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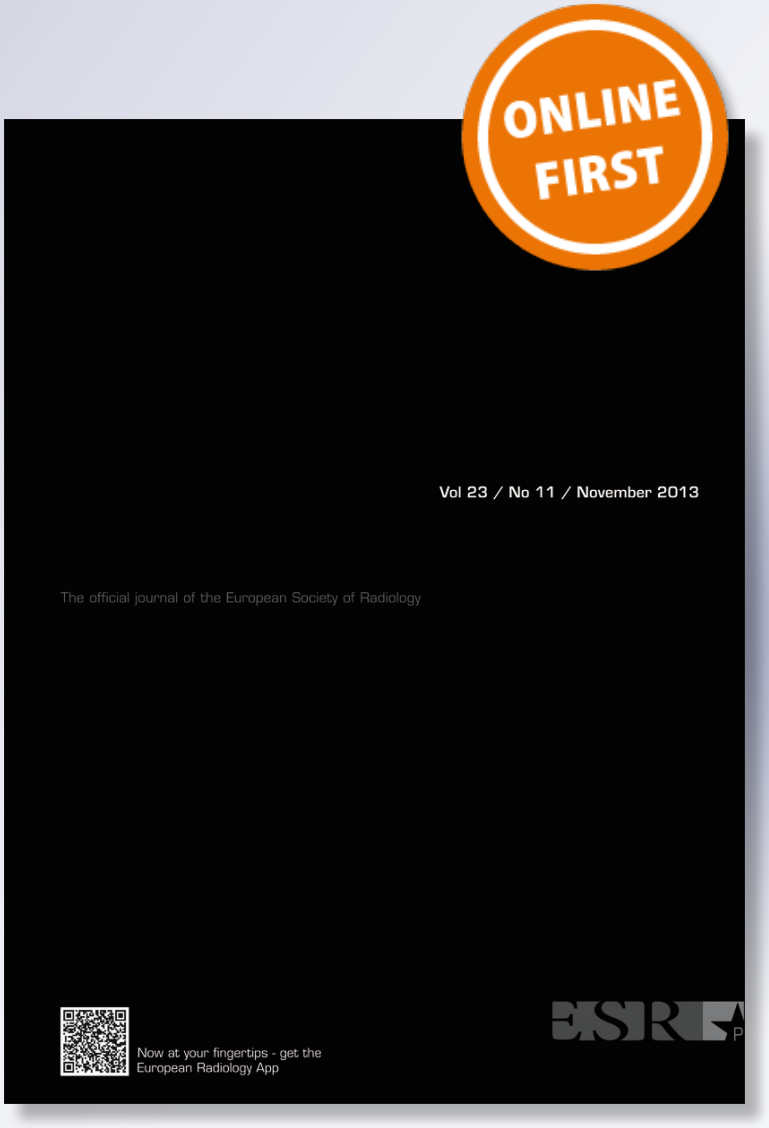
Federica Palorini, Daniela Origgi, Claudio Granata, Domenica Matranga & Sergio Salerno

European Radiology

ISSN 0938-7994

Eur Radiol
DOI 10.1007/s00330-013-3031-7



Springer

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Adult exposures from MDCT including multiphase studies: first Italian nationwide survey

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Received: 21 May 2013 / Revised: 12 August 2013 / Accepted: 9 September 2013

Abstract
Objectives To evaluate the radiation dose in routine multidetector computed tomography (MDCT) examinations in Italian population.
Methods This was a retrospective multicentre study included 5,668 patients from 65 radiology departments who had undergone common CT protocols: head, chest, abdomen, chest–abdomen–pelvis (CAP), spine and cardiac. Data included patient characteristics, CT parameters, volumetric CT dose index ($CTDI_{vol}$) and dose length product (DLP) for each CT acquisition phase. Descriptive statistics were calculated, and a multi-regression analysis was used to outline the main factors affecting exposure.
Results The 75th percentiles of $CTDI_{vol}$ (mGy) and DLP (mGy cm) for whole head were 69 mGy and 1,312 mGy cm, respectively; for chest, 15 mGy and 569 mGy cm; spine, 42 mGy and 888 mGy cm; cardiac, 7 mGy and 131 mGy cm for calcium score, and 61 mGy and 1,208 mGy cm for angiographic CT studies. High variability was present in the DLP of abdomen and CAP protocols, where multiphase examinations dominated (71 % and 73 % respectively): for abdomen, 18 mGy, with 555 and 920 mGy cm in abdomen and abdomen–pelvis acquisitions respectively; for CAP, 17 mGy, with 508, 850 and 1,200 mGy cm in abdomen, abdomen–pelvis and CAP acquisitions respectively.
Conclusion The results of this survey could help in the definition of updated diagnostic reference levels (DRL).
Key Points
- *Radiation dose associated with multidetector CT (MDCT) is an important health issue.*
- *This national survey assessed dose exposures of 5,668 patients undergoing MDCT.*
- *Dose indices correlate with BMI, voltage, rotation time, pitch and tube current.*
- *These results may contribute to an update of national diagnostic reference levels.*

Keywords Nationwide survey · Radiation protection · Multidetector CT · Patient dose · Diagnostic reference levels

Abbreviations and Acronyms

AIFM	Italian Society of Medical Physics
BMI	body mass index
CAP	chest–abdomen–pelvis
CI	confidence interval
$CTDI_{vol}$	volumetric computed tomography dose index
DLP	dose length product
DRL	diagnostic reference levels
ECTCM	electrocardiographically controlled tube current modulation
FOV	field of view
GEE	generalized estimating equations
MDCT	multidetector computed tomography
MV	mean value

F. Palorini · D. Origgi
Fisica Sanitaria Istituto Europeo di Oncologia, Milan, Italy

C. Granata
UOC di Radiologia Istituto Giannina Gaslini, Genoa, Italy

D. Matranga
Dipartimento di Scienze per la Promozione della Salute e Materno-infantile "G. D'Alessandro", Università degli Studi di Palermo, Palermo, Italy

S. Salerno (✉)
Dipartimento di Scienze Radiologiche, Policlinico Università di Palermo, Via del Vespro 127, 90127 Palermo, Italy
e-mail: sergio.salerno@unipa.it

Published online: 10 October 2013

RIS	radiology information system
SD	standard deviation
SIRM	Italian Society of Radiology

Introduction

Computed tomography (CT) has dramatically changed since the publication of the first European guidelines for computed tomography in 1999 [1], wherein diagnostic reference levels (DRL) were proposed, and its update in 2004 [2].

The most fundamental change to CT is the increased number of detector rows, but evolution has also been seen in hardware improvements (x-ray tube, detectors, etc.) and software developments (dose reduction systems, new reconstruction algorithms) that allow faster acquisition and higher image quality to be achieved [3–9].

A practical consequence of this rapid evolution is that CT examinations are no longer limited to a single anatomical region and a maximum of two CT data acquisitions (without and with contrast media). Instead, whole-body and multiphase examinations are increasingly common.

The resulting relevant increase in dose to the patient is an issue of international concern that has emerged in the scientific literature over the last 10 years [10, 11] despite a number of advances in dose reduction systems, indicating that further optimisation is still required [5–9]. Equally, awareness and guidance on the risk associated with these increased dosages are needed, but the present Italian DRLs established by Italian law (D.Lgs. 187/2000) [12] refer to the old European guidelines of 1999.

The volumetric CT dose index ($CTDI_{vol}$) and the dose length product (DLP) are still the two main CT dose descriptors, and can be collected from the dose report, which is a page summary sheet produced by the CT system at the end of each CT examination. As the $CTDI_{vol}$ and DLP are calculated with reference to phantom measurements, they provide only a rough estimation of the dose to the patient, but are nonetheless a useful tool for protocol optimisation and dose reduction [2].

This article provides a comprehensive overview of the state of practice of multidetector CT (MDCT) examinations in Italy for common clinical disorders. It is part of a major project that started in 2010 and was sponsored by the Italian Society of Radiology (SIRM) in collaboration with the Italian Society of Medical Physics (AIFM). In this retrospective multicentre study, we collected acquisition and dosimetric parameters from a large number of patients who underwent CT examinations for common clinical indications. The study was approved and registered by ClinicalTrials.gov (Identifier: NCT01436006).

Previous Italian studies refer to single-slice CT [13] or to DRL collection in single Italian regions (Val d'Aosta [14] and Emilia Romagna [15]). Similar analyses have previously been conducted in the UK [16] and Germany [17], but were concerned mainly with single- or four-slice CT. Other studies in patients of paediatric age have been performed in Switzerland [18], Germany [19] and France [20]. More recent experience with MDCT has been examined in Ireland [21] and Malta [22], both in a small group of hospitals. Less detailed reports, based on the collection of local DRLs, are also available, but they do not give a full description of everyday practice [23–26].

This survey aimed to provide extensive and up-to-date information on the practice of MDCT in Italy that can serve as a benchmark for future European analyses and for improving CT imaging and dose optimisation.

We evaluated the magnitude of radiation dose to patients, in terms of $CTDI_{vol}$ and DLP, and the CT acquisition settings including the use of dose reduction systems. Particular attention was paid to multiphase examinations: we collected both the DLP, referring to a single acquisition (DLP), and the DLP of a complete patient examination (total DLP). The association of radiation dose with the different acquisitions and patient characteristics was also investigated.

Materials and methods

Data collection

This retrospective multicentre study was organised in two phases. The first was intended to select a significant sample including those centres that perform a relevant number of adult examinations per year and carry out a regular programme of quality checks in their CT units. The second was devoted to collecting details of the CT examinations carried out in those centres (including CT protocol and dosimetric parameters) for each patient. In both phases, the participating centres (see Appendix) filled in pre-established forms and uploaded them to an on-line database.

Phase 1

All radiologist members of SIRM (of public, private or academic hospitals) and regularly performing MDCT studies in adults were invited to participate to this open-call study. This study was approved by the ethics committee of the two leading centres (European Institute of Oncology of Milan, and University Hospital Palermo).

In the preliminary questionnaire the centres were asked to indicate the number of CT examinations performed in 2009 for six different CT protocols: head, abdomen, chest, spine, heart and chest–abdomen–pelvis (CAP).

In addition, they were asked to report the main features of their MDCT apparatus: the CT system manufacturer, model, year of installation and the number of detector rows. Finally, they were asked to measure the $CTDI_{vol}$ following the European

guidelines EUR16262/1998 [1] and to verify that the measured value was within ±10 % of the console displayed $CTDI_{vol}$.

Phase 2

All centres performing at least 10,000 CT examinations per year using CT systems capable of acquiring at least 16 slices simultaneously and with a responsible medical physicist were invited to participate. The clinical indications for the protocols of interest were trauma, ischaemic stroke, haemorrhage for head; cancer diagnosis and staging, infection for chest; cancer diagnosis and staging, vascular disorder, abscess and trauma for abdomen; cancer for CAP; general indications for spine; coronary disease of native vessels for cardiac acquisitions (Table 1). The requested clinical indications are the most frequent according to the 2009 Italian report [27], the previous experience conducted by Shrimpton et al. [16] and the US IMV benchmark report [28], except for cardiac CT study, which is an emerging CT indication.

In preparation for the second phase, the centres were grouped according to their geographical location according to the four macro-areas of the nation: North East, North West, Centre, and South and Islands. Each centre was then asked to provide data from individual CT examinations proportionally to the total volume of CT studies performed in 1 year for each protocol and to the total number of examinations performed in the corresponding macro-area [27]. The sample size for the individual CT examinations was planned to guarantee a confidence level of 95 % and an absolute error of 5 % on the average dose, with simple random sampling and assuming that the standard deviation of dose values per CT acquisition series was twice the one estimated in a similar German nationwide survey of exposure practice for 11- to 15-year-old children [19].

The reporting centres completed pre-established forms developed following the UK survey 2003 [16], with adaptation for MDCT examinations. The data sheet included the clinical indication and the main data of the patients enrolled in the survey: the age, the gender, the pseudonymous ID number (in order to easily retrieve the examination reports in case we needed to verify reported data) and, if available, the weight and height. Since a patient's CT investigation may involve several CT acquisition phases, the centres recorded the technical and dosimetric data for each of them as described in the Appendix.

Data validation

The data set was verified for completeness and consistency with broad and cross checks of the records in the database.

First of all, missing values and outliers from the individual parameter distributions were sought in order to identify possible mistakes. As data were manually registered in the data sheet, the outliers were mainly caused by mistakes in unit conversion or transcription errors, for example in comma positioning or inversion of fields. Those were immediately corrected. Further, possible inconsistencies in the data were tested for by making use of redundancies in the information collected (e.g. the $CTDI_{vol}$ multiplied by the anatomical length of the CT acquisition should be lower than the DLP). Errors outlined in this way were compared with CT examinations provided by the same centre in order to point out unusual acquisitions.

All data sheets identified by this process were then analysed in detail. If necessary, the participating centres were requested, by mail, phone or both, to perform integration of the incomplete data or correction of inconsistent data.

Table 1 CT studies included in the survey, with the number of CT scanners, the clinical indications considered, the number of patients examined and the number of CT acquisitions performed

CT protocol	*n* of CT scanners	Clinical indication	*n* of patients	*n* of CT acquisitions
Head	59	Ischaemic stroke and/or haemorrhage	764	1,027
		Trauma (no circle of Willis)	345	386
Chest	67	Vascular/infection	587	805
		Cancer diagnosis and staging (no screening low dose)	681	922
Abdomen	64	Abscess	225	475
		General vascular event	150	370
		Cancer diagnosis and staging (no HCC study, no CT urography)	686	1,851
		Trauma	161	284
CAP	65	Cancer staging	1,237	2,905
Cardiac	11	Coronary disease of native vessels	287	457
Spine	38	General indication	545	731
Total	70[a]		5,668	10,213

CAP chest–abdomen–pelvis, *HCC* hepatocellular carcinoma

[a] Total is not sum as in most centres scanners were used for more than one protocol

At the end of this process, forms with more than one missing value or inconsistencies, not ascribable to transcription errors or mistakes in unit conversions, were excluded from analysis.

As it was known that some older CT systems provided dose reports containing the maximum instead of the mean $CTDI_{vol}$ values for acquisitions with automatic dose modulation, the mean $CTDI_{vol}$ in such cases was estimated from the DLP divided by the CT acquisition length.

Data validation and analysis were conducted using programs written in the R language (software version R 2.10.1 GUI 1.31 Leopard build 64-bit (5537)).

Statistical analysis

For continuous, normally distributed variables, such as patient weight and height, results were expressed as mean values (MV) ± standard deviation (SD) The non-normally distributed variables, such as $CTDI_{vol}$, DLP, voltage (kV), tube rotation time (s), reconstructed slice thickness (mm), z-coverage length (mm), CT acquisition field of view (FOV) (mm), pitch and tube current (mA), and average mAs, were described with the median value and the interquartile range (the 25th–75th percentiles), unless otherwise stated. Categorical variables, such as tube current modulation (with/without), CT technique (spiral/axial), contrast media (with/without), and, for cardiac studies, acquisition method (prospective/retrospective), beta-blockers administration (with/without) and electrocardiographically controlled tube current modulation (ECTCM) (with/without), were expressed as percentages.

In-depth analysis was performed in order to investigate how $CTDI_{vol}$ is associated with the different CT acquisition techniques and with the patient anatomical characteristics. Owing to the non-normality of $CTDI_{vol}$ values, its logarithm was used to approximate the normal distribution. At univariate analysis, $\log(CTDI_{vol})$ distributions were compared with categorical variables, using nested ANOVA or the non-parametric k-sample equality of medians tests. The comparison of $\log(CTDI_{vol})$ distributions with continuous variables was instead performed either with parametric or non-parametric ANCOVA. All continuous variables were standardized.

Thereafter, a multivariate analysis was performed for $CTDI_{vol}$ including only statistically significant explanatory variables at univariate analysis ($P<0.05$). In order to take into account the correlation structure existing for patients observed within the same radiology unit, the $CTDI_{vol}$ was modelled through a generalized estimating equations (GEE) model with gamma distribution and log link [29, 30]. Final results are given as exponential coefficients and corresponding confidence intervals (CI). All analyses were performed using StataMP version 11.0 (StataCorp LP, College Station, TX) and statistical significance was assumed at a level of $P<0.05$.

Results

The sample

In response to the phase 1 survey and the following in-depth reports, the study sample involved a total of 65 radiology departments with 70 MDCT systems, and included data from 5,942 randomly chosen adult patients, who underwent CT using one of the six CT protocols. In the data validation process we corrected 5 % of completed fields, and excluded 274 data sheets. In this way the 95 % of the collected forms were recovered, yielding a total of 5,668 patient CT examinations and 10,213 CT acquisitions in the final study sample (Table 1). The CT examinations were performed between January and November 2011. The 70 MDCT systems involved in the study represented 8 % of the 871 systems estimated in Italy in 2009 [27]. In light of the number of responses received we verified an actual confidence level of 70 % with 9 % as margin of error on dose parameters.

Figure 1 shows the percentages of MDCT systems and patients included in the sample according to macro-area, CT protocol, number of slices and manufacturers.

The sampling rate was broadly appropriate (85 % of requested), although North West was over-represented and the other geographic domains were somewhat under-represented, especially for spine and cardiac protocols, because fewer centres perform these studies.

The 16- and 64-slice MDCTs accounted for the majority of the systems in the study (26 [37 %] and 34 [49 %] respectively). Nearly all of the CT manufactures are represented, with GE machines being the most prevalent (43 %) (Fig. 1).

The patients included in the sample were almost equally divided between women and men: 2,647 (47 %) and 3,044 (53 %) respectively, with an average age of 64±16 for both genders. The height and weight of the patients were retrospectively recovered for a subset of sample only (23 % of all patients for weight and 29 % for height). We found mean weight and height to be 68±13 kg and 163±7 cm for women and 77±12 kg and 173±8 cm for men, corresponding to an average BMI (body mass index) of 26±8 kg/m^2 for both genders. This BMI value is slightly above that of the standard man commonly considered for establishing the DRLs. However, the study population had a mean age of 64 years and, at this age, the average BMI being higher is in agreement also with the data of the National Institute of Statistics (ISTAT) [31].

CT parameters

Table 2 shows the CT system settings chosen in each protocol.

Since the introduction of MDCT, although most head acquisitions are performed with CT acquisitions covering the whole head, some examinations (157) are still performed in

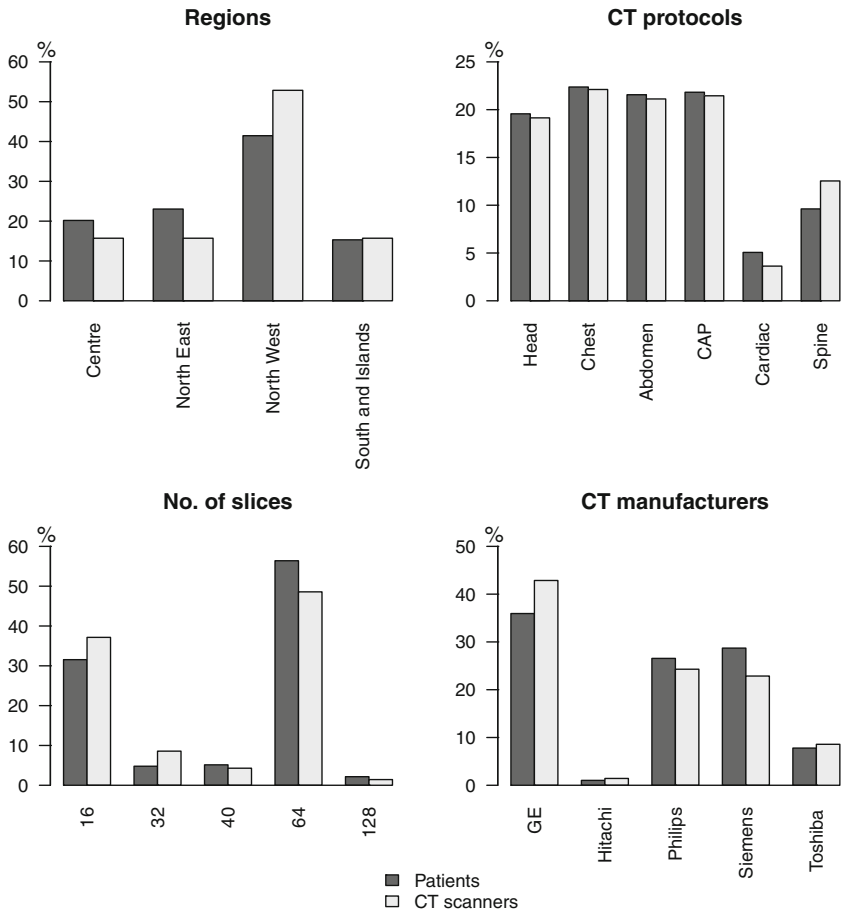

Fig. 1 Percentages of patients (*dark grey*) and CT systems (*light grey*) included in the sample according to geographic region, CT protocol, number of slices and manufacturer

two shorter sequences (posterior fossa and the supratentorial region). These examinations were therefore analysed separately.

For cardiac acquisitions, six of the 11 centres routinely performed a calcium score test before the angiographic phase, four of them performed only the angiographic CT acquisition, and one centre used both methods. The calcium scoring and angiographic CT acquisitions were separately reported.

A tube voltage of 120 kV was the leading choice in all protocols except for posterior fossa CT acquisitions, where 63.9 % of acquisitions were performed with higher voltages. Note that a significant part of angiographic studies (40.6 %) were performed at lower voltages, whereas for spine 43.9 % of CT acquisitions were performed at higher values.

Tube current modulation was widely applied in all protocols, except those on the whole head (30.7 %) and in calcium score acquisitions (29 %). For angiographic CT examinations, acquisitions with or without modulation were almost equally distributed (53.6 % and 46.4 % respectively). The lowest values of tube current settings were found for head in two parts, chest, abdomen and CAP acquisitions where, for example, we have median values equal or below 250 mA in the case of fixed tube current. For chest, abdomen and CAP protocols, the tube rotation time was also quite low: median values of 0.5, 0.6 and 0.6 s respectively. Higher values were found for head and spine CT (1 s as median value).

An exception was the angiographic acquisition in heart studies, where a high tube current (median 650 mA), used to maintain high image quality, was associated with a very low tube rotation time (median 0.35 s), necessary to reduce movement artefacts due to heart beating.

Helical CT was almost always used in chest, abdomen and CAP acquisitions (more than 99 % of cases), with a median pitch of 0.98, 0.97 and 0.98, respectively. Spiral CT data acquisitions were also commonly used in spine (65 %) and cardiac angioCT studies (76.8 %), whereas axial imaging dominated for calcium scoring and head acquisitions (86.6 % and 52.6 % respectively). When the head was acquired in two parts, however, the axial mode was the unique choice (100 % of CT acquisitions).

The highest values of reconstructed slice thickness were found for head (median value 4.5 mm). In this case, when it was acquired in two parts, the supratentorial region was reconstructed at 5 mm, and the posterior fossa at lower slice thickness (2.5 mm). Lower slice thicknesses were used for spine, chest, abdomen, CAP and calcium score acquisitions,

Table 2 Main CT scan characteristics, presented as percentages, for categorical variables, and as median values (with interquartile range in parenthesis) for the continuous ones

Characteristics	Head			Chest	Abdomen	CAP	Cardiac CT		Spine
	Whole head	Head in 2 parts					Calcium score	Angio CT	
		Supratentorial	Posterior Fossa						
Use of contrast media	16.4 %	12.4 %	11.2 %	45.9 %	64.2 %	74.4 %	0.0 %	94.2 %	0.5 %
Tube voltage (kV)									
≤110	0.0 %	0.0 %	0.0 %	2.5 %	0.7 %	0.3 %	4.9 %	40.6 %	0.1 %
120	84.1 %	90.4 %	36.1 %	92 %	94.8 %	94.1 %	91.5 %	59.4 %	56.0 %
≥130	15.9 %	9.6 %	63.9 %	5.5 %	4.5 %	5.6 %	3.7 %	0.0 %	43.9 %
Tube current modulation	30.7 %	61.8 %	61.8 %	85.4 %	85.3 %	86.2 %	29 %	53.6 %	82.4 %
Fixed tube current (mA)	310 (250–394)	250 (180–260)	250 (180–260)	200 (140–300)	250 (200–356)	250 (200–356)	304 (300–304)	650 (550–819)	320 (250–350)
Tube current range (mA)[a]									
Min	100 (100–140)	100 (100–116)	100 (100–257)	100 (80–140)	100 (80–199)	100 (80–188.5)	NA	350 (37.68–599)	100 (100–100)
Max	320 (287.5–360)	340 (204–500)	340 (259–420)	400 (300–500)	500 (350–550)	500 (370–580)	NA	650 (600–776)	600 (380–600)
Tube rotation time (s)	1 (0.75–1.8)	1 (1–1)	1 (1–1.5)	0.5 (0.5–0.7)	0.6 (0.5–0.75)	0.6 (0.5–0.75)	0.33 (0.33–0.4)	0.35 (0.33–0.35)	1 (1–1)
Scan FOV (mm)	250 (238–320)	250 (250–250)	250 (250–250)	412 (359–500)	457 (380–500)	465 (392–500)	297 (200–419)	320 (240–320)	300 (163–500)
Spiral acquisition	47.4 %	0.0 %	0.0 %	99.6 %	99.5 %	100 %	13.4 %	76.8 %	65.4 %
Pitch[b]	0.64 (0.53–0.8)	–	–	0.98 (0.89–1.15)	0.97 (0.81–1)	0.98 (0.84–1.15)	0.29 (0.25–0.33)	0.22 (0.2–0.24)	0.6 (0.52–0.89)
Reconstructed slice thickness (mm)	4.5 (2.5–5)	5 (5–5)	2.5 (2.5–2.5)	2.5 (2–5)	3 (2–5)	3 (2–5)	2.5 (2.5–3)	0.625 (0.625–0.8)	2.4 (1.25–2.5)
Scan length (mm)	155 (141–169)	95 (77–98)	57 (39–59)	321 (296–355)	425 (308–468)	451(346–600)	175 (150–270)	154 (137–202)	–
Average mAs	440 (273–500)	360 (360–360)	360 (360–360)	136 (97–180)	166 (122–237)	142 (112–198)	–	–	240 (195–310)
Prospective acquisition	–	–	–	–	–	–	61.6 %	26.3 %	–
Use of beta blockers							14.6 %	43.7 %	
ECTCM	–	–	–	–	–	–	31.1 %	19.8 %	–

ECTCM electrocardiographically controlled tube current modulation

[a] For acquisitions with tube current modulation

[b] For spiral acquisitions

with a range of 2.4–3.5 mm. The lowest thickness was found in angiographic acquisitions, with 0.625 mm as median value.

In Table 2 we also show the anatomical length of the examination. As expected, the shorter head acquisitions sum to the whole head length. We also remark that anatomical lengths span a wide range for abdomen and CAP studies. The distribution of z-axis coverage lengths (Fig. 2a) showed the presence of two Gaussian peaks because in clinical practice an abdomen protocol can refer either to abdomen or abdomen–pelvis acquisitions.

Contrast medium was more often used for abdomen, CAP and cardiac studies. The CT acquisition FOV was larger for chest, abdomen and CAP acquisitions. The values obtained for collimation, reconstruction filter and image quality index (not reported in Table 2) were not consistent or largely unavailable.

Dosimetric values

Table 3 summarises the dosimetric values obtained in each protocol, including all the relative clinical indications, with sub-analyses on peculiar CT phases or anatomical regions. We show the mean $CTDI_{vol}$ obtained in each CT acquisition, the DLP per acquisition and the total DLP, which is relative to the complete patient CT examination (that can comprise more than one CT acquisition).

In Fig. 2b–d we show, as an example, the distribution of $CTDI_{vol}$ and DLP indices for the abdomen protocol. They are non-normally distributed and show a positive skew. This is a general feature found in all protocols. However, data are presented with their mean value (MV), standard deviation (SD) and the 25th, 50th and 75th percentiles for easier comparison with previous studies. Despite the validation analysis, data still show high variability.

As expected, there is a notable difference between DLP and total DLP in those protocols where many phases per patient CT examination are carried out (abdomen, CAP), see Fig. 3.

Multiphase examinations

The very fast acquisition times, allowed by the high performance of MDCT systems, has led to an increase of multiphase studies and, likewise, to a wide variety of CT protocols—even within the same centre—for the same anatomical region and clinical indication.

In this study we found that multiphase examinations account for 71 % and 73 % of all CT examinations in abdomen and CAP protocols respectively (Fig. 3). This is particularly true for cancer and haemorrhage clinical indications in abdominal studies, where the multiphase studies account for 81 % and 79 % respectively, and a relevant part of the CT studies is performed with at least three CT acquisition phases (59 % and 54 % respectively).

In head, chest and spine, the percentages of multiphase CT examinations are lower: 18 %, 31 %, and 16 % respectively.

Figure 4 shows how the total DLP, which is the relevant parameter used to estimate the risk relative to patient exposures, increases with the number of phases.

As we noted above (Table 2, Fig. 2a), the different acquisitions in abdomen and CAP protocols covered a wide range of anatomical lengths. This is because a single abdominal study (e.g. cancer diagnosis) can comprise four phases, with some of

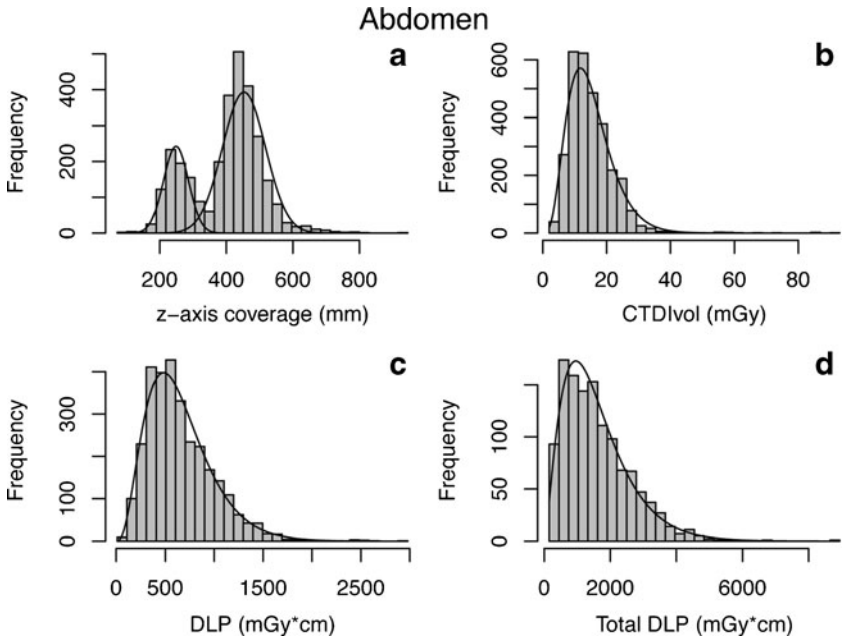

Fig. 2 Distribution of **a** z-axis coverage, **b** $CTDI_{vol}$, **c** DLP and **d** total DLP for the abdomen protocol. Best-fit Gaussian curves are superimposed on the two peaks of z-axis coverage distributions, while the best-fit gamma curves are superimposed on the dose distributions. The $CTDI_{vol}$ and DLP distributions for all the other protocols are similar with the exceptions that three Gaussian peaks were found in z-axis coverage distributions for CAP protocols and only one peak for all the other protocols (data not shown)

Table 3 Mean value (MV), standard deviation (SD) and 25th, 50th and 75th percentiles for $CTDI_{vol}$ (mGy), DLP (mGy cm) and total DLP (mGy cm) for each CT protocol

CT protocol	Exams	*n* of CT acquisitions	Anatomical region/ type of sequence	Parameter	MV	SD	25th	50th	75th
Head	952	1,073	Whole head	$CTDI_{vol}$	64	17	56	60	69
				DLP	1,086	336	867	1,041	1,312
				Total DLP	1,223	493	892	1,133	1,382
	157	170	Supratentorial	$CTDI_{vol}$	53	16	40	54	67
				DLP	488	178	323	470	610
		170	Posterior fossa	$CTDI_{vol}$	79	18	67	77	91
				DLP	434	153	299	435	479
		–	Supratentorial + posterior fossa	Total DLP	999	411	721	881	1,117
Chest	1,268	1,727	Chest	$CTDI_{vol}$	12	6	8	12	15
				DLP	453	237	282	416	569
				Total DLP	620	450	341	502	754
Abdomen	1,222	845	Abdomen	$CTDI_{vol}$	15	9	10	14	18
				DLP	450	279	266	403	555
		2,135	Abdomen–pelvis	$CTDI_{vol}$	15	6	10	14	18
				DLP	733	320	487	677	920
		2,980	All	$CTDI_{vol}$	15	7	10	14	18
				DLP	653	334	406	580	843
				Total DLP	1,595	1,010	799	1,399	2,157
CAP	1,237	733	Abdomen	$CTDI_{vol}$	14	8	9	13	17
				DLP	414	244	259	371	508
		1,210	Abdomen–pelvis	$CTDI_{vol}$	14	6	10	13	17
				DLP	695	308	473	637	850
		962	CAP	$CTDI_{vol}$	14	5	10	14	17
				DLP	963	367	679	940	1,200
		2,905	All	$CTDI_{vol}$	14	6	10	14	17
				DLP	713	378	436	637	933
				Total DLP	1,675	921	1,016	1,478	2,115
Cardiac	287	293	Angiographic CT	$CTDI_{vol}$	43	24	22	45	61
				DLP	836	517	376	834	1,208
		164	Calcium score	$CTDI_{vol}$	7	5	3	7	7
				DLP	130	115	91	114	131
		–	All	Total DLP	941	568	522	945	1,373
Spine	545	731	Spine	$CTDI_{vol}$	34	20	20	27	42
				DLP	617	571	114	527	888
				Total DLP	830	544	472	711	1,060

$CTDI_{vol}$, DLP and total DLP of the head protocols are referenced to the 16-cm PPMA phantom; all the other values are referenced to the 32-cm phantom

them focused on smaller anatomical regions (e.g. liver alone). In Fig. 2a we show the anatomical length distribution for the abdomen protocols, which shows two Gaussian peaks corresponding to abdomen (with a z-axis coverage of 26±6 cm) and abdomen–pelvis (46±6 cm) regions. Similar patterns were found for CAP acquisitions, but with three peaks: abdomen (with a z-axis coverage of 26±5 cm), abdomen–pelvis (44±5 cm) and complete CAP (64±5 cm) acquisitions. For all the other protocols we found only one peak.

Acquisitions for bolus synchronization

Although not required, some centres provided data (121 patients) for bolus synchronization acquisitions, performed when contrast media are used. These are dynamic sequences, with a very short z-axis coverage (0.5 or 1 cm), executed at low tube currents, that synchronize the subsequent CT data acquisitions to the required opacification by contrast enhancement.

Despite these acquisitions having a small impact on the total DLP value (13 (10–18) mGy cm), the local dose delivered to

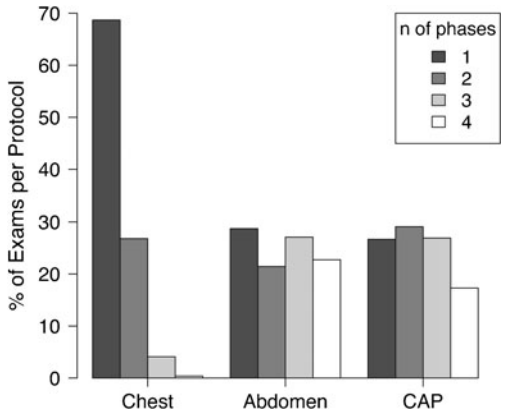

Fig. 3 Percentages of CT examinations divided according to the number of CT acquisitions executed in the three most common body protocols. Note that multiphase ($n>1$) CT examinations dominate in case of abdomen and CAP protocols

this short anatomical region (20 (13–26) mGy) was close to the $CTDI_{vol}$ values for the main examination protocols (see Table 3).

Dose predictors

From the multivariate analysis we found that the $CTDI_{vol}$ was significantly associated with BMI, tube voltage, tube rotation time, pitch and fixed tube current (all $P<0.05$) (Table 4). $CTDI_{vol}$ increased with higher values of all parameters ($\exp(b)>1$) except for pitch ($\exp(b)=0.72$). In particular, we found a correlation between $CTDI_{vol}$ and BMI for chest, abdomen and CAP protocols in Fig. 5. Compared with the abdomen, the $CTDI_{vol}$ was significantly lower for chest ($\exp(b)=0.84$) and higher for head ($\exp(b)=2.18$), but there was no significant difference for the CAP ($P=0.083$) and spine protocols ($P=0.35$).

Considering the cardiac protocol alone, contrast media, voltage, CT technique, acquisition methods and reconstructed slice thickness were significantly associated with $CTDI_{vol}$ (all $P<0.001$). $CTDI_{vol}$ was higher for spiral acquisitions, for CT acquisitions with contrast medium and for thin slices. We further noted that 73.7 % of the CT angiograms were still performed in the retrospective protocol with a $CTDI_{vol}$ of 53 (35–62) mGy and only 26.3 % were acquired in prospective acquisition protocol though the latter involved a significantly lower dose (10 (7–17) mGy).

Discussion

National and international surveys of CT practice are recommended for estimating dose exposure to the population due to CT examinations [1, 32] as well as for determining reference values that can be used as benchmarks for dose optimisation.

The introduction of MDCT has brought with it the use of more varied exposure conditions relative to previous CT systems, not only through technological advances, but also from a clinical transition, as CT examinations have become less organ-targeted by providing more extensive coverage and dynamic information.

CT optimisation now requires a good knowledge of both CT technology and dose dependencies in order to tailor the choice of acquisition parameters to the clinical indication and patient size. The choice of parameters certainly differs between the various CT systems and, for the same CT indication, may also vary widely from hospital to hospital. These differences are reflected in our work.

This study is the first nationwide Italian survey on MDCT, and covers five common radiological CT examinations as well as cardiac CT. The International Commission on Radiological Protection (ICRP) recommends that DRLs are set for "common diagnostic procedures" [32] because less commonly performed examinations can be subject to confounding factors in the statistical analysis, and do not represent everyday practice. As we do not have detailed data on the number of CT examinations performed in Italy for each protocol, but only a total number per year [27], we estimate that the six analysed

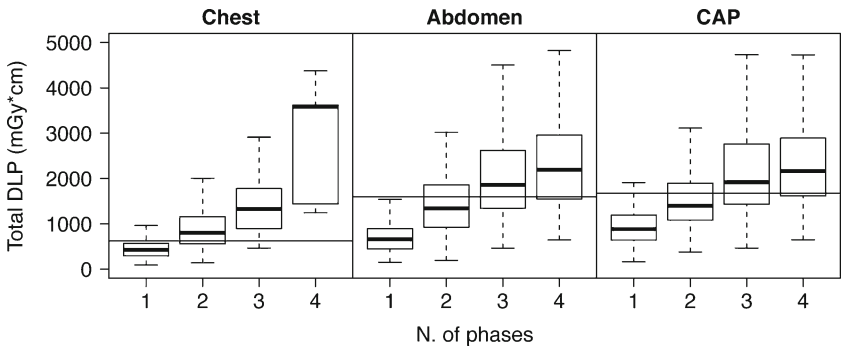

Fig. 4 Total DLP versus the number of phases per CT examination for the most common body protocols. The height of the box displays the interquartile range with the 25th and 75th percentiles represented by the *lower* and *upper edges* of the box, respectively. The *horizontal bold line* in the box corresponds 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. The *bold horizontal line* corresponds to the median value per protocol

Table 4 Association between $CTDI_{vol}$ and scanning modalities and patient BMI: exponential coefficients and 95 % confidence intervals (CIs) of the GEE analysis and relative *P* values

Variables[a]	Exp(*b*)	95 % CI	*P* value
BMI (kg/m^2)*[b]	1.14	(1.11; 1.16)	<0.001
CT protocol vs abdomen protocol**			
Spine	0.91	(0.73; 1.12)	0.350
Head	2.18	(1.89; 2.52)	<0.001
Chest	0.84	(0.77; 0.92)	<0.001
CAP	1.07	(0.99; 1.15)	0.083
Contrast media (yes vs no)**	1.01	(0.99; 1.04)	0.338
Tube voltage (kV)[b]*	1.11	(1.08; 1.15)	<0.001
Tube current modulation (yes vs no)**	1.00	(0.94; 1.05)	0.941
Tube rotation time (s)[b]*	1.12	(1.01; 1.24)	0.035
Scan FOV (mm)[b]*	1.03	(0.96; 1.11)	0.355
Pitch[b]*	0.72	(0.69; 0.75)	<0.001
Reconstructed slice thickness (mm)[b]*	0.95	(0.88; 1.03)	0.229
Fixed tube current (mA)[b]*	1.20	(1.16; 1.23)	<0.001

[a] Acquisition mode, reconstruction filter, scanning technique, scan length were omitted as they resulted non-statistically significant at univariate analysis

[b] Standardized variables

*For a quantitative explanatory variable, exp(*b*) expresses the relative variation in $CTDI_{vol}$ when it changes by 1 unit

**For a categorical explanatory variable, exp(*b*) expresses the relative variation in $CTDI_{vol}$ of each category versus the reference

protocols account for 75 % of all the examinations performed according to the US IMV CT benchmark report [28].

Unlike previous studies and unlike the experience of the UK dose survey, we gathered additional data in order to better describe current practice. In particular, we included the now widely diffuse CAP examinations [33] and, for each patient examination, we analysed the data corresponding to each phase of CT data acquisition, in order to correctly account for multiphase studies [34].

We remark that we collected less data than expected (56 %) for spine examinations, because many centres declared that referrals for CT spine have diminished through replacement by MR studies and/or included in CAP examinations in the case of trauma. Further, the spine data were not homogeneous, with a wide variation seen in z-axis coverage as some centres perform CT on single vertebra, whereas others cover a larger spine region. Cardiac studies, on the other hand, are growing in number, but are still highly specific examinations performed in a few dedicated centres; they were analysed in order to have a picture of this emerging practice. We concentrated our study on MDCT systems that can acquire 16 or more slices, because they now represent the most widely diffused CT apparatus in Italy [27] and according to a US market analysis [35] will continue to account for a major share of the market over the next 5–6 years. In future surveys, however, it will likely be necessary to include other examinations, e.g. CT colonoscopy or CT screening, as well as giving particular attention to 128-slice or more MDCT systems as their use expands.

In Table 5 we compare the 75th percentiles of $CTDI_{vol}$ and DLP of the present study to other European surveys, based on data collection of patient CT examinations on MDCT systems [2, 16, 21]. European DRLs, established by the 2004 European guidelines, and the very recent Dose Data Med 2 [36] results, based on a DRL collection in several European countries, are also reported, whereas national DRL collections were omitted [37]. We discuss the results in detail below.

Head

The 75th percentile of the $CTDI_{vol}$ (69 mGy) for the whole head (Table 5) is in agreement with other surveys; however, we record a higher DLP (1,312 mGy cm). This may be due to the relatively frequent use of spiral acquisitions (47.4 %), because they are affected by over-ranging effects that are, now, included in the reported DLP. Those effects can account roughly for a 20 % increase in the DLP for those CT acquisition lengths [38].

Also to be considered is that some centres still divide the head study into two different parts, with higher radiation dose due to a dedicated posterior fossa (91 mGy) CT data acquisition. However, as these are always axial acquisitions, the over-ranging effects are not present and the DLP (1,117 mGy cm) is smaller than that obtained in whole-head CT.

Body (chest, abdomen, CAP)

As mentioned in the results, the clinical practice for body CT examinations has become quite complex, because modern CT technology allows fast acquisitions and many different CT techniques. This has resulted in a wide variety in the CT studies being performed, even for the same clinical indication within the same centre.

In the dosimetric analysis reported in Table 3, Figs. 3 and 4, we highlight some aspects of present clinical practice that have acquired important roles in determining patient dose since the introduction of MDCT. In particular, the number of multiphase CT examinations (Fig. 3) has increased greatly for the abdomen and CAP protocols; a single abdominal study can consist of acquisitions of different anatomical coverage, concentrated on the abdomen alone or covering both the abdomen and pelvis region, whereas a CAP study can include, not only the CAP acquisition, but also abdomen and abdomen–pelvis CT acquisitions. We therefore analysed the $CTDI_{vol}$ and the DLP, important for dose optimisation, separately from the total DLP, important for the evaluation of the total dose absorbed by the patient and, in general, for the estimation of population exposure risk. In addition, we separated the contributions to exposure due to CT acquisitions of

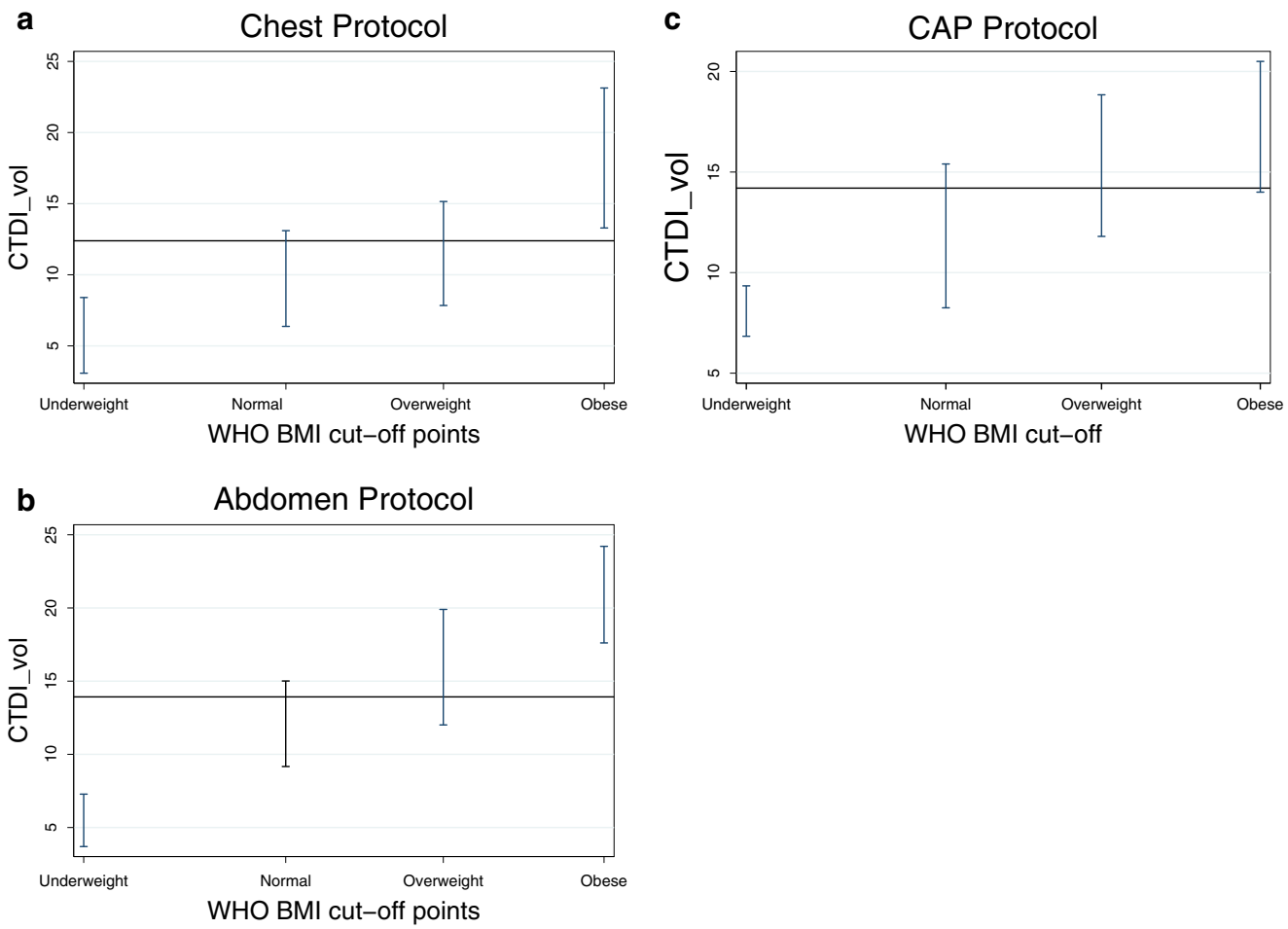

Fig. 5 Interquartile range of $CTDI_{vol}$ (mGy) versus World Health Organisation BMI (kg/m^2) cut-off points for chest, abdomen and CAP protocols. The *horizontal line* indicates the $CTDI_{vol}$ median by protocol; underweight, BMI<18.5; normal, 18.5<BMI<25; overweight, 25<BMI<30; obese, BMI>30

Table 5 75th percentiles of $CTDI_{vol}$ and DLP from the present survey and comparison with the 75th percentiles from previous large surveys and with the European Guidelines recommendations and European Dose Datamed2 (DDM2) project

Anatomical regions	Italy 2011 (this survey)		UK 2003 [16] [b]		Ireland 2010 [21]		EUR 2004 [2]		Dose Datamed2 2010 [36][c]	
	$CTDI_{vol}$	DLP	$CTDI_{vol}$	DLP	$CTDI_{vol}$	DLP	$CTDI_{vol}$	DLP	$CTDI_{vol}$	DLP
Head [a]	69	1,312		931	66	940	60	990	50–75 (60)	760–1,300 (1,000)
Posterior fossa	91	479	103	–	–	–	–	–	–	–
Supratentorial	67	610	63	–	–	–	–	–	–	–
Chest	15	569	13	576	9 (11)	390	12	430	10–30 (10)	270–700 (400)
Abdomen	18	555	14	472	–	–	–	–	13–35 (25)	400–740
Abdomen–pelvis	18	920	14	550	12	598	16	726	–	460–1,200 (800)
CAP	17	1,200	13	937	11	845	–	–	–	–
Cardiac	61	1,208	–	–	–	–	–	–	–	–
Spine	42	888	–	–	–	–	–	–	–	–

[a] $CTDI_{vol}$ and DLP of the head are referenced to the 16-cm PPMA phantom; all the other values are referenced to the 32-cm phantom

[b] The values taken from the UK survey are those obtained for multislice CT scanners

[c] From DDM2 project we show the range of mean values collected in each country and the most frequent value (in parentheses)

the abdomen, abdomen–pelvis and CAP anatomical regions: whereas their $CTDI_{vol}$ values are similar and compatible with the analysis performed including all those phases (14 (10–18) and 14(10–17) mGy for abdomen and CAP respectively), their DLP differ significantly. In abdomen studies, for example, we found a 75th percentile DLP of 555 mGy cm for the abdominal CT acquisition and of 920 mGy cm for the combined abdomen and pelvis, resulting in a 75th percentile DLP of 843 mGy cm for the overall abdomen protocol distribution. This difference becomes important in the context of choosing a reference level, because the intermediate value of 843 mGy cm from the overall analysis may be inappropriate for the optimisation of either abdominal or abdomen–pelvis acquisitions.

In comparison with other surveys, our $CTDI_{vol}$ and DLP 75th percentiles were higher, suggesting the need for further optimisation. The present Italian law (D. Lgs 187/2000) is still based upon the DRL of the 1999 European guidelines, the higher values of which could have lowered the attention level. However, our data are within the DDM2 [36] range and in agreement with recent DRL collections in Germany and France [25, 26].

It is notable that, in the abdomen and CAP protocols, the total DLP (Fig. 4 and Table 3) has reached very high values as a direct consequence of the increased number of phases. As shown in Fig. 4, the total DLP in four-phase examinations reached median values (2,195 mGy cm) that are more than three times higher than the single-phase acquisition DLP (656 mGy cm) and are 50 % higher than the median values found from the overall abdomen analysis (1,399 mGy cm).

Our multiphase data cannot be compared with other surveys easily, as in most cases they did not explicitly deal with this issue. A comparison can be made with the recent Irish survey [21], where an analysis of multiphase abdominal studies was included. The 75th percentile for DLP (2, 156 mGy cm) in the present survey was almost twice the value they reported (1,115 mGy cm). This can be explained in part by our higher $CTDI_{vol}$ (18 mGy vs 13 mGy), although a major factor could also be the higher number of phases performed. However this possibility cannot be verified as they state neither the number of phases nor the clinical indications.

In the chest protocol, multiphase examinations are present, but account for only 31 % of all chest examinations, with correspondingly small variation in anatomical coverage. The 75th percentiles we found for $CTDI_{vol}$ and DLP (15 mGy and 569 mGy cm respectively) are slightly above the values reported in other surveys, but in good agreement with the DDM2 results [36] (see Table 5).

Cardiac

Except for one centre, a 64-slice MDCT system was the choice for cardiac applications.

Since over half of the centres performing cardiac CT (6 of 11) acquire the calcium scoring before the angiographic acquisition, we analysed the data for both (Tables 2 and 3). We found the angiographic phases to be slightly below the values recorded in the international Hausleiter study [39] for $CTDI_{vol}$ (45 (22–61) mGy vs 52.7 (37.1–72.8) mGy), and DLP (834 (376–1,208) mGy cm vs 885 (568–1,259) mGy cm). The calcium score CT acquisitions have a much smaller impact on patient dose, contributing just 7 (3–7) mGy to the $CTDI_{vol}$ and 114 (91–131) mGy cm to the DLP.

Optimisation

The update of DRLs to new clinical practice is the starting point for dose optimisation, as it allows centres to easily compare their practice.

Our results suggest that the increased number of multiphase examinations is the principal factor affecting the total dose delivered to the patient. Attention should be paid in order to reduce the number of unnecessary acquisitions and to carefully select patients undergoing multiphase studies. In this context, although updated DRLs can still refer to single CT acquisitions ($CTDI_{vol}$ and DLP) in order to attempt optimisation of single-phase CT acquisitions, the monitoring of total DLP and number of phases may help in controlling the consistent increase of patient exposure due to multiphase examinations. Before the introduction of MDCTs, the distinction between DLP and total DLP was less important, because single-phase acquisitions dominated heavily.

Meanwhile, dose reduction should still be sought with a careful selection of CT acquisition parameters, possibly customized to clinical indication and patient characteristics. BMI, indeed, is a known major determinant factor of image quality for body examinations [39] and it is well known that image noise increases with higher BMI when CT parameters, such as tube current and voltage, are kept constant.

For those centres that collected patient height and weight, we observed that $CTDI_{vol}$ increased with BMI, probably owing to a proper tube current adaptation obtained with the automatic modulation systems. A further improvement and dose reduction, however, are expected by also adapting tube voltage (kV) to BMI, which until now has seldom been different from 120 kV. The only exception was represented by the cardiac protocols. Furthermore, despite the extensive employment of spiral CT acquisitions, high pitch values (>1) were rarely chosen. Finally, in the cardiac protocol, the prospective mode should be encouraged whenever possible even in angiographic phases, because a dose reduction of 80 % could be reached.

Promising CT dose reduction technologies, like the iterative reconstruction algorithms or tube voltage adapting systems, were not considered in this analysis as they started appearing around the time of data collection. Future large-scale surveys will be needed to establish the effect of these emerging techniques on clinical practice.

Limitations

The recruitment for this survey may have been biased toward radiology departments interested in dose optimisation. The wide range of participating centres, however, appears representative of the national situation [40]. In fact, we included large academic hospitals and small district hospitals with a diffuse regional distribution mainly from the National Health Service that actually perform the large majority of the MDCT examinations in Italy. An all-inclusive patient survey would be more precise, but would also require a huge amount of time and money and, probably, would become rapidly old before its completion.

The registration of tube current modulation settings and beam collimation is not standardized between different CT manufacturers; consequently those parameters were not included in the statistical analysis. Their effects on dose are included in the $CTDI_{vol}$ and DLP. Finally, a dedicated analysis would be useful in order to fully understand the implications of new dose reduction algorithms.

Conclusion

In summary this nationwide audit of MDCT practice can act as a starting point for updating Italian DRLs, and could be a reference for European optimisation programmes.

Exposure levels were evaluated for the most common CT protocols, including multiphase studies, where the highest doses were registered. The high variability in CT protocols and comparison with other surveys suggests that dose reduction could be achieved.

DRLs are a quality control measure to avoid bad practice; therefore $CTDI_{vol}$ and DLP, though for single CT acquisitions, are still necessary for obtaining optimisation. At the same time, total DLP and the number of CT acquisitions of multiphase examinations could be useful to keep under control the relevant dose increase due to these growing practices.

The use of the radiology information system (RIS), as well as structured reports and automatic tools for dose monitoring, may help in CT patient data collection, reducing operator work and manual reporting errors. However it is important to keep in mind that some patient data such as weight, height or clinical indication are manually recorded before patient examination and can therefore include mistakes. Furthermore, the variety of procedures (that can include multiple acquisitions on various anatomical regions or different indications) still imposes the need for careful data collection and a detailed analysis in order to compare homogeneous data.

Large-scale patient dose surveys still remain an important approach to evaluating dose exposure in clinical practice and should encourage radiologists and radiographers to optimise their MDCT protocols.

Acknowledgments We are pleased to acknowledge the collaboration of numerous radiologist colleagues and medical physicists (listed in the Appendix) that has allowed the achievement of this large-scale data collection. We are also grateful to the Italian Society of Radiology (SIRM) who financed and supported the study, and to the Italian Society of Medical Physics (AIFM), for its active collaboration.

Appendix

Participating centres

AOUP Policlinico Palermo, Ospedale P. V. Fazzi Lecce, Ospedale P.O. Spirito Santo Pescara, Ospedali Riuniti Ancona, Ospedale Maggiore Trieste, Azienda Ospedaliero Universitaria Careggi Firenze, A.O OIRM Sant'Anna Torino, Ospedale Belcolle ASL Viterbo, IRCCS Policlinico San Donato Milanese, Fatebenefratelli Sangiovanni Calabita Roma, Istituto Oncologico Veneto IRCCS Padova, Istituto Europeo di Oncologia Milano, Hsr Giglio Cefalù, Ospedale AOU Maggiore della Carità Novara, Ospedale San Donato Usl 8 Arezzo, Ospedale Carlo Poma Mantova, Istituto per la ricerca e la cura del cancro di Candiolo, Fondazione IRCC Policlinico San Matteo Pavia, Ospedale Circolo Fondazione Macchi Varese, Ospedale Niguarda Milano, Istituto Tumori Genova, ASL Cuneo 1, AO SS. Antonio e Biagio e C. Arrigo Alessandria, PO Santa Maria delle Grazie Pozzuoli, Ospedale San Bassiano Ulss3 Bassano del Grappa, Ospedale Santa Maria delle Croci Ravenna, Istituti Ospitalieri Cremona, A.O Città della salute e della scienza Torino, Ospedale Regionale U. Parini Ausl Valle d'aosta, Asl2 Savonese Ospedale Santa Corona Pietra Ligure, San Raffaele Milano, Azienda Ospedaliero Universitaria di Modena Policlinico, Azienda Ospedaliera San Gerardo Monza, Azienda Ospedaliera Polo Universitario L. Sacco Milano, Azienda Sanitaria di Firenze Ospedale del Mugello, Policlinico Universitario Messina, Azienda Sanitaria Locale Torino Ospedale Martini, Ospedale Asl 1 Imperiese Stabilimento Ospedaliero Imperia, Sanremo e Bordighera, Azienda Ospedaliera di Careggi Firenze, ASL 2 Savonese Ospedale Santa Maria di Misericordia Albenga, Azienda Ospedaliera Universitaria Santa Maria della Misericordia Udine, Ospedale Schio Thiene, Fondazione IRCCS Cà Grande Ospedale Maggiore Policlinico Milano, Ospedale Santa Chiara Trento, Asl 3 Genovese Villa Scassi Genova, Istituti Fisioterapici Ospedalieri Regina Elena Roma, Centro Cardiologico Monzino Milano, Fondazione IRCCS Istituto nazionale Tumori Milano, Ulss 20 Verona Ospedale Fracastoro, Azienda Ospedaliera Santa Maria della Misericordia Perugia, Asl Sassari Ospedale Santissima Annunnziata, Spedali Civili di Brescia, Azienda Ospedaliera Provincia Lecco, AOU Ospedale OORR San Giovanni di Dio e Ruggi D'aragona Salerno, Azienda Ospedaliera di Catanzaro

Pugliese-Ciaccio, ASL TO 1 Ospedale Evangelico Valdese, Ospedale di Bressanone

Electronic appendix

For each CT examination performed, the phase 2 datasheet included the main data of the patients enrolled in the survey (age, gender, pseudonymous ID number and, if available, the weight and height) and the clinical indication.

For the main technical parameters that can affect dose, the datasheet included: tube voltage, use of automatic (anatomy-based) tube current modulation, fixed tube current value (for acquisitions without automatic modulation), the available current range (for automatic modulated acquisitions), tube rotation time, reconstructed slice thickness, beam collimation, CT field of view (CT acquisition FOV), z-axis length, the use of axial or spiral CT technique, pitch (for spiral acquisitions), reconstruction filter, the use of contrast agent and, if available, the image quality index used and the average mAs. For cardiac acquisitions, the presence of electrocardiographically controlled tube current modulation (ECTCM), the administration of beta-blockers, and the use of prospective vs retrospective acquisition mode were also recorded.

Finally, the dosimetric parameters of each phase were retrieved from the dose reports in terms of mean CTDIvol and Dose Length Product (DLP). The total DLP, referring to the complete patient examination, was also collected for completeness.

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