-Wilk test. Our dosimetric results were based on the 16-cm phantom for head studies and the 32-cm phantom for chest and abdomen studies. Chest and abdomen dose indices based on the 16-cm phantom were divided by two in reference to the 32-cm phantom [8].

We also calculated the SSDE for chest and abdomen studies. We used Table 3 of the AAPM 204 report [8] to obtain the body effective diameter as a function of patient age. Corresponding conversion factors for the SSDE from $CTDI_{vol32}$ values were calculated with an exponential fit of values on Table 1 [8]. Results are reported for the three age groups.

We used the k-sample equality of medians test to compare the dosimetric results among the three age groups. The Kruskal-Wallis test was used to compare dose indices from paediatric and general units, and our results in children with those from our recent national survey on adults [15]. Correlations between age and weight, height and body mass index (BMI) were assessed with the Pearson coefficient. We also described the different CT acquisition parameters in terms of median value and interquartile range for the continuous variables, and in terms of counts and percentages for the categorical ones.

A multivariate analysis was also made in order to investigate how $CTDI_{vol}$ was associated with anatomical region to be studied, gender, age, CT manufacturer, number of slices and CT acquisition parameters such as tube voltage, axial versus spiral acquisition, automatic tube current modulation, use of contrast media, and tube rotation time. The deviance, defined as −2 times the log-likelihood, was used to choose the best-fitting multivariate model. In order to estimate the variability of dosimetric data across different centres, a variance components model was used, with CT sequences nested within centres. Final results were given as exponential coefficients and corresponding 95% confidence intervals (CI), while heterogeneity was given as centres level variance. The command XTMIXED of the statistical software Stata/MP 11.2 (StataCorp, College Station, TX) was used for multivariate analysis.

Finally, we compared the exposure levels found in this survey with those reported in similar studies performed in European countries and in our recent national survey on MDCT in adults [15]. The present study was approved by the ethics committees of the leading centres.

Results

Recruitment and data acquisition

In response to the phase 1 survey, 38 centres declared to perform paediatric exams. Among them, 25 centres had a CT scanner with 16 slices or more and performed more than 200 MDCT studies per year in children, so they were invited to participate to the study. Of these, 6 were specialised paediatric radiology services and 19 were general radiology services, with 6 and 22 CT scanners, respectively.

In phase II, the 25 centres performing paediatric studies uploaded a total of 1,009 forms from CT examinations.

Statistical analysis

After data validation, 993 (98.4%) of 1,009 forms concerning CT examinations in children were deemed suitable for the study (210 from paediatric units and 783 from general units).

The CT examinations included in this study were performed with 28 CT scanners including devices with 16 slices (n=10), 32 slices (n=3), 40 slices (n=1), 64 slices (n=12) and 128 slices (n=2). Models were from GE Healthcare (n=10), Philips Healthcare (n=8), and Siemens Healthcare (n=10). Automatic tube current modulation was present in all CT scanners, whereas iterative reconstruction software was not implemented in any of them at the time of this study.

Data were almost equally distributed between girls and boys, with 454 (46%) and 539 (54%) patients, respectively. We collected data of 491 patients (49%) in the 1–5 age group, 255 patients (26%) in the 6–10 age group and 247 patients (25%) in the 11–15 age group.

The total number of CT studies was 417 (42%) for head, 326 (33%) for chest, and 250 (25%) for abdomen.

Data regarding weight and height were available in 303 (31%) and 269 (27%) of 993 patients. Age was found to be significantly correlated with weight (r=0.86, P<0.001) and height (r=0.89, P<0.001) but not with the BMI (r=0.03, P=0.578); the BMI value was quite low in all age groups (mean value 17.8±5.0 kg/m^2). Detailed analysis of dose indices according to age and anatomical region is shown in Table 1. For each age group, dose values are reported for single sequences ($CTDI_{vol}$ and DLP) and complete studies (total DLP).

Significant differences in dose indices among the three age groups were found for all CT protocols (P<0.001). For head studies, in the 1–5 age group the third-quartile values of

Table 1 Detailed analysis of dose indices according to age and anatomical region given in volume-weighted CT dose index ($CTDI_{vol}$; mGy) and dose length product (DLP; mGy cm)

CT protocol	Age, y	Exams	Sequences	Parameter	25%	50%	75%
Head	1–5	216	224	$CTDIvol_{16}$	21.7	26.3	30.6
				DLP_{16}	324	409	504
				Total DLP_{16}	335	418	512
	6–10	90	96	$CTDIvol_{16}$	31.1	34.8	56.4
				DLP_{16}	483	594	852
				Total DLP_{16}	495	615	876
	11–15	111	120	$CTDIvol_{16}$	33.3	41.7	58.2
				DLP_{16}	508	631	985
				Total DLP_{16}	540	701	989
	Adults [15]	952	1,373	$CTDI_{vol}$			69
				Total DLP			1,382
Chest	1–5	153	199	$CTDIvol_{32}$	1.1	1.6	2.5
				DLP_{32}	21	32	49
				Total DLP_{32}	27	41	77.3
	6–10	88	108	$CTDIvol_{32}$	1.6	2.7	3.8
				DLP_{32}	42	67	108
				Total DLP_{32}	48	71	113
	11–15	85	102	$CTDIvol_{32}$	2	3.7	6.6
				DLP_{32}	57	111	195
				Total DLP_{32}	77	125	203
	Adults [15]	1,268	1,727	$CTDI_{vol}$			15
				Total DLP			754
Abdomen	1–5	122	184	$CTDIvol_{32}$	2.5	3.6	5.7
				DLP_{32}	75	109	151
				Total DLP_{32}	105	146	193
	6–10	77	119	$CTDIvol_{32}$	4.1	4.4	7
				DLP_{32}	136	187	227
				Total DLP_{32}	172	248	392
	11–15	51	67	$CTDIvol_{32}$	7.3	10	14
				DLP_{32}	270	427	602
				Total DLP_{32}	325	486	703
	Adults [15]	1,222	2,980	$CTDI_{vol}$			17
				Total DLP			2,157

DLP refers to a single sequence; total DLP refers to the complete study, which can include multiple sequences. $CTDI_{vol16}$ and DLP_{16} refer to a 16-cm diameter head polymethyl-methacrylate (PMMA) phantom for head examinations, and $CTDI_{vol32}$ and DLP_{32} refer to a 32-cm adult body PMMA phantom for examinations of chest and abdomen. 25%: 1st quartile; 50%: 2nd quartile; 75%: 3rd quartile. Adults values were taken from the 2011 Italian survey on MDCT in adults [15]

$CTDI_{vol16}$ (mGy), DLP_{16} (mGy cm), and total DLP_{16} (mGy cm) were 30.6, 504 and 512, respectively; in the 6–10 age group they were 56.4, 852 and 876; in the 11–15 age group they were 58.2, 985 and 989. In our recent national survey on adults [15] we found 69 and 1,382 for $CTDI_{vol16}$ and total DLP_{16}, respectively.

For chest studies, in the 1–5 age group the third-quartile values of $CTDI_{vol32}$ (mGy), DLP_{32} (mGy cm) and total DLP_{32} (mGy cm) were 2.5, 49, and 73.3, respectively; in the 6–10 age group they were 3.8, 108 and 113; in the 11–15 age group they were 6.6, 195 and 203. The third-quartile values of $CTDI_{vol32}$ and total DLP_{32} observed in adults [15] were 15 mGy and 754 mGy cm, respectively.

For abdomen studies, in the 1–5 age group the third-quartile values of $CTDI_{vol32}$ (mGy), DLP_{32} (mGy cm) and total DLP_{32} (mGy cm) were 5.7, 151 and 193, respectively; in the 6–10 age group they were 7, 227 and 392; in the 11–15 age group they were 14, 602 and 703. The third-quartile values of $CTDI_{vol32}$ and total DLP_{32} observed in adults [15] were 17 mGy and 2,157 mGy cm, respectively.

Our $CTDI_{vol}$, DLP and total DLP values were significantly lower ($P<0.05$) than the values observed in our analogous national survey in adults [15], although the difference decreased with increasing age.

Significant differences of $CTDI_{vol}$ between general and paediatric units were found only for head (all age groups) and chest studies (1–5 and 6–10 age groups). For head studies, the third-quartile values of $CTDI_{vol16}$ of general vs. paediatric units were 39.7 vs. 25.7 mGy for the 1–5 age group ($P=0.001$), 58.4 vs. 33.4 mGy for the 6–10 age group

(P=0.001) and 55.0 vs. 38.3 mGy for the 11–15 age group (P=0.001). For chest, the third-quartile values of $CTDI_{vol32}$ of general vs. paediatric units were 3.4 vs. 2.2 mGy for the 1–5 age group (P=0.014), 4.2 vs. 2.9 mGy for the 6–10 age group (P=0.002) and 6.4 vs. 3.9 mGy for the 11–15 age group (P=0.134). For abdomen studies, the third-quartile values of $CTDI_{vol32}$ of general vs. paediatric units were 4.4. vs. 5.9 mGy for the 1–5 age group (P=0.331), 6 vs. 7.3 mGy for the 6–10 age group (P=0.130) and 17.3 vs. 14 mGy for the 11–15 age group (P=0.118).

In Fig. 1 we report the box-and-whisker plots of $CTDI_{vol}$ and SSDE of the abdomen and chest studies for the three age groups. With SSDE, we observed an increase of all percentile values and interquartile ranges (25th–75th percentiles) in all groups. The percentage increase of the 75th percentile of SSDE in comparison with $CTDI_{vol}$ was about 100% for the 1–5 age group, about 70% for the 6–10 age group and about 50% for the 11–15 age group.

The CT system settings chosen in each anatomical region for each age group are shown in Table 2.

The use of reduced voltage (less than 120 kV, standard setting for adult CT examinations) was evaluated. Regardless of age and anatomical region, tube voltage was below 120 kV in 524 (43%) out of 1,219 CT sequences. A tube voltage below 120 kV for the 1–5, 6–10 and 11–15 age groups was used in 21.6%, 2.1% and 0% of sequences, respectively, performed for head studies; in 82.9%, 63% and 49% of sequences performed for chest, and in 65.2%, 52.9% and 9% for abdomen. In the 1–5 age group, a number of chest and abdominal studies were performed with 80 kV, resulting in 37.2% and 29.9% of acquisitions, respectively. Voltage values above 120 kV were set for 12 (2.9%) of 417 sequences performed for head studies, and 4 (1.1%) of 370 sequences performed for studies of the abdomen.

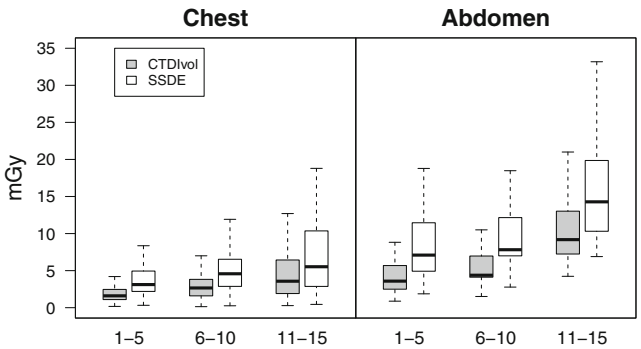

Fig. 1 $CTDI_{vol}$ versus SSDE in chest and abdomen studies in each age group (1–5 years, 6–10 years, 11–15 years). The height of the box displays the interquartile range with the 25th and 75th percentiles represented by the lower and upper edges of the box, respectively. The horizontal bold line in the box corresponds to the median. The lower whisker is the 25th percentile minus 1.5 times the interquartile range; the upper whisker is the 75th percentile plus 1.5 times the interquartile range. *$CTDI_{vol}$* volumetric computed tomography dose index, *SSDE* size-specific dose estimate

Median fixed tube current setting was set at 250 mA (1–5 age group) and 300 mA (6–10 and 11–15 age groups) for head; 66 mA (1–5 age group) and 100 mA (6–10 and 11–15 age groups) for chest; 99 mA (1–5 age group), 200 mA (6–10 age group) and 230 mA (11–15 age group) for abdomen. Automatic tube current modulation was available on all CT scanners, although it was not used systematically. Automatic tube current modulation was used in 80.5% of sequences for abdominal studies, 68.5% of sequences for chest studies and 50.5% of sequences for head studies.

Spiral acquisitions were almost always performed in abdomen and chest protocols (98.6% and 90.5% of cases, respectively), while axial scans prevailed in head studies (71.4% of scans). In chest studies all axial acquisitions were additional expiratory views performed to evaluate air trapping. Tube rotation time was 0.5 s in most chest and abdomen examinations and 1 s in most head studies. Median pitch was 0.4 for head and 1.3 for chest studies, respectively. Median pitch in abdominal studies was 1 in the 1–5 and 6–10 age groups and 1.2 in the 11–15 age group.

As expected, the z-axis coverage increased with age in all protocols, with the exception of head studies in the 11–15 age group. In the 1–5, 6–10 and 11–15 age groups the median values were 144 mm, 155 mm and 155 mm, respectively, for head; 156 mm, 216 mm and 263 mm for chest; and 234 mm, 321 mm and 395 mm for abdomen. In chest and abdominal studies, the z-axis coverage was quite different among the three age groups, while in head scans it was similar in the 6–10 and 11–15 age groups.

Contrast enhancement was used in 223 (89%) of 250 abdomen examinations, 161 (49%) of 326 chest examinations and 18 (4%) of 417 head examinations.

CT examinations included multiple acquisitions in 23 (6%) of 417 studies of the head, 68 (21%) of 326 studies of the chest and 67 (27%) of 250 studies of the abdomen, for a total of 1,219 CT acquisitions (Table 3). In head studies, a second acquisition was performed with contrast enhancement in eight children and for movement artifacts in four uncooperative children; in the remaining 11 children the study was performed with two separate acquisitions, the first for the supratentorial structures and the second for the posterior fossa. In 68 chest studies multiple acquisitions were performed for evaluation of air trapping with a second axial large-gap acquisition in full expiration in cooperative children (57 studies) and two axial large-gap acquisitions in each lateral decubitus in uncooperative children (11 studies). In abdomen studies, multiple acquisitions were performed in 39 children with neoplasms, 19 with trauma and 9 with abdominal abscess. The percentage of multiphase examinations in the chest and abdomen CT studies was significantly lower than the percentage observed in our recent survey in adults (P<0.001), where multiphase exams accounted for 31% and 71% of all adult CT examinations in chest and abdomen studies, respectively [15].

Table 2 The CT system settings chosen in each anatomical region by age groups, including main CT scan characteristics, presented as counts (with percentages in brackets) for categorical variables, and as median values (with interquartile range in brackets) for continuous variables

	Head			Chest			Abdomen		
Characteristics	1–5 y	6–10 y	11–15 y	1–5 y	6–10 y	11–15 y	1–5 y	6–10 y	11–15 y
Tube voltage (kV)									
80	2 (0.1%)	-	-	74 (37.2%)	19 (17.6%)	4 (3.9%)	55 (29.9%)	34 (28.6%)	-
90	-	-	-	7 (3.5%)	4 (3.7%)	2 (2%)	-	3 (2.5%)	1 (1.5%)
100	48 (21.5%)	2 (2.1%)	-	84 (42.2%)	45 (41.7%)	44 (43.1%)	65 (35.3%)	26 (21.8%)	5 (7.5%)
120	166 (74.1%)	92 (95.8%)	118 (98.3%)	34 (17.1%)	40 (37%)	52 (51%)	64 (34.8%)	56 (47.1%)	57 (85%)
130	5 (2.2%)	-	-	-	-	-	-	-	4 (6%)
140	3 (1.3%)	2 (2.1%)	2 (1.7%)	-	-	-	-	-	-
Automatic tube current modulation	117 (52.2%)	42 (43.8%)	63 (52.5%)	130 (65.3%)	82 (75.9%)	68 (66.7%)	160 (87.0%)	96 (80.7%)	42 (62.7%)
Fixed tube current (mA)	250 (130–300)	300 (200–300)	300 (270–310)	66 (45–128)	100 (55–147)	100 (75–125)	99 (85–202)	200 (159–403)	230 (200–277)
Tube current range (mA)[a]									
Min	120 (100–151)	145 (100–150)	149 (100–166)	76 (50–80)	80 (50–100)	100 (46–100)	100 (86–100)	100 (97–100)	120 (91–194)
Max	189 (175–210)	200 (200–220)	320 (217–320)	120 (100–150)	150 (120–250)	164 (110–210)	135 (120–150)	160 (138–300)	200 (150–318)
Spiral acquisition[b]	70 (31.3%)	22 (22.9%)	34 (28.3%)	180 (90.5%)	100 (92.6%)	90 (88.2%)	184 (100%)	118 (99.2%)	63 (94.0%)
Pitch[c]	0.43 (0.3–0.6)	0.42 (0.3–0.51)	0.47 (0.33–0.64)	1.375 (1.2–1.4)	1.26 (1.1–1.4)	1.375 (1.0–1.4)	1.2 (1.015–1.2)	1 (1–1.2)	1 (0.8–1.2)
Scan length (mm)	144 (129–155)	155 (143–167)	155 (140–165)	156 (123–180)	216 (186–242)	263 (216–295)	234 (197–278)	321 (283–365)	395 (340–425)
Tube rotation time (s)	1 (0.7–1)	1 (0.8–1)	1 (0.8–1)	0.5 (0.5–0.5)	0.5 (0.4–0.5)	0.5 (0.5–0.5)	0.5 (0.5–0.5)	0.5 (0.5–0.5)	0.5 (0.5–0.5)
Scan field-of-view (mm)	200 (160–250)	250 (220–250)	250 (193–264)	250 (201–230)	320 (256–320)	320 (317–320)	250 (231–320)	312 (260–320)	320 (319–385)
Reconstructed slice thickness (mm)	2.4 (2–5)	4.8 (2.4–5)	3 (2.4–5)	2 (1–2.5)	2 (1–4)	2 (1–2.5)	2 (1–2.5)	2 (1–2.25)	2 (1–2.25)

[a] Acquisitions with tube current modulation

[b] In chest studies, all axial acquisitions were additional expiratory views performed to evaluate air trapping

[c] Spiral acquisitions only

Table 3 Distribution of the number of phases, according to anatomical region, in CT studies performed in Italy

	Total number of studies	Single phase	2 phases	3 phases	4 phases
Head	417	394 (94.5%)	23 (5.5%)	-	-
Chest	326	258 (79.1%)	57 (17.5%)	11 (3.4%)	-
Abdomen	250	183 (73.2%)	65 (26%)	1 (0.4%)	1 (0.4%)

In Table 4 we report the results of the multivariate analysis. Variance among participating centres was statistically significant (variance=0.07, 95% CI=0.03–0.16; $P<0.001$). $CTDI_{vol}$ was significantly higher ($P<0.001$) in the 6–10 and 11–15 age groups than in the 1–5 age group, irrespective of anatomical region. Gender, axial vs. spiral acquisition, number of slices and CT manufacturer were not associated with $CTDI_{vol}$ ($P>0.05$). The $CTDI_{vol}$ of head studies was significantly higher ($P<0.001$) and $CTDI_{vol}$ of the chest lower ($P<0.001$) than the $CTDI_{vol}$ of abdominal studies. In all groups, $CTDI_{vol}$ was significantly lower ($P<0.001$) with tube voltage <120 kV versus tube voltage ≥120 kV. With automatic tube current modulation activated, $CTDI_{vol}$ was significantly lower ($P<0.001$).

Finally, we compared the exposure levels observed in this survey with those reported in similar studies performed in European countries (Table 5). In our survey radiation exposure in terms of $CTDI_{vol}$ and DLP for a single acquisition appears to be the lowest for CT examinations of the head in the 1- to 5-years age group and for chest examinations in all age groups. The dose indices of CT studies in the remaining groups appear to be comparable with those reported in the other national surveys [4, 16–19].

Table 4 Results of the multivariate analysis show associations between $CTDI_{vol}$ and patient characteristics and scanning modalities

Variables	Exp(b)	95% CI	*P*-value
Gender (male vs. female)	0.96	(0.92; 1.00)	0.069
Age groups 6–10 y vs. 1–5 y	1.26	(1.19; 1.33)	<0.001
Age groups 11–15 y vs. 1–5 y	1.55	(1.46; 1.65)	<0.001
Head vs. abdomen CT protocol	2.23	(2.00; 2.48)	<0.001
Chest vs. abdomen CT protocol	0.65	(0.61; 0.69)	<0.001
Axial vs. spiral acquisition	0.95	(0.86; 1.05)	0.310
Tube rotation time (s)	1.17	(1.12; 1.23)	<0.001
Administration of contrast media (yes vs. no)	1.04	(1.02; 1.06)	<0.001
Voltage (kV)<120 vs. ≥120	0.57	(0.53; 0.60)	<0.001
Automatic tube current modulation activated vs. non-activated	0.92	(0.88; 0.95)	<0.001
Number of slices (>32 vs. ≤32)	1.01	(0.92; 1.11)	0.775
GE vs. Siemens	1.17	(0.90; 1.51)	0.237
Philips vs. Siemens	1.10	(0.85; 1.41)	0.471
Among-centres variance (95% CI)	0.07	(0.03; 0.16)	<0.001

We also compared the total DLPs from multiphase studies of this survey with those reported in the German survey [4]. Our total DLP was higher in abdominal studies in all age groups and in head studies in the 6–10 age group.

Discussion

We report the first Italian nationwide study on radiation doses in children from common MDCT examinations of head, chest and abdomen performed in both paediatric and general radiology departments.

According to the recent Dose Datamed 2 project on diagnostic reference levels for X-ray procedures in Europe, just six European countries have established DRLs for paediatric CT examinations, namely Austria, France, Germany, Norway, Ireland, and Switzerland [20]. Furthermore, very few surveys on CT dose in children have been published in Europe — just the 2003 UK CT survey [16], the 2008 Swiss CT survey [17], the 2005–2006 German CT survey [4], the 2009 French MDCT survey [18], and the 2009 Greek CT survey [19].

All these surveys included CT studies of head, chest and abdomen for common indications (trauma, infection, staging), with the exception of the UK 2003 survey [16], which did not include abdominal studies.

The 1- to 5-year (or 0- to 5-year [17], or 5-year [16]), or 6- to 10-year (or 10-year [16]) age groups were included in all surveys, whereas the 11–15 age group was considered just in the German [4] and Swiss [17] surveys. The 0–1 (or 1-year) age group was considered only in the German [4], UK [16] and French [18] studies. The age group 0 to 1 year was not considered in our study because of the expected low number of examinations performed [4, 16].

The comparison of the dose indices proposed in our study with those reported in the above-mentioned national surveys is not straightforward because of the great differences in methodology. The surveys from Switzerland [17], France [18] and Greece [19] were based on the estimated dose indices alone of the protocols commonly used in the participating centres for specific indications and age groups, whereas the surveys from Germany [4] and UK [16] were based on measured doses of CT studies acquired from a sample of patients.

In agreement with the methodology followed in the German [4] and UK [16] surveys, our study was based on data collection from MDCT studies performed in children.

Table 5 Exposure levels by age groups observed in this survey vs. those reported in similar studies performed in European countries, including the 75th-percentile doses from the present study and the proposed DRLs in the United Kingdom [16], Germany [4], Switzerland [17], France [18] and Greece [19]

CT protocol	1–5 y (or 5 y)			6–10 y (or 10 y)			11–15 y		
Head	$CTDI_{vol16}$	DLP_{16}	Total DLP_{16}	$CTDI_{vol16}$	DLP_{16}	Total DLP_{16}	$CTDI_{vol16}$	DLP_{16}	Total DLP_{16}
Present survey	30.6	418	512	56.4	852	876	58.2	985	989
Germany 2008	49	611	640	58	711	784	64.5	920	1,007
UK 2003°	43	465		51	619		-	-	
Switzerland 2008	30	420		40	560		60	1,000	
France 2009	40	600		50	900		-	-	
Greece 2009	-	650		-	975		-	-	
Chest	$CTDI_{vol32}$	DLP_{32}	Total DLP_{32}	$CTDI_{vol32}$	DLP_{32}	Total DLP_{32}	$CTDI_{vol32}$	DLP_{32}	Total DLP_{32}
Present survey	2.5	49	77	3.8	108	113	6.6	195	203
Germany 2008	4.4	73	76	6.0	128	128	8	244	259
UK 2003°	6.5	114		8.5	184		-	-	
Switzerland 2008	8	200		10	220		12	460	
France 2009	3.5	63		5.5	137		-	-	
Greece 2009*	-	168		-	289		-	-	
Abdomen	$CTDI_{vol32}$	DLP_{32}	Total DLP_{32}	$CTDI_{vol32}$	DLP_{32}	Total DLP_{32}	$CTDI_{vol32}$	DLP_{32}	Total DLP_{32}
Present survey	5.7	151	193	7	227	392	14	602	703
Germany 2008	4.7	147	155	7.4	227	227	10.1	402	546
UK 2003	-	-		-	-		-	-	
Switzerland 2008	9	300		13	380		16	500	
France 2009	4.5	121		7	245		-	-	
Greece 2009*	-	420		-	560		-	-	

$CTDI_{vol}$ volumetric CT dose index, *DRL* diagnostic reference levels

°$CTDI_{vol32}$ and DLP_{32} for chest examinations in 5- and 10-year group were calculated by dividing by two the original values of the $CTDI_{vol16}$ and DLP_{16} reported in the UK 2003 survey

*DLP_{32} for chest and abdomen examinations in 5- and 10-year group were calculated by dividing by two the original values of the DLP_{16} reported in the Greece 2009 survey

However, our survey included only studies performed with MDCT scanners with at least 16 slices because this was most representative of clinical practice at the time of the survey. We did not include dosimetric data from obsolete scanners with less-developed tools for dose optimisation; otherwise our dose indices could have been based on data not reflecting recent technical improvements. We did not consider the contribution of topograms to radiation exposure because this information was not available in the great majority of the CT scanners included in this survey.

In our survey $CTDI_{vol}$ and DLP values for a single acquisition were suitable for each anatomical region and age group because they were below both the values observed in our analogous national survey in adults [15] and those obtained in the other European surveys in children. In particular, $CTDI_{vol}$ of chest studies was significantly lower than $CTDI_{vol}$ of abdominal studies. However, although the dose indices were significantly decreased in younger age groups in all studies, as shown by multivariate analysis, the $CTDI_{vol}$ of abdomen studies in the 11–15 age group remained close to the values observed in our survey in adults. Therefore an optimisation of the practice in this age group should be advocated.

With the exception of our study and the German CT survey [4], none of the other national CT surveys in children [16–19] took into account total DLP as dose index. However, the wide availability of MDCT scanners makes the distinction between DLP and total DLP very important because multiphase CT examinations can be very easily performed. It is well-known that the number of acquisitions performed in a CT study is one of the most important parameters affecting patient exposure. Therefore the monitoring of total DLP may help in controlling dose.

Total DLP values in our survey were much lower than values observed in adults [15], which reflects the reduced use of multiphase examinations in children compared to adults. Nevertheless, the use of multiple acquisitions in our sample of patients resulted in a noticeable raising of doses, which should be carefully evaluated.

In our survey the total DLP of abdomen studies in all age groups was quite high in comparison with findings in the German survey [4]. This finding could be a result of the choice

to perform multiple scans in almost 30% of our patients, although non-enhanced scans and multiple contrast-enhanced acquisition phases are rarely justified in children. Actually, the percentage of multiphase studies was not explicitly reported in the German survey; however it could be lower than ours because single-slice CT scanners were prevalent. Furthermore, our higher total DLP values could be also a result of larger z-axis coverage, which can include the pelvis.

The great spread of dose indices and the variance analysis among the Italian radiology departments underline the large variety of CT protocols used in the different centres for similar CT studies in similar groups of patients. Furthermore, a significant difference in dose delivery was found between paediatric and general units in head and chest protocols, with lower values in paediatric units.

These results suggest that an optimisation process should be started, taking into account appropriate image-quality requirements and number of acquisition phases necessary for a given indication.

Size-specific dose estimate is a new dose index considered to be a better estimate of patient individual dose because, unlike $CTDI_{vol}$ and DLP, it takes into account patient size. Patient size can be obtained from the lateral or anteroposterior body dimension measured in a topogram or CT exam or it can be deduced from age [8]. In our retrospective study the images of topograms and CT examinations were not available so we estimated SSDE from patient age.

According to our results, in all anatomical regions and age groups the third quartiles of SSDE values were higher and had higher variability than the corresponding $CTDI_{vol}$ values, especially in the 1–5 age group. This trend is similar to that observed in a recent survey by Goske et al. [21], in which SSDE was taken into account. In our study SSDE values were still below the $CTDI_{vol}$ values observed in our survey in adults [15] with the exception of abdomen studies in the 11–15 age group. This finding further suggests that a better optimisation is needed in this group of patients. Our assessment of SSDE through age is probably suboptimal, because of the large variability in size among patients of the same age [22]. However, the prevalence in our sample of underweight or normal-weight children — confirmed by the low BMI and the very good correlation of height and weight with patient age observed by us — suggests that, at least in our case, age could be considered a reasonable surrogate of body size. Our results on SSDE should be considered a preliminary estimate to be improved in future studies based on actual patient diameters. Nevertheless they highlight that $CTDI_{vol}$ can lead to a remarkable underestimation of absorbed dose in children. Therefore the use of SSDE, which was not developed at the time of data collection for this survey, may help in a better optimisation of CT protocols.

On the other hand, BMI can be difficult to use for protocol optimisation in children because it is usually quite low in this group of patients and poorly correlated with children's age and size. Weight might be a better measure in children.

Concerning the CT settings in our survey, tube voltage lower than 120 kV was used in 43% of CT sequences. However, although kV reduction is a common practice in paediatric CT, no specific guidelines are available to set appropriate tube voltage in children. Actually, it is well known that low kV decreases dose exposure and is beneficial in CT angiography, where the increased enhancement with iodinated contrast media far outweighs the increase in noise. However, in non-angiographic studies with administration of contrast medium, an excessively low tube voltage may just increase the noise in areas free from contrast agent, with possible occurrence of beam hardening and streaking artefacts. The choice of a reduced tube voltage can be a difficult task, depending on patient's size and diagnostic query, and should be thought of as a trade-off among image contrast, noise and artefacts. Systems with automatic kV modulation based on patient anatomy could help operators in the best kV choice.

Our survey shows that the use of automatic tube current modulation is correlated with a significantly lower $CTDI_{vol}$. However the participating radiology centres did not systematically use it, especially in head and chest CT studies, suggesting that an optimisation process is needed in this respect. Automatic tube current modulation does not guarantee reduction of radiation exposure and users should consider a target image quality. If image quality is higher than needed, patient overexposure can occur. Therefore dose limitation with automatic tube current modulation is achieved only when the image quality or image noise setting is appropriate to the clinical purpose of the study. However, notwithstanding these limitations, several studies have found that automatic tube current modulation can reduce dose in comparison with a fixed tube current setting [23–25].

Regarding pitch, in our survey the pitch values chosen for head spiral acquisitions were often below 1; higher values should be recommended in order to obtain dose reduction.

One limitation of our survey is that image quality of the studies is not taken into account. The great variability of dosimetric data observed among different centres and different surveys could be caused by the lack of agreement on the image quality needed for a specific study. Furthermore, the dose required to get a specific image quality strongly depends on the equipment used. The DRL term itself can be confusing because complying with a diagnostic "reference" dose is not necessarily the same as following the ALARA (as low as reasonably achievable) principle in that there is no scope for further reduction of radiation exposure [26]. The implementation of robust quality indices could be a further step toward dose optimisation.

Conclusion

This study reviews current practice in Italian centres performing paediatric CT imaging with MDCT scanners. Dose values were suitable for each anatomical region and age group. The dose values per acquisition were below those published in the most recent Italian survey on MDCT exams in adults and were in agreement with those reported in other paediatric surveys.

However total DLP per patient was fairly high as a consequence of the frequent use of multiple MDCT acquisitions, and $CTDI_{vol}$ and SSDE of abdomen studies in the 11–15 age group were close to adult values. Furthermore, dose values were significantly lower for head and chest studies performed in paediatric centres in comparison with general radiology centres. Future optimisation programs should pay attention to these issues and possibly encourage the use of standardised CT protocols.

A better dose optimisation in children could be achieved with the introduction of size-specific CT protocols, with an increased use of automatic tube current modulation systems and a proper adaptation of CT settings, in particular kV and pitch. The introduction of iterative reconstruction algorithms and kV adapting systems could help in this task.

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