CT paediatric doses in Belgium: a multi-centre study

Results from a dosimetry audit in 2007-2009

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February 2010

The authors gratefully acknowledge financial support from the Belgian Federal Agency of Nuclear Control (FANC) for the project "*Multicenter studie rond de dosisevaluatie bij de CT-scan in de pediatrie"* and are thankful to the members of the Agency, in particular: M Biernaux, A Fremout and W De Roovere.

Summary and recommendations

This multi-centre study evaluated CT exposure of children in Belgium by investigating radiological practice and patient doses for five common CT examinations over five age ranges. The study was conducted by a consortium of Belgian research groups of both medical physicists and radiologists that are involved in paediatric CT. The study was initiated in 2007 and data was collected and processed until 2009. After a nation-wide mailing, 18 hospitals representing 21 radiology centers participated in the study. The hospitals (7 university hospitals and 11 general hospitals) were dispersed over the whole Belgian region. In local audits by a group of medical physics experts, dosimetry measurements were performed by determining the standard CT dose descriptors for each particular CT examination protocol that was used for children. The applied technical scan parameters by the CT users were obtained and reviewed, and radiological image quality was assessed by paediatric radiologists. The collected data were compared to results from other European nation-wide studies.
This section briefly summarizes the findings and recommendations.

18 hospitals participated in this multi-center study, representing 21 CT scanners and a total of 161 different CT scan protocols. Compared to earlier reported data from multi-center studies, the used scanner technology is very modern (high-end equipment). All CT scanners were Multi Slice CT's (MSCT) of which 43% were current state of the art 64-slice CT scanners. High-end scanners are usually equipped with novel radiation protection tools in CT such as automated tube current modulation (ATM), dedicated paediatric scan protocols with reduced kV, adaptive collimation to reduce overscanning effects on spiral CT, and the display of dose descriptors for any particular scan. These tools are particularly helpful in paediatric CT dose optimization.

There is a strong radiation protection awareness of the CT users today. All of the centers adapt the technical CT exposure parameters when scanning children. None of the centers scan children with exposure settings that are established for adults. Besides reducing tube current also tube voltage reduction is applied, mainly with body examinations (chest and abdomen) of the youngest age groups. 62% of all hospitals have at least 1 paediatric scan protocol with a tube voltage <120 kV. ATM is mainly used for head (59%) and body protocols (chest 65% and abdomen 67%).

Highest doses were observed with centers that use a single ATM scan protocol with high default dose settings for children of all ages, regardless of their body size. This methodology specifically results in high doses for the youngest age groups (0 – 5 years). Lowest doses were observed with centers that perform a careful manual tube current adaptation in function of body size. While the ATM system can be a helpful radiation protection tool, users should be aware that it does not automatically scan the patient with an appropriate dose, especially in the youngest age groups. The level of dose modulation depends on the default dose setting by the user. This default dose setting (such as reference mAs, noise index, etc) for any particular paediatric CT examination should be below the reference values that are established for adults. The regulation of the ATM depends on the type of CT scanner, personal contacts during the dose audits showed that the CT-users are not very familiar or experienced in presetting the ATM system and that it often is a source of confusion.

Manually reducing tube current values from established adult protocols according to the body tissue halve value layer (a factor of 2 for each 4 cm equivalent body diameter) could result in inferior image quality. A more gentle tube current reduction technique by halving the mAs for each 8 cm body diameter is recommended.

For body CT examinations (chest, abdomen, etc), almost all scanners today display patient dose descriptors ($CTDI_{vol}$ and DLP) that relate to the large 32 cm dosimetry body phantom, regardless of the paediatric body size. CT users should be aware that this metric underestimates patient dose in paediatric CT and that this has also consequences on the accuracy of patient dose registration. CT manufacturers should agree on a clear uniform index to display which makes it possible to relate the dose to a dosimetry phantom size. During their QC, Medical Physics experts should specifically determine the CTDI values for all paediatric CT body protocols in an appropriate paediatric dosimetry phantom. Whereas a standard 16 cm dosimetry phantom is a reasonable representation of patient size over the whole paediatric age range, phantoms with smaller diameters (between 8 and 16 cm) provide a better representation of younger age groups, such as infants. The establishment of CDTI standards with smaller phantoms could be helpful in paediatric CT dosimetry.

Specific attention should be paid when scanning newborns and infants in spiral CT mode with wide beam 64-slice MSCT's. The additional exposure from overscanning effects can mount up to 20-30% due to the short scan ranges.

The next table summarizes the obtained 3rd quartile dosimetry data in this study. These data should not be considered as diagnostic reference levels (DRLs). They can be used as a provisional benchmark and should be re-evaluated in the future with the addition of more robust data from big patient dose samples leading to empirical dose distributions.

Obtained 3rd quartile CTDIvol (mGy) and DLP (mGycm) data of this study in function of age group (years)

Age group	Dose quantity	CT examination				
		Head	Chest	Abdomen	Sinus	Inner ear
<1	CTDIv	35	8.4	7.8	16	66
	DLP	280	76	101	80	231
1-5	CTDIv	43	9.3	11	16	66
	DLP	473	111	209	80	231
5-10	CTDIv	49	9.0	9.5	16	66
	DLP	637	144	238	96	264
10-15	CTDIv	50	13	13	16	66
	DLP	650	260	403	160	264

Compared to results from other European studies (France, Germany, Switzerland, United Kingdom, Greece), the observed 3rd quartile dosimetry data in this study are at the low end side and agree well with data from the most recent French and Swiss studies. Although this is encouraging, very large differences in dose distributions between centers are still observed. For the youngest age group, the rounded ratio's of maximal and minimal CTDIv's are: 3 for head, 18 for chest, 8 for abdomen, 24 for sinus and 8 for inner ear.

It is encouraging that manufacturers and the radiological community continue to develop new radiation protection tools for paediatric CT. Promising new tools in development are the availability of 60 kV scan protocols for infants, iterative reconstruction techniques, overscanning countermeasures and organ dose modulation. The introduction of these systems on the market will have the potential to further decrease CT doses.

The next general table summarizes the typical technical scan protocol parameters that were observed in this study, together with observed 3rd quartile dose values. These can be used as guidance for centers that are not used to paediatric CT scanning.

General table with typical scan parameters from this study, together with observed 3rd quartile $CTDI_{vol}$ values

CT-Examination	Age 0-1 year, weight 3.5 – 9.5 kg				Age 1-5 year, weight 9.5 – 19 kg			
	Scan length (cm)	Tube voltage (kV)	Pitch	$CTDI_{vol}$ (mGy)	Scan length (cm)	Tube voltage (kV)	Pitch	$CTDI_{vol}$ (mGy)
Head	8 – 11	120	0.64	35	11 – 13	120	0.65	43
Chest	9 – 12	80 – 110	1.3	8.4	12 – 16	80 – 110	1.4	9.3
Abdomen	13 – 19	80 – 110	1.2	7.8	19 – 25	80 – 110	1.3	11
Sinus	5	100 – 120	0.83	16	5 – 6	100 – 120	0.83	16
Inner ear	3.5	120	0.81	66	3.5 - 4	120	0.81	66
CT-Examination	Age 5 - 10 year, weight 19 – 33 kg				Age 10 - 15 year, weight 33 – 55 kg			
	Scan length (cm)	Tube voltage (kV)	Pitch	$CTDI_{vol}$ (mGy)	Scan length (cm)	Tube voltage (kV)	Pitch	$CTDI_{vol}$ (mGy)
Head	13	120	0.63	49	13	120	0.65	50
Chest	16 – 20	100 – 120	1.3	9.0	20 – 27	100 – 120	1.3	13
Abdomen	31 – 43	100 – 120	1.3	9.5	31 – 43	100 – 120	1.3	13
Sinus	6 – 10	100 – 120	0.83	16	10	100 – 120	0.83	16
Inner ear	4	120	0.81	66	4	120	0.81	66

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1. INTRODUCTION

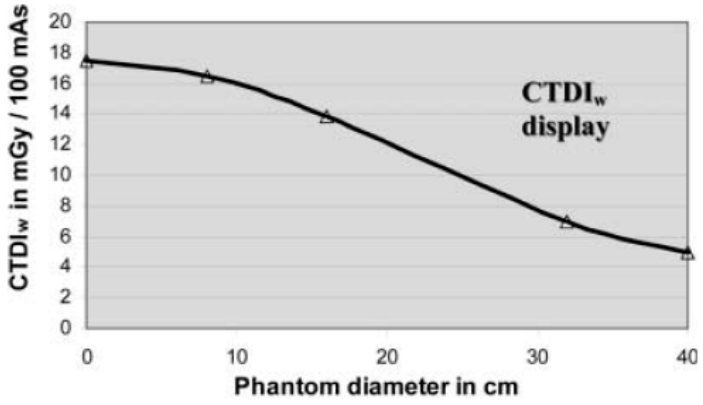
It is well known that a CT scan delivers a radiation dose that is typically at the high end of the diagnostic dose range, and although CT examinations represent only a few percent of the total number of x-ray examinations, they are already the largest contributor to the collective effective dose from medical exposures. The recent technical developments in CT, with in particular the advent of multi-slice scanning, have extended the range of its applications. As a result, it is likely that the number of CT-examinations will continue to increase and therefore also its proportion to the collective dose. Also the scanning of children, in particular, benefit from the technical development of Multi Slice CT (MSCT). MSCT CT has the potential of (1) imaging faster, (2) imaging larger volumes, and (3) imaging same volumes with a better geometrical resolution. Faster imaging (1) allows CT examinations where motion artefacts previously contraindicated its use. For example, scanning of young (moving) children becomes now possible. Or, for example, an examination where scanning with magnetic resonance imaging (MRI) requires general anaesthesia with intubation, can be performed on CT without anaesthesia (and complementary risk) due to its high speed. Imaging larger volumes (2) in a short time allows, for example, the examination of malignant lymphoma staging of the neck and entire trunk in one scan. Improved (3) isotropic resolution allows organ evaluation in different planes. Also, children have smaller organs and less fat (less contrast) than adults, which means that improved image quality is advantageously for this patient group.

There is also a specific concern when scanning children. Due to the high dynamic range of CT detectors, there is a risk of utilising not-optimised technical scan factors. The technical limitation of the tube determines the maximum amount of exposure, not the detector. Therefore, children can be easily scanned with technical factors that are established for adults, yielding unnecessary high doses. In 2001, a series of articles were published [1, 2] that addressed this issue; the authors indicated that the majority of paediatric CT examinations were made with the same exposure settings that are used for adults. Moreover, studies also indicated that CT users are not always aware of the scan parameters that they apply. In a study of Hollingsworth et al. that investigated scan parameter settings, 20-25% of the CT users did not know the scan parameters that they use for scanning children [3].

Scanning smaller volumes with equal exposure settings results in elevated absorbed radiation doses. This is illustrated by figure 1 that shows the weighted CTDIw, which represents the average dose in a cylindrical phantom from one tube rotation, in function of phantom diameter [4]. Note that the dose to a 16 cm phantom (which can represent a child) is about twice the dose to a 32 cm phantom (adult) for the same exposure setting.

A second consideration is that organ doses (and effective dose), when normalised to CTDI, are significantly greater for paediatric patients than for adult patients when using the same scan technique. This effect is propagated due to the fact that in the smaller paediatric body, all organs are located closer to the scan field and are therefore more exposed to internal scatter radiation than with adults. This, in combination with their elevated susceptibility to radiation effects, necessitates proper optimisation by adapting scan protocols according to their size or anatomy.

Figure 1. Influence of phantom diameter on normalised CTDIw, from [4]



Recent years, radiation protection for CT paediatrics received increased attention in international medical community. The United States Food and Drug Administration (FDA) published a set of recommendations in order to keep radiation doses during CT as low as reasonably achievable, especially for paediatric and small adult patients [5]. They stress the importance of adjusting CT scanner parameters appropriately for each individual's weight and size, and for the anatomical region being scanned. Also the European Commission supported research for the assessment of patient dose in paediatric CT and the NRPB published a review report on doses form CT that also contained data from pediatric CT [6, 7]. There still are, however, only few international data on reported doses in a multi-centre set-up, and up to now no such data has been published from Belgian centres on a large scale. The objective of this study was to carry out a survey to assess paediatric patient doses for common CT examinations at different hospitals in Belgium.

2. MATERIALS AND METHODS

A multi-center study with local dose audits was set up for this project. At first, a national mailing was performed in order to inform and cordially invite radiology centers to participate in this study. By a web based survey, participating CT centers were asked to provide CT scanner specifications and CT scan protocol details that they apply for a selection of CT examinations for children (age 0 to 15 years). Afterwards, local audits were performed by certified medical physicists to assess radiation doses and technical image quality by phantom measurements. During these visits, the data of the earlier returned survey were checked for completeness and consistency. In a last fase, selected CT examinations were obtained by experienced paediatric radiologists to assess diagnostic quality.

A consortium of Belgian research groups (table 1) was put together for this study, selected on basis of their experience with CT paediatric imaging. Attention was paid to both physics and clinical aspects, and to the bilingual composition of the group. The physics group was specifically in charge of the local dose audits, the clinical group on image quality evaluation. The Agency (FANC) was mainly represented by An Fremout and Michel Biernaux.

Table 1. Research groups involved in the study

Institution	Contact
Physics aspect	
UZ Brussel, Radiologie	Nico Buls
UZ Leuven, Radiologie	Hilde Bosmans
Bel V	Chantal Mommaert
Université de Liége	Françoise Malchair
Clinical aspect	
UCL St Luc	Philippe Clapuyt
CH de Jolimont-Lobbes	Philippe Everarts

2.1. Mailing and questionnaire

In order to include as much radiology centers as possible to the project, a national survey was performed. This survey, conducted between May and July 2007, consisted of a mailing to 96 Belgian hospitals. In this mailing, the radiology centers were informed about the project and were cordially invited to participate if they performed CT scans on children.

Information was collected in relation to standard protocols for five common CT examinations and standard (average-sized) patients. These particular examinations, shown in table 2 with their common clinical indications, were selected as representing the bulk of core practice for paediatric patients. Full details were requested of the scan settings applied for each scan sequence of the CT protocols on a standard form. These included: anatomical landmarks of the scan volume, scan direction, gantry tilt, tube voltage, tube current or ATM, tube rotation time, beam width (NxT), table feed per tube rotation, displayed dose indicators, reconstructed slice thickness, slice increment and reconstruction filter. In the study, the paediatric population was separated into four age groups (<1 year; 1-5 years; 5-10 years and

10-15 years). The centers were requested to provide separate information for each age group.

Table 2. Selected CT examinations for this study and their typical clinical indication. Paediatric population was separated into four age groups.

CT examination	Indication
Head	Trauma including non-accidental
Head, sinus	Evaluation of sinusitis
Head, inner ear	Evaluation of hearing loss
Chest	Detection of malignancy, congenital abnormality, chronic lung disease
Abdomen	Detection of malignancy, tumour staging

2.2. Standards in CT dosimetry

The product of tube current and rotation time (mAs) is often referred to as the radiographic exposure and is a key acquisition parameter since it strongly affects to noise in the reconstructed images as well as the local absorbed dose. However, it is not useful to compare values of radiographic exposure (mAs) for different scanners since this quantity does not take into account the considerable differences in scanner design, such as the composition and shape of the beam filter and the beam geometry. In other words, radiographic exposure is not well correlated on an absolute scale with either patient dose or image quality. Dedicated dosimetric quantities provide a better means for the evaluation of acquisition protocols with regard to patient dose. Therefore, standardized CT dosimetry metrics were used to evaluate patient doses in this study.
The principal dosimetric quantity used in CT is the CT dose index (CTDI). This is defined as the integral along a line parallel to the axis of rotation (*z*) of the dose profile (*D(z)*) for a single rotation and a fixed table position, divided by the nominal thickness of the x-ray beam. CTDI can be conveniently assessed using a pencil ionisation chamber with an active length of 100 mm, so as to provide a measurement of $CTDI_{100}$, expressed in terms of absorbed dose to air [8, 9]:

$$CTDI_{100} = \int_{-50mm}^{+50mm} \frac{D(z)}{N \times T} dz \ \text{(mGy)} \qquad \textit{eq. 1}$$

where *N* is the number of tomographic sections, each of nominal thickness *T* (mm), from a single rotation. For multi-slice CT scanners, where N > 1, *NxT* (mm) represents the total detector acquisition width (eg 4 x 5 mm), and is equivalent to the nominal beam collimation. Reference dosimetry for CT is based on such measurements made within standard CT dosimetry phantoms; these presently comprise homogeneous cylinders of polymethylmethacrylate (PMMA), with 15 cm length and diameters of 16 cm (adult head) and 32 cm (adult body). The combination of measurements made at the centre (*c*) and 10 mm below the surface (*p*) of a phantom leads to the following reference dose quantities which can be applied to serial or spiral scanning, for both single- or multi-slice geometry scanners.

Weighted and volume CT dose index ($CTDI_w$, $CTDI_{vol}$)

The weighted CTDI in the standard adult head or body CT dosimetry phantom for a single rotation corresponding to the exposure settings used in clinical practice is defined as:

$$CTDI_w = \frac{1}{3} \times CTDI_{100,c} + \frac{2}{3} \times CTDI_{100,p} \text{ (mGy)} \qquad \textit{eq. 2}$$

where $CTDI_{100,p}$ represents an average of measurements at four equally-spaced locations around the periphery of the phantom. Monitoring of CTDIw per rotation takes account of the exposure settings selected, such as tube current and tube voltage.

The volume weighted $CTDI_{vol}$ is derived form the $CTDI_w$ and takes into account the scan pitch. It is defined by the International Electrotechnical Commission [8] as:

$$CTDI_{vol} = \frac{CTDI_w}{pitch} \text{ (mGy) with } pitch = \frac{table\ feed}{N \times T} \qquad \textit{eq. 3}$$

The table feed is the distance (mm) moved by the patient support in the *z*-direction between consecutive serial scans or per rotation in helical scanning; *NxT* (mm) is the nominal beam collimation (equation 1). Both are selected by the CT user. The ratio between both, which is defined as the pitch (*p*), is dimension less. $CTDI_{vol}$ is the ultimate dose descriptor in CT from one tube rotation since it represents the average value of the weighted CTDI throughout the volume scanned in a particular sequence. $CTDI_{vol}$ is recommended for display on the CT scanner console [8].

Dose-length product (DLP)

Monitoring of the dose-length product (DLP) provides control over the volume of irradiation and the overall exposure for an examination. Since $CTDI_{vol}$ represents the average dose per tube rotation, it can be easily derived by taking into account the scan length. The dose-length product (DLP) for a complete examination is simply defined as:

$$DLP = CTDI_{vol} \times L \text{ (mGycm)} \qquad \textit{eq. 4}$$

where L is the scan length (cm), limited by the outer margins of the exposed scan range, irrespective of pitch (which is, of course, already included in CTDIvol). For a helical scan sequence, this is the total scan length that is exposed during (raw) data acquisition, including any additional rotation(s) at either end of the programmed scan length necessary for data interpolation. For serial scanning, L is the distance between the outer margins of the first and last slices in a sequence.

Currently the volume Computed Tomography Dose Index ($CTDI_{vol}$) and Dose Length Product (DLP) are widely recognised in CT. The $CTDI_{vol}$ represents the average dose from one tube rotation and is particularly useful for assessment of differences in technique parameters between centers such as tube current, beam collimation and

tube voltage. It is an excellent parameter for comparison between different scan protocols and different scanners [9]. The DLP is derived from the $CTDI_{vol}$ and takes into account the scan length and number of sequences. Both CTDI and DLP are recommended by various organisations to be used as metrics to assess Diagnostic Reference Levels (DRL) in CT. Also, according guidelines of the IEC (IEC 60601-2-44) manufacturers assess and display both values on the scanner console to inform the user.

Effective dose (E)

It is important to recognize that the potential biological effects from radiation depend not only on the radiation dose to a tissue or organ, but also on the biological sensitivity of the tissue or organ irradiated. Effective dose, *E*, is a dose descriptor that reflects this difference in biologic sensitivity [10]. It is a single dose parameter that reflects the risk of a non-uniform exposure in terms of an equivalent whole-body exposure. The concept of effective dose was designed for radiation protection of occupationally exposed personnel. It reflects radiation detriment averaged over gender and age, and its application has limitations when applied to medical populations. However, it does facilitate the comparison of biologic effect between diagnostic exams of different types. It is important to remember, however, that the effective dose describes the relative "whole body" dose for a particular exam and scanner, but is not the dose for any one individual. Specific values of effective dose can be calculated using several different software packages, which are mainly based on the use of data from one of two sources, the National Radiological Protection Board (NRPB) in the United Kingdom [11] or the Institute of Radiation Protection (GSF) in Germany [12]. To minimize controversy over differences in effective dose values that are purely the result of calculation methodology and data sources, a generic estimation method was proposed by the European Working Group for Guidelines on Quality Criteria in Computed Tomography [9]. Effective dose values calculated from the NRPB Monte Carlo organ coefficients [11] were compared to DLP values for the corresponding clinical exams to determine a set of coefficients *k*, where the values of *k* are dependent only on the region of the body being scanned (head, neck, thorax, abdomen, or pelvis) and the age (Table 3). Using this methodology, *E* can be broadly estimated from the DLP [13]. For paediatric patients, the data is normalised to *DLP* determined in the 16 cm diameter CT dosimetry phantom.

$$E \approx k \times DLP \ \text{(mSv)} \qquad \textit{eq. 5}$$

Table 3. Normalized effective dose per dose-length product (DLP) for adults and paediatric patients of various ages over various body regions. Conversion factor for adult head and all paediatric patients assume use of the head CT dose phantom (16 cm). From Shrimpton et al [7].

Body Region	*k* (mSv mGy^{-1} cm^{-1})				
	0 year	1 year	5 year	10 year	Adult
Head	0,011	0,0067	0,0040	0,0032	0,0021
Chest	0,039	0,026	0,018	0,013	0,014
Abdomen and pelvis	0,049	0,030	0,020	0,015	0,015
Trunk	0,044	0,028	0,019	0,014	0,015

2.3. Conducted dosimetry measurements in this study

For each site and for each scan protocol both the normalised values of weighted CTDI ($_nCTDI_w$) were measured for the various combinations of tube voltage, beam collimation and beam shaping filter that are applied in the clinical scan protocols. This was done according standardized methods as described in previous sections by measuring the dose with a CT pencil ionisation chamber in the center and periphery of a Ø16 cm dosimetric phantom. As discussed before, reference dosimetry for CT is based on measurements made within standard CT dosimetry phantoms of 16 cm (adult head) and 32 cm (adult body). In principle this two phantom approach could be extended to reference dosimetry in paediatric CT, although it has been concluded instead that the smaller (16 cm) phantom can serve as an appropriate standard in relation to all types of examination on children of all ages. Such a single standard dosimetry phantom provides a reasonable representation of patient size over the paediatric age range (Table 4), whilst maintaining a link with the established dosimetric system for adult patients [14]. This is recommended by several authors and organisations [13, 15]. Also organ -and effective dose calculations of children in CT are often normalized to the CTDIw measured in the standard 16 cm diameter CT phantom [16]. It should be remembered, however, that the prime purpose of such reference dose quantities is for comparison of performance in CT, rather than providing direct estimates of absorbed doses to patients. For example, the mean dose to a transverse section of the head of a newborn patient will be about twice the mean dose to the standard 16 cm diameter dosimetry phantom under similar conditions of exposure [15].

Table 4. Diameters of cylindrical PMMA phantoms having the same thickness and mass as particular sections of mathematical anthropomorphic phantoms [from 14]

Age	Equivalent PMMA diameter (cm)		Cristy anthropomorphic phantom	
	Head	Body	Weight (kg)	Height (cm)
Newborn	9.7	10.6	3.51	55
1 year	13.1	13.9	9.36	75
5 years	15.4	17.1	19.1	109
10 years	16.1	19.9	33.2	139
15 years	16.9	24.3	54.5	164

Despite the fact that all scanners in the study display CTDIvol and DLP on the scanner console, the physics group decided to perform in situ dosimetry measurements at each site for mainly two reasons:

- in order to compare the accuracy of the dosimetry values of the scanner console;
- it is often unclear which CTDI is displayed for children protocols (related to a 16 cm or 32 cm phantom).

Clinical exposure conditions

Besides measuring the normalised dosimetric quantities as described above, the $CTDI_{vol}$ of each applied scan protocol was calculated based on the exposure factors that were used for scanning a standardised phantom. For this purpose the 16 cm

standard paediatric dosimetry phantom and 22 cm AAPM image quality phantom are used. Both phantoms were scanned under clinical conditions, with automated tube current (ATM) if applied, and relevant exposure parameters were obtained to determine $CTDI_{vol}$ and DLP. This is used as a parameter for comparison between different scan protocols and different scanners. Although the 16 cm phantom is recommended as an appropriate standard to all types of examination on children of all ages, we decided to also include a larger 22 cm diameter phantom to represent the body for ages > 10 years (table 4). All measurements were performed in situ by one of the four physics groups. Prior to the visits, a cross check benchmark test was performed in concert on one CT scanner (Siemens Emotion 16), in order to compare the QC equipment sets and to set up a uniform dosimetry protocol.

3. RESULTS and DISCUSSION

3.1. Participating centers and scanner technology

Out of the 96 contacted hospitals, 18 participated in the study, representing 21 imaging departments (Table 5). It concerns 7 university hospitals and 11 general hospitals. The hospitals were dispersed over the whole Belgian region (figure 2): 10 are located in Flanders, 3 in Brussels and 5 in Wallonia. The CT park of the participating hospitals is very modern (figure 3): all CT scanners are multislice CT scanners (MSCT) of which 9 were today's high end 64-slice (*N*) CT's, and all are equipped with automatic tube current modulation (ATM). In the conduct of the study, all data were treated in an anonymous way, with the 21 imaging departments being randomised coded by alphabetical letters from A to U.

Table 5. Participating hospitals

Name	Location	Scanner	*N*	ATM
University Hospitals (10 CT dept.)				
Universitair Ziekenhuis Antwerpen	Wilrijk	GE Lightspeed VCT	64	Yes
Universitair Ziekenhuis Leuven	Leuven	Siemens Volume Zoom	4	Yes
Universitair Ziekenhuis Leuven	Leuven	Siemens Sensation 16	16	Yes
Universitair Ziekenhuis Leuven	Leuven	Siemens Sensation 64	64	Yes
Universitair Ziekenhuis Gent	Gent	Siemens Volume Zoom	4	Yes
Université Catholique de Louvain	Kraainem	Philips Brilliance 64	64	Yes
Universitair Ziekenhuis Brussel	Jette	Philips Brilliance 64	64	Yes
Universitair Ziekenhuis Brussel	Jette	Siemens Sensation 16	16	Yes
Université Libre de Bruxelles	Anderlecht	Siemens Sensation 16	16	Yes
Centre Hospitalier Universitaire de Liège des Bruyères	Chênée	Siemens Sensation 16	16	Yes
General Hospitals (11 CT dept.)				
Centre Hospitalier Régional de la Citadelle	Liège	Siemens Sensation 16	16	Yes
Algemeen Stedelijk Ziekenhuis	Deinze	GE Lightspeed VCT	64	Yes
Onze Lieve Vrouw ziekenhuis	Aalst	Siemens Definition	64	Yes
Heilig Hart Roeselare	Roeselare	GE Lightspeed VCT	64	Yes
Sint Andries	Tielt	GE Lightspeed 16	16	Yes
Sint Thérèse	Montignies	Siemens Emotion 16	16	Yes
Sint Vincentius	Antwerpen	Toshiba Aquillion 16	16	Yes
Algemeen Stedelijk Ziekenhuis	Aalst	Siemens Sensation 64	64	Yes
Sint Blasius	Dendermonde	GE Lightspeed 16	16	Yes
Centre Hospitalier de Dinant	Dinant	Toshiba Aquillion 64	64	Yes
Clinique de l'Espérance	Montegnée	GE Lightspeed Ultra	8	Yes

N = number of simultaneously acquired slices per rotation
ATM = Automatic Tube Current Modulation

Figure 2. Geographic distribution of participating hospitals

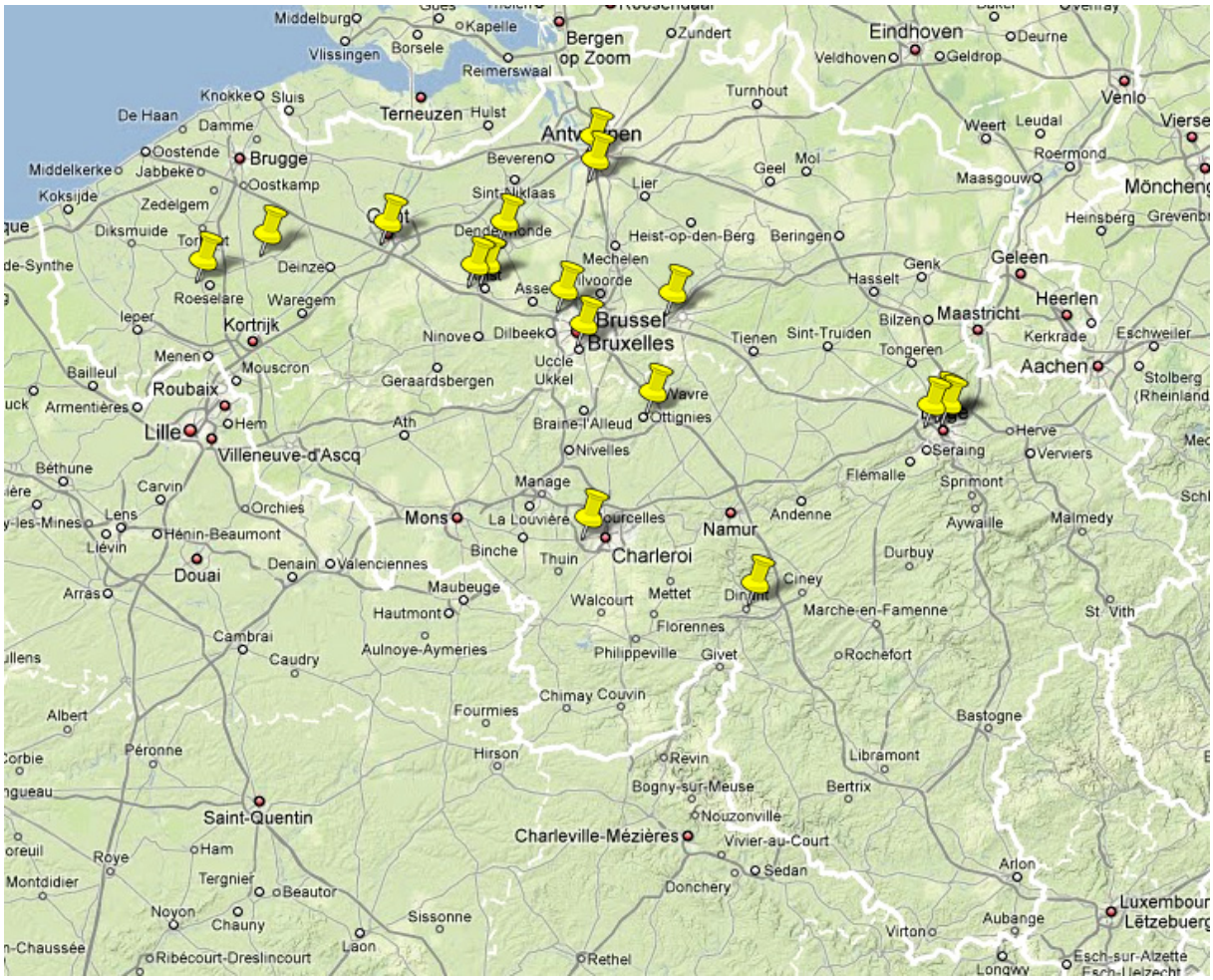
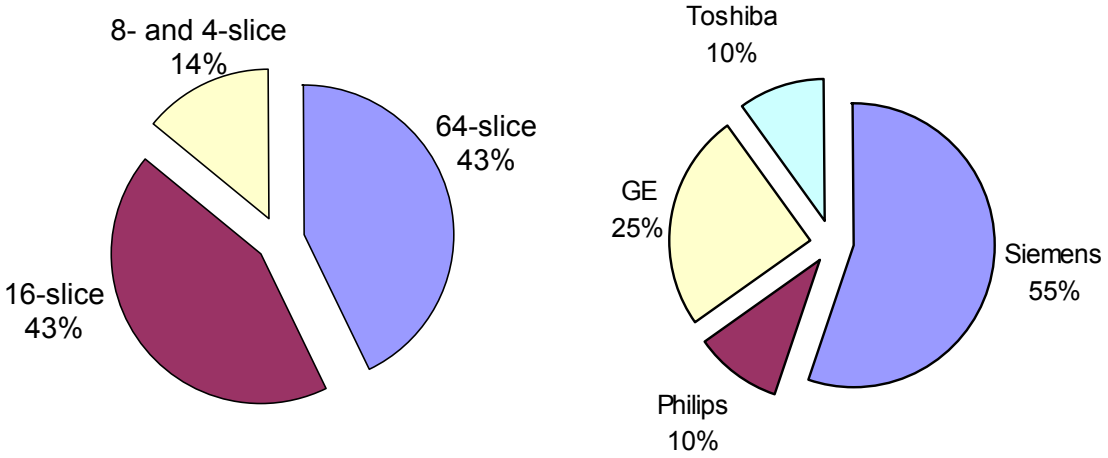


Figure 3. Distribution of the scanner technology (left) and CT manufacturers (right) of the imaging departments participating in this study.



Comparison with other surveys

Table 6 compares the characteristics of the CT units in this study with recent published multicenter studies on paediatric CT. Compared to earlier reported data from multicenter studies on paediatric CT doses, the participation of 21 CT units is quite supporting. Also, the presence of a very modern CT park is distinctive from what is observed in recent published multicenter studies. The advantage of recent scanners is that they are usually equipped with radiation protection tools such as ATM or dedicated paediatric scan protocols with reduced kV. Three recent multi-center studies [17, 18, 19] that examine paediatric CT doses report the use of older, less performant CT equipment. From the 12 CT units that participated in the Greek study of Yakoumakis et al, only 7 (58%) were multislice CT's: six 16 slice CT's and one dual slice CT [18]. None of the participating centers used a 64 slice CT. Also, the authors do not mention the presence of any ATM system on the scanners; all the scan protocols use fixed tube current (mAs) values. In the Swiss study of Verdun et al, 11 CT units participated of which 8 (73%) used multislice CT's: six 16 slice CT's, one 8 slice CT and one 64 slice CT [19]. Arch and Frush performed an email based survey in the US concerning paediatric scanning parameters. From the 61 CT units in their study, 94% were multislice CT's of which the largest fraction were 16 slice CT's (44%), 32% were 64 slice CT's [17].

Table 6. Characteristics of participating CT units compared to recent literature

Study	Year	Country	Participating CT units	Multislice CT's	64x slice	16x slice	<16x slice
This study	2010	Belgium	21	100%	43%	43%	16%
Yakoumakis [18]	2009	Greece	12	58%	0%	50%	8%
Verdun [19]	2008	Switzerland	11	73%	9%	55%	9%
Arch [17]	2008	USA	59	93%	35%	55%	3%
Brisse [20]	2009	France	20	100%	40%	50%	10%
Galanski [21]	2007	Germany	63	85%	na	na	Na
Shrimpton [7]	2005	UK	126	37%	0%	4%	33%

Shrimpton: involves CT-units for both adult and paediatric

3.2. Technical CT-scan parameters

From the 21 imaging centers, a total of 161 scan protocols were obtained. This represents a median of 7 paediatric scan protocols per center. The maximum number of applied scan protocols per center was 28 (UZ Gent), the minimum number 1 (CHC Espérance). The details of the applied scan protocols indicate the awareness of the centers regarding radiation exposure of children. Table 7 shows the paediatric protocol behaviour of the centers. Table 8 and figures 3 and 4 show the scan protocol details in function of examination type.
The data in table 7 clearly demonstrate the awareness towards radiation protection. First of all, all centers in the study apply dedicated scan protocols for children, *ie* they do not apply adult protocols. Instead they adopt technical scan parameters to "adjust" to the paediatric body. All centers apply tube current (mA) reduction, either automated by ATM or manually by presets, and a large number of centers (62%) have at least one protocol with reduced tube voltage (kV). The advent of ATM systems on the scanners simplified the necessity of adequate tube current (mA)

selection in function of patient's size; it is not longer necessary to select a mA value based on the weight or age of the patient.

Table 7. Scan protocol behaviour of participating centers

Total number of CT centers	21	
Centers that use dedicated paediatric CT scan protocols	21	100%
Centers with at least 1 scan prococol adapted to patient weight	4	19%
Centers with at least 1 scan prococol adapted to patient age	9	43%
Centers that use at least 1 general scan protocol for all ages	12	57%
Centers that use kilovoltage < 120 kV for at least 1 protocol	13	62%
Centers that use reduced mA cfr adults for at least 1 protocol	21	100%
Centers that use ATM for at least 1 protocol	16	76%
Centers that set manual tube current for at least 1 protocol	13	62%

ATM = Automatic Tube Current Modulation

Figure 3. Scan protocol details: frequency of tube current selection (fixed or ATM)

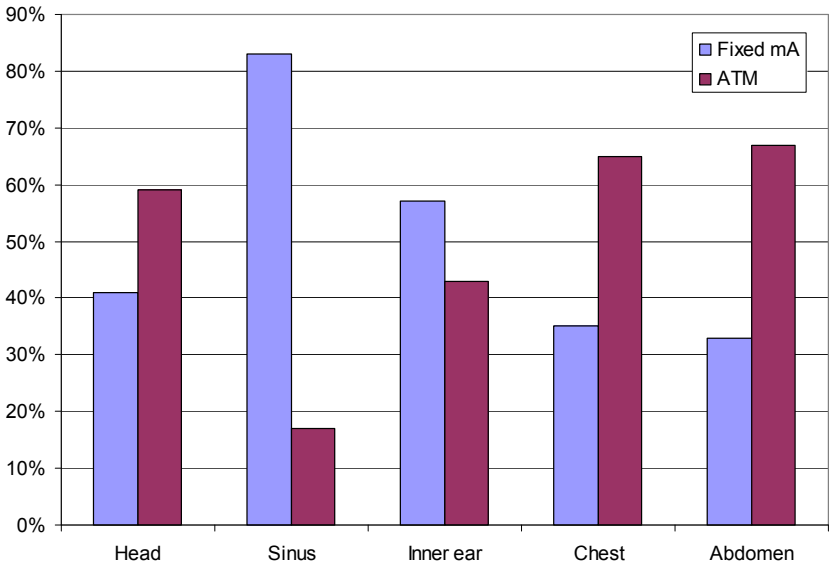


Figure 4. Scan protocol details: frequency of selected tube potential (kV)

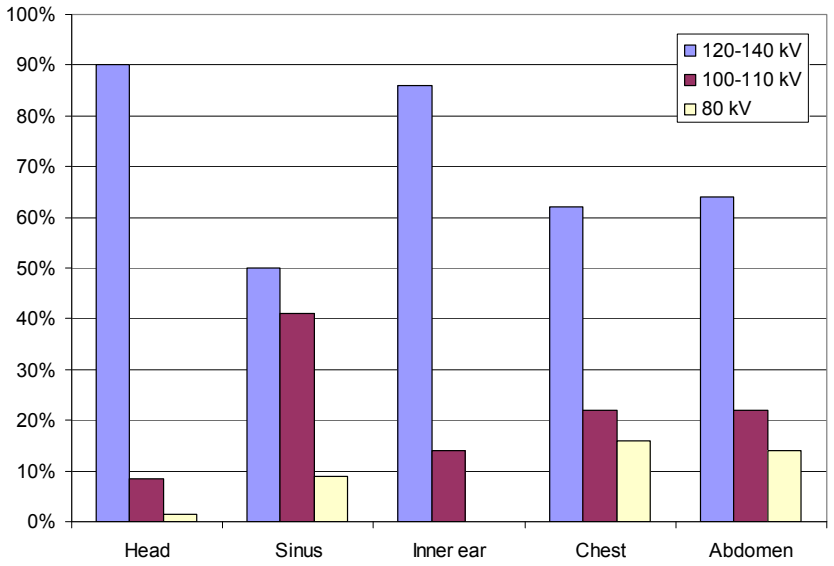


Table 8. Scan protocol details

CT examination		
Head		
	Total number of protocols	68
	General protocols (all ages)[a]	59%
	Protocols with age banding	41%
	Protocols with weight banding	0%
	Protocols with 120 – 140 kV	90%
	Protocols with 100 - 110 kV	8.5%
	Protocols with 80 kV	1.5%
	Protocols with fixed tube current	41%
	Protocols with ATM	59%
Chest		
	Total number of protocols	62
	General protocols (all ages) [a]	55%
	Protocols with age banding	19%
	Protocols with weight banding	26%
	Protocols with 120 – 140 kV	62%
	Protocols with 100 - 110 kV	22%
	Protocols with 80 kV	16%
	Protocols with fixed tube current	35%
	Protocols with ATM	65%
Abdomen		
	Total number of protocols	63
	General protocols (all ages) [a]	53%
	Protocols with age banding	17%
	Protocols with weight banding	30%
	Protocols with 120 – 140 kV	64%
	Protocols with 100 - 110 kV	22%
	Protocols with 80 kV	14%
	Protocols with fixed tube current	33%
	Protocols with ATM	67%
Sinus		
	Total number of protocols	12
	General protocols (all ages) [a]	100%
	Protocols with age banding	0%
	Protocols with weight banding	0%
	Protocols with 120 – 140 kV	50%
	Protocols with 100 - 110 kV	41%
	Protocols with 80 kV	9%
	Protocols with fixed tube current	83%
	Protocols with ATM	17%
Inner ear		
	Total number of protocols	7
	General protocols (all ages) [a]	100%
	Protocols with age banding	0%
	Protocols with weight banding	0%
	Protocols with 120 – 140 kV	86%
	Protocols with 100 - 110 kV	14%
	Protocols with 80 kV	0%
	Protocols with fixed tube current	57%
	Protocols with ATM	43%

ATM = Automatic Tube Current Modulation

[a] General protocols are calculated multiple times as they are valid over the entire age range

Tube current reduction (mA)

Adapting the number of photons per tube rotation according to the volume to be scanned is usually a first step towards dose optimisation. This can be done by controlling the tube current. The half value thickness of tissue in CT is approximately 4 cm, thus the image noise in a 16 cm phantom scanned with 50 mAs is about equal to the noise in a 32 cm phantom scanned with 400 mAs. Various authors recommend adapting tube current to patient size [2, 3, 4, 22]. However, proposing typical tube current values according to patient weight is not always usable as tube output is very scanner type specific. The theoretical halve value thickness consideration could be used to manually adapt the mAs value in function of patient size, namely mAs should be halved for each 4 cm difference in tissue equivalent body diameter, in order to achieve images with a constant noise level. However, the results of a study where mAs settings were manually adapted in this manner did not support this: whereas the resulting images exhibited almost the same noise independent of the patient diameter, CT images of smaller size patients were subjectively rated inferior by the radiologists [23]. This finding was interpreted as being mainly due to the fact that slim patients have less body fat, which serves as a natural contrast agent. Therefore, it is not sufficient to maintain a constant noise level; instead, images of slim patients need to be less noisy in order to maintain a constant contrast-to-noise ratio. As a consequence, dose adaptation should be made in a more gentle fashion, i.e. by a factor of 2 for each 8 cm difference in tissue-equivalent body diameter, instead for each 4 cm difference [21].

A system in CT that can aid the optimisation of scan parameters is automated tube current modulation (ATM). The goal of automated tube current modulation is to adapt the tube current (mA) to the patient's attenuation. Tube current is constantly modulated as the patients' attenuation varies both along the *z*-axis (e.g. shoulder versus lung) and angular (e.g. anterior posterior versus lateral). This results not only in a dose optimised scan, but also in improved image quality as the image noise should remain constant in all slices of the same scan. Preliminary studies that applied current modulation with children showed a significant dose reduction of about 30%, depending on the scanned patient region [24]. Although these promising developments suggest that CT doses to children could be reduced, the effect in clinical routine is still unclear.

ATM is widely used by the centers in our study, 76% of the centers have at least one ATM protocol (table 1). Despite the fact that all scanners are equipped with ATM (Table 5), not all centers use it for children. A considerable amount of centers (62%) have at least one protocol where they choose to use a fixed reduced tube current setting. This is mainly for sinus and inner ear investigations in axial mode (Table 8, figure 3). ATM is mainly used for head (59%) and body protocols (chest 65% and abdomen 67%).

Tube voltage reduction (kV) and pitch (p)

Also tube voltage reduction is applied by a large number of centers; 62% have at least one scan protocol with a tube voltage < 120 kV, which is the standard tube voltage setting for adult CT examinations. In CT, tube voltage reduction is less

straightforward than tube current reduction. Typically, adult CT scans are performed with a tube voltage of 120 kV, and less frequently at 140 kV. The use of reduced tube voltage is frequently advocated for children. Several papers describe the advent of reducing tube voltage for smaller patient sizes and children and although they clearly demonstrate dose reductions, they also report image quality issues. Scanning with reduced tube voltage may not only introduce image artifacts mainly due to photon starvation, it also affects the CT number scale (Hounsfield Units HU). CT numbers (HU) represent the attenuation of biological tissues in the body relative to water and are typically determined for a beam energy of 120 kV. Since photon attenuation is energy dependent, changing the beam energy will substantially shift the CT numbers of materials. Users should be aware of this as they may use the absolute CT numbers to identify biological tissues in the body. Also, in contrast to tube current reduction by the ATM, tube voltage reduction is not performed automatically by the scanner. It requires a manual setting by the user. As shown in table 8 and figure 4, tube voltage reduction is mainly applied for body (chest 38% and abdomen 36%) and sinus (50%) protocols, less for head (10%) and inner ear (14%) protocols. For the body protocols tube voltages are even reduced down to 80 kV for the smallest age groups (chest 65% and abdomen 67%). Figure 5 shows the average tube voltage of the different examinations for the considered age groups. For the body examinations, the graph clearly shows the trend of selecting reduced tube voltages for younger age groups (0-5 years). In general, tube voltage selections for head examinations are higher than for body examinations.

Table 9 compares the fraction of protocols with tube voltage reduction with data from recent and older published multicenter studies on paediatric CT. Compared to earlier reported data. All recent studies (>2007) show the same trend: there is a shift to the use of lower tube voltage protocols, which is more pronounced for the body protocols. The fraction of protocols with reduced tube voltage in this study is high, only the French study of Brisse shows more use of low kV protocols [20]. Despite the fact that CT scanners were always able to use lower tube voltages, the results from two older studies (2003) demonstrate that low tube voltage protocols were hardly used. In a large scale American study by Hollingsworth et al, only 3% of the chest protocols and 1% of the abdomen protocols had a tube voltage <110 kV [25]. In a Belgian regional study by Pages et al none of the protocols used lower tube voltages [26]. The fact that the CT scanners in these two studies were able to use lower tube voltages indicates that there is today an increased awareness in radiation protection management related to paediatric CT.

Figure 5. Observed average tube voltage in function of age group.

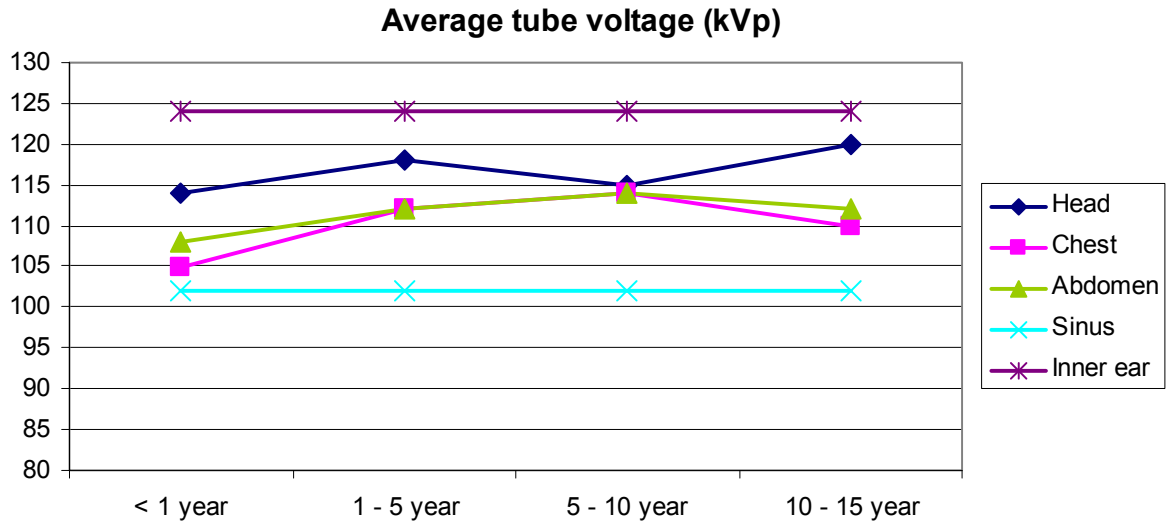


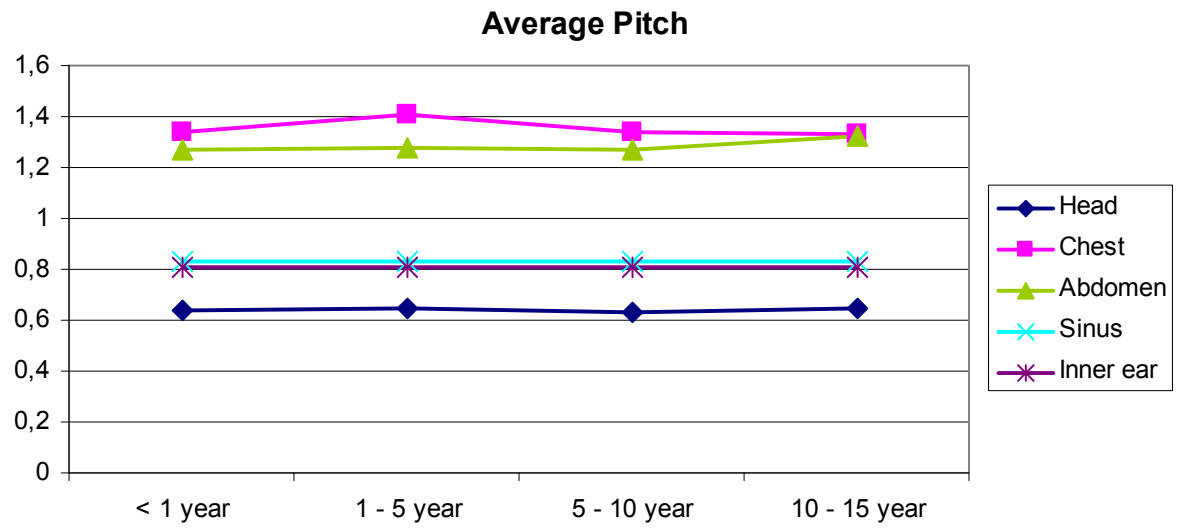
Table 9. Fraction of protocols with reduced tube voltage (<110 kV)

Study	CT examination			
	Head	Chest	Abdomen	Sinus and Inner ear
This study	9%	39%	40%	32%
Yakoumakis [18]	22%	26%	26%	Na
Arch [17]	Na	38%	22%	Na
Brisse [20]	11%	68%	69%	23%
Galanski [21]	10%	35%	17%	21%
Pages [26]	Na	0%	0%	Na
Hollingsworth [25]	Na	3%	1%	Na

Na: Not available

Data of the observed average pitch values are shown in figure 6. In contrast to the observed trend in tube voltage selection, pitch values remain rather constant in function of patient size. Highest pitch values are observed for the body examinations: these range from 0,97 to 1,75 with slightly higher average values for chest (av pitch chest = 1,36, av pitch abdomen = 1,29). For spiral head protocols pitch values range from 0,5 to 0,9 with an average value of 0,64. For sinus and inner ear examinations, the average values are very similar, respectively 0,83 and 0,81; observed values range between 0,45 and 1,70.

Figure 6. Observed average pitch values in function of age group.



Scan volume – scan region (cm)

For the five examinations, there are no significant differences between the anatomical landmarks of the scan volume that are applied by the participating centers in the study. The centers apply the same typical landmarks; the scan length is automatically adjusted in function on the size of the child. Age dependent typical scan lengths are also available in literature and are usually tabulated on basis of clinical data by measurements on scan projection radiographs for a series of averaged sized patients [9, 7, 20]. Table 10 shows the typical anatomical landmarks of the scan volume and the corresponding typical scan length (*L*) in function of the age of the child, derived from [7 and 20]. The abdomen examination in this study is a full abdomen scan from the diaphragm to the pubic symphysis, and not a shorter upper abdominal scan which is usually stopped at the level of the kidneys. Logically, the body protocols show the largest scan length variation in function of age. For the head protocols, the scan length changes only a few centimetres.

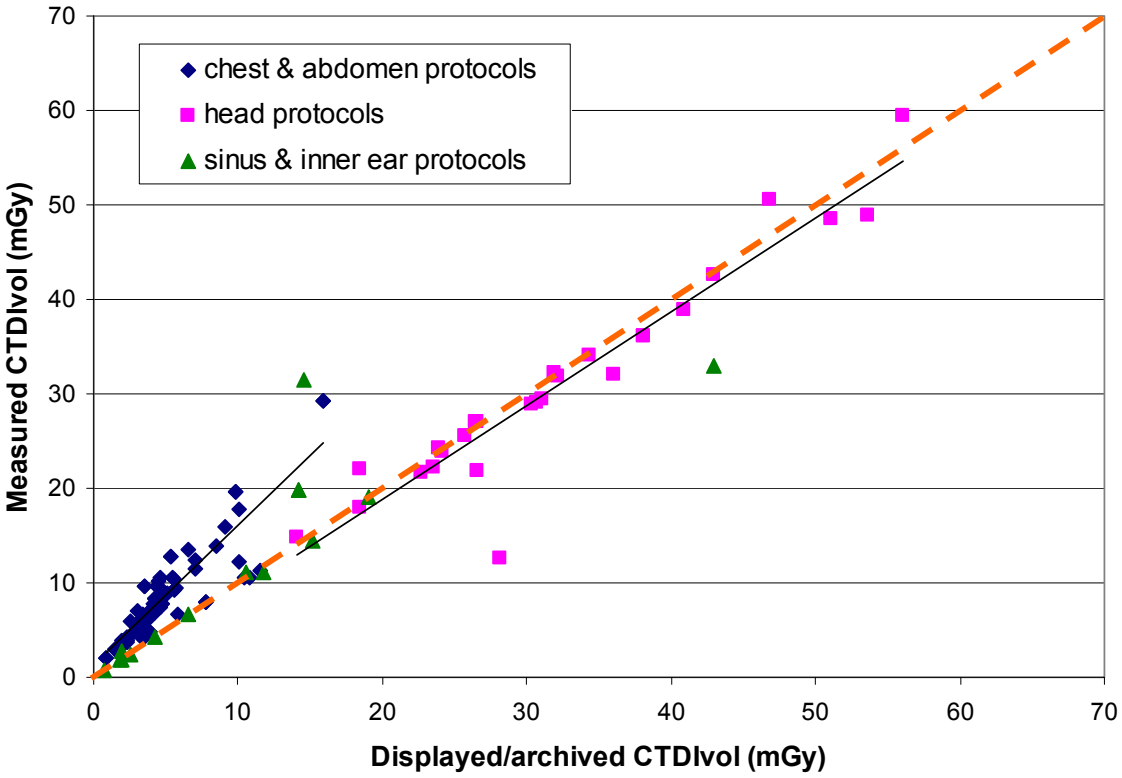
Table 10. Typical scan volume

CT examination	Anatomical landmarks		Typical scan length *L* (cm)				
	Cranial	Caudal	0 y	1 y	5 y	10 y	15 y
Head	Vertex	Skull base	8	11	13	13	13
Sinus	Superior margin of frontal sinus	Occlusial plane	5	5	6	10	10
Inner ear			3,5	3,5	4	4	4
Chest	C7/T1	Sinus	9	12	16	20	27
Abdomen	Diaphragm	Pubic symphysis	13	19	25	31	43

3.3. Accuracy of displayed dose descriptors ($CTDI_{vol}$ – DLP)

During the audits by the physicists, the reported $CTDI_{vol}$ values from the local scan protocols were compared to the measured data with the 16 cm standard dosimetry phantom. Figure 7 shows a scatterplot of these measurements, grouped according to the scan region of the protocols: body (chest and abdomen), head, and sinus and inner ear. The dashed orange line represents the function “measured CTDIvol = displayed CTDIvol”. All protocols above this line underestimate the dose, the protocols under this line overestimate the dose.

Figure 7. Measured CTDIvol versus displayed CTDIvol



As shown by the graph, the displayed $CTDI_{vol}$ values for head, sinus and inner ear examinations agree quite well with the measured data. The median deviation between both is only 5,3% and 5,1% for head en sinus-inner ear protocols respectively. However, for body examinations there is a systematic underestimation of the dose by a median value of 45%. The reason for this is that for body protocols most CT-scanners display a calculated $CTDI_{vol}$ (and the derived DLP) value that is determined in a 32 cm diameter adult dosimetry phantom. This is probably due to the fact that a lot of users define paediatric protocols by downscaling copies of adult protocols. The CTDI determined for a 32 cm phantom is not suitable for paediatrics, where the $CTDI_{vol}$ value in the standard 16 cm phantom is more appropriate. Under similar exposure conditions, the ratio between the $CTDI_{vol}$ measured in a 16cm phantom and the $CTDI_{vol}$ measured in a 32 cm phantom is about two. Thus, a displayed $CTDI_{vol}$ that is calculated for a 32 cm adult phantom underestimates the paediatric radiation dose roughly by a factor of two. Head, sinus and inner ear

protocols do not suffer from this flaw as the CTDI for these protocols is always determined for a 16 cm phantom.

Obviously, this flaw does not affect the paediatric patient dose directly. However, the CT-scan user should be very much aware that for body protocols the displayed and archived CTDI (and derived DLP) values do not automatically reflect the correct dose to the child and probably underestimate it by about half. This becomes very important when local patient dosimetry recording is performed.

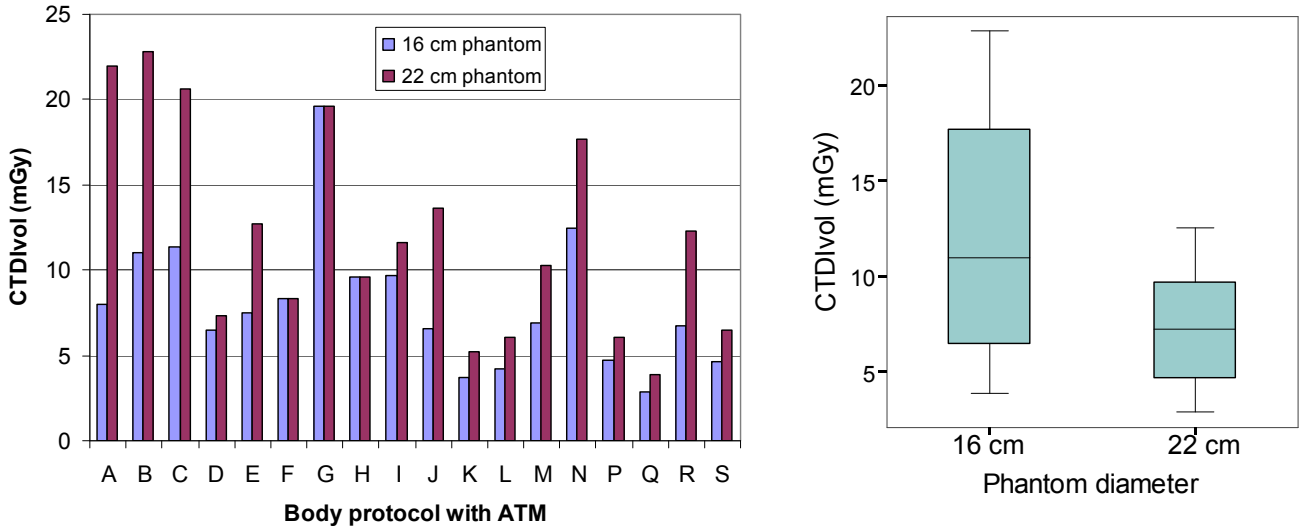
3.4. The effect of phantom size on the ATM system

As reported in the previous sections, all scanners are equipped with an ATM system and it is used very frequently: about 60% of all head and body protocols use ATM (see table 5 and figure 3). The goal of an automated tube current modulation is to adapt the tube current (mA) to the patient's attenuation. Tube current is constantly modulated as the patients' attenuation varies both along the *z*-axis (e.g. shoulder versus lung) and angular (e.g. anterior posterior versus lateral). This should not only result in a dose optimised scan, but also in improved image quality as the image noise should remain constant in all slices of the same scan.

However, ATM is not fully automated; it requires the CT-user to select a level of dose intensity by a default dose setting. Today, the method of selection of dose intensity with ATM is not standardized and depends on the CT manufacturer. With some manufacturers the user selects a desired "reference noise index", other manufacturers allow the user to select a "reference mAs value".

Scans with different size phantoms allow to appreciate the effectiveness of an ATM system. For this, during the local dose audits, the influence of the ATM in function on object size was evaluated. For body (abdomen and chest) protocols that use ATM in the age group of 10 years, a scan sequence was performed on the 16 cm diameter dosimetry phantom and the 22 cm diameter CT performance phantom. Thus, both phantoms were scanned with equal acquisition settings (ie for a 10 yr old child) under ATM conditions. Figure 8 shows the measured $CTDI_{vol}$ of these scans, 18 scanners were evaluated. Figure 8a shows the change in $CTDI_{vol}$ for each protocol/scanner, figure 8b shows a boxplot of the accrued data. As expected, most CT scanners (15 out of 18) automatically reduce the dose level when smaller objects are scanned. The median $CTDI_{vol}$ for the 22 cm phantom reduced from 10,9 mGy down to 7,2 mGy (by 34%) for the 16 cm phantom. The maximal reduction was 64% for protocol A, whereas 3 protocols (F, G, H) showed no reduction. The possible reason for these three is that the user (inadvertently) selected a baseline cut-off mA value in the ATM system settings. The personal contacts during the dose audits showed that the CT-users are not very familiar or experienced in presetting the ATM system and that it often is a source of confusion. Usually factory settings are applied.

Figure 8. Impact of phantom size on $CTDI_{vol}$ values for 18 body protocols with ATM



3.5. Obtained dosimetry data

Table 11 displays the results of the $CTDI_{vol}$ and DLP values for the head, chest and abdomen examinations for all age groups. The data is expressed as median, third quartile values and range. For the head examinations, data is grouped over both sequential and spiral protocols. The data of the sinus and inner ear examinations are not included in the table as the radiology centers make no classification according patient age; all children are scanned with the same settings. Following data were obtained for sinus and inner ear respectively: $CTDI_{vol}$ sinus (median 5.4 mGy, 3rd Q 16 mGy, range 0.8 - 20 mGy), $CTDI_{vol}$ inner ear (median 43 mGy, 3rd Q 66 mGy, range 11 - 89 mGy).

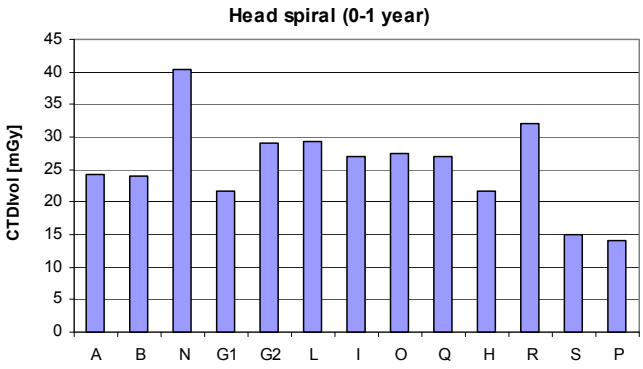
Table 11. Obtained dosimetry data CTDIvol (mGy) and DLP (mGycm) for head, chest and abdomen protocols in function of age groups (years).

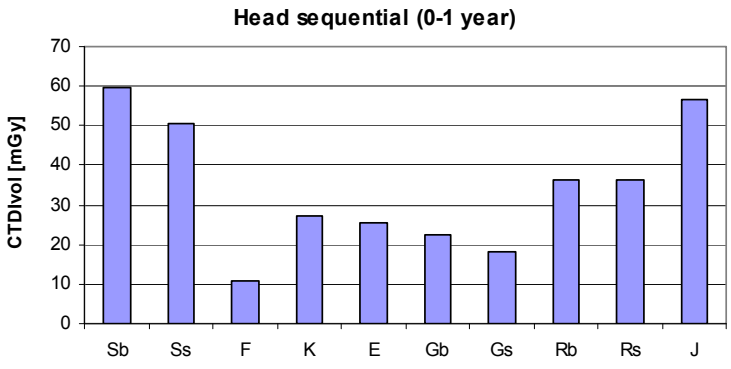
Age group	Dose quantity	Head			Chest			Abdomen		
		Median	3rd Q	Range	Median	3rd Q	Range	Median	3rd Q	Range
<1	CTDIv	27	35	11-60	6.5	8.4	1.2-29	6.9	7.8	2.8-22
	DLP	216	280	88-480	59	76	11-261	90	101	36-286
1-5	CTDIv	32	43	11-64	6.6	9.3	2.0-37	7.7	11	4.0-25
	DLP	352	473	121-704	79	111	24-444	146	209	76-475
5-10	CTDIv	36	49	11-64	7.5	9.0	2.9-37	7.7	9.5	4.0-25
	DLP	468	637	143-832	120	144	46-592	193	238	100-625
10-15	CTDIv	34	50	11-60	9.0	13	3.9-29	9.3	13	4.0-21
	DLP	442	650	143-780	180	260	78-580	288	403	124-651

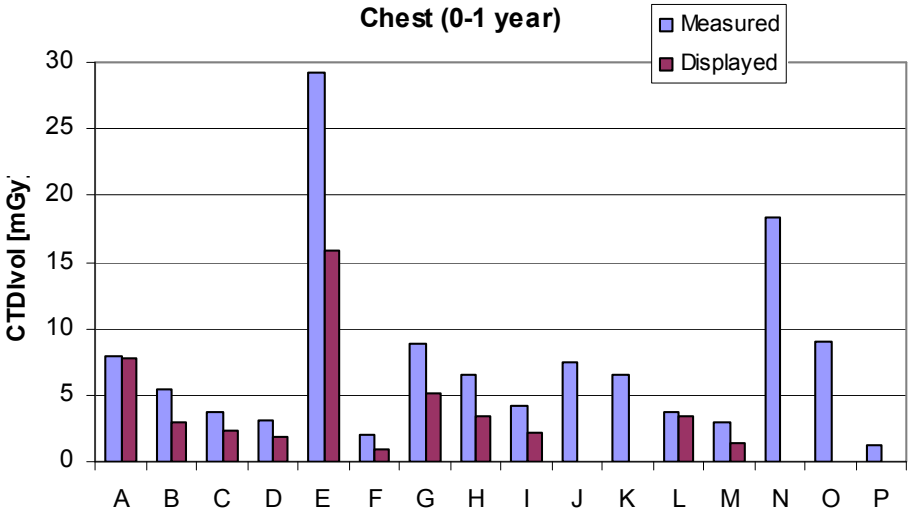
The following figures 9 to 13 show the $CTDI_{vol}$ dose distribution for all the centers. The figures are grouped according age range. For head examinations, data is presented in separate graphs for spiral and sequential scanning. Sequential scanning of the base and skull of the head is indexed with a *b* and *s* respectively. For body protocols, both displayed and measured $CTDI_{vol}$ is shown, for head protocols only the measured $CTDI_{vol}$. Also for the body protocols, the centers are grouped according to the use of tube current: the first section list centers that use a manual mAs value, the second section list centers that use ATM. This is indicated in the figure titles. Centers that have multiple protocols for the same age group are numerically indexed.

The data show that there remain very large differences in dose distributions between centers. For example, for the youngest age group, the rounded ratio's of maximal and minimal $CTDI_{vol}$'s are: 3 for head, 18 for chest, 8 for abdomen, 24 for sinus and 8 for inner ear.
On average, highest doses were observed with centers that use a single ATM scan protocol (with a high default dose settings) for children of all ages, regardless of their body size, or centers that use a fixed tube current setting for children of all ages. This methodology specifically results in high doses for the youngest age groups (0 – 5 years). Lowest doses were observed with centers that perform a careful manual tube current adaptation in function of body size. While the ATM system can be a helpful radiation protection tool, users should be aware that it does not automatically scan the patient with an appropriate dose, especially for the youngest age groups. The level of dose modulation depends on the default dose setting by the user. The default dose setting (such as reference mAs, noise index, etc) for any particular paediatric CT examination should be below the reference values that are established for adults. The regulation of the ATM depends on the type of CT scanner and can be a source of confusion.
For example, centers N and S, both use ATM with a high (adult) default dose setting in combination with a 120 kV tube voltage. This results in high doses. Also, centre N uses a pitch of only 0.97 which is very low compared to the average pitch value of 1.34 for the other centers. Centre E uses a fixed tube current setting for chest examinations, but this value remains constant for all sizes. As a result, doses are also very high for the youngest age groups. Centers F and G both apply manual tube current setting and low kilovoltages in function of body weight. This results in consistently low doses.

Figure 9. Obtained dose distribution for head, chest and abdomen examinations for age group 0-1 years. Third quartile values are respectively: 35 mGy head, 8.4 mGy chest and 7.8 abdomen. For chest protocols, centers A-G use manual mAs. For abdomen protocols, centers A-G use manual mAs. All other centers use ATM.







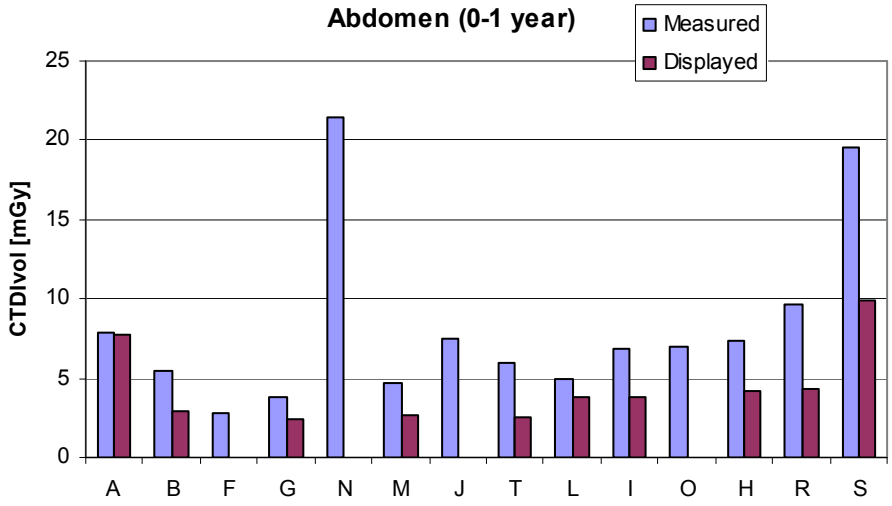
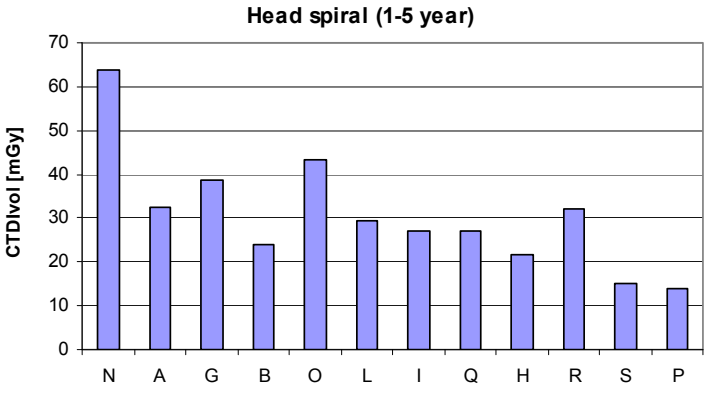
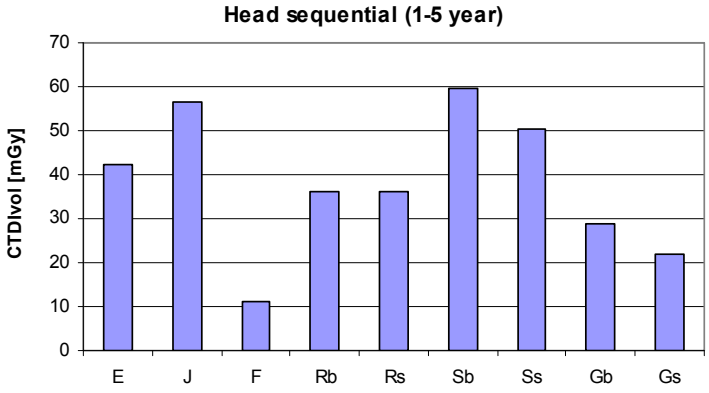
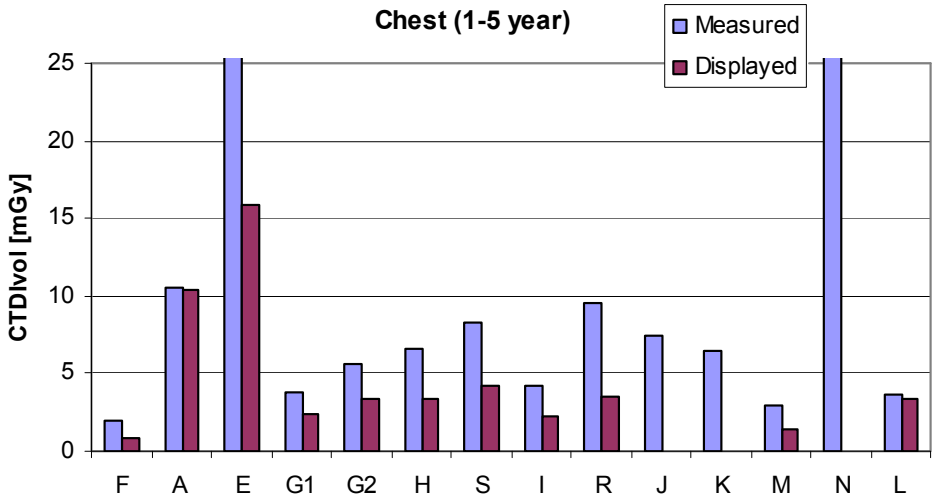


Figure 10. Obtained dose distribution for head, chest and abdomen examinations for age group 1-5 years. Third quartile values are respectively: 43 mGy head, 9.3 mGy chest and 11 abdomen. For chest protocols, centers F-G2 use manual mAs. For abdomen protocols, centers F-G use manual mAs. All other centers use ATM.







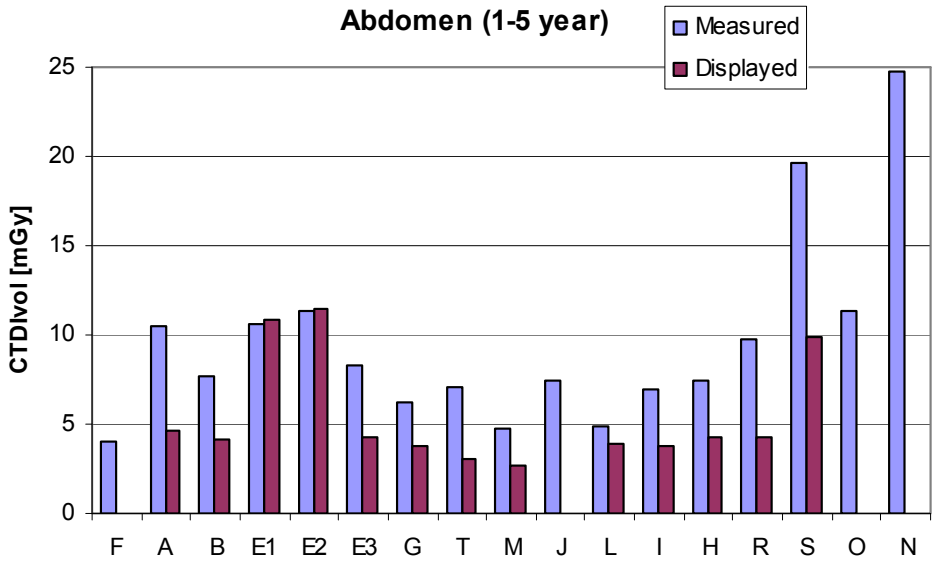
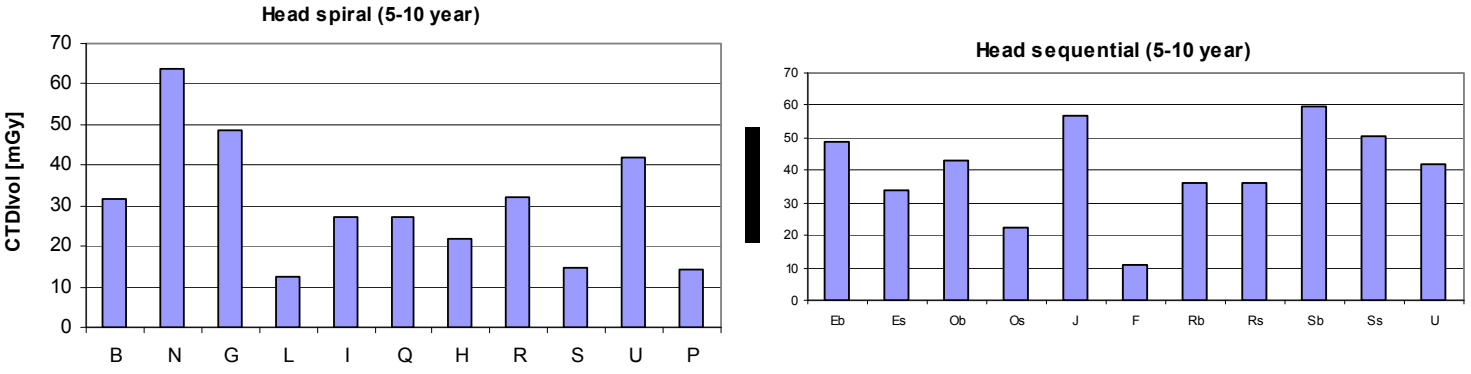
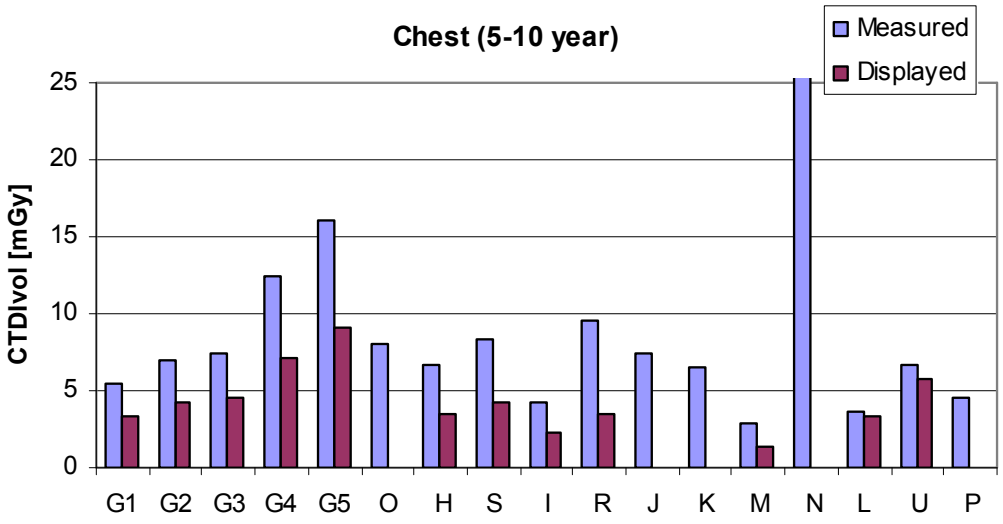


Figure 11. Obtained dose distribution for head, chest and abdomen examinations for age group 5-10 years. Third quartile values are respectively: 49 mGy head, 9.0 mGy chest and 9.5 abdomen. For chest protocols, centers G1-G5 use manual mAs. For abdomen protocols, centers F-G2 use manual mAs. All other centers use ATM.





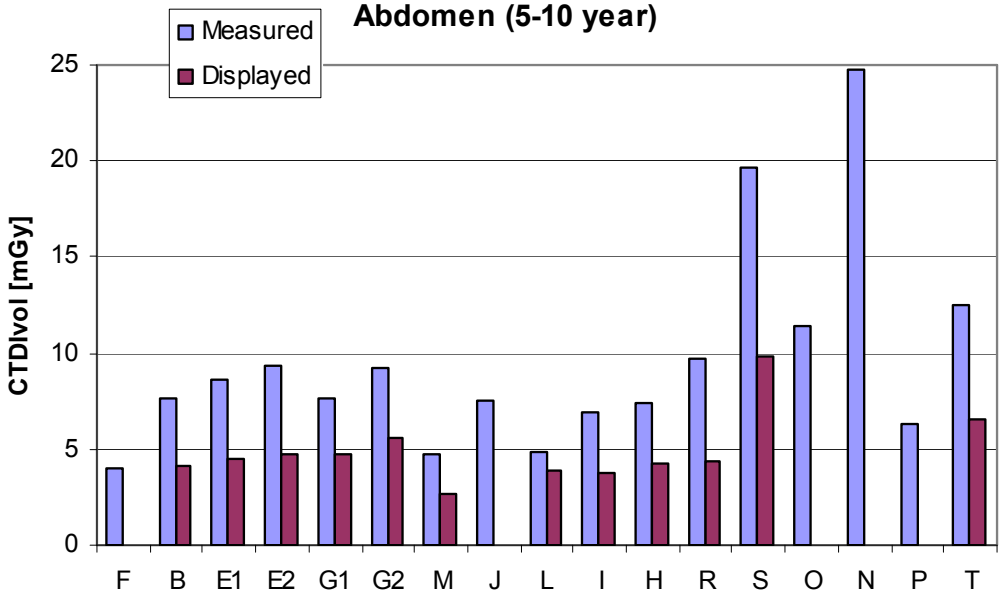
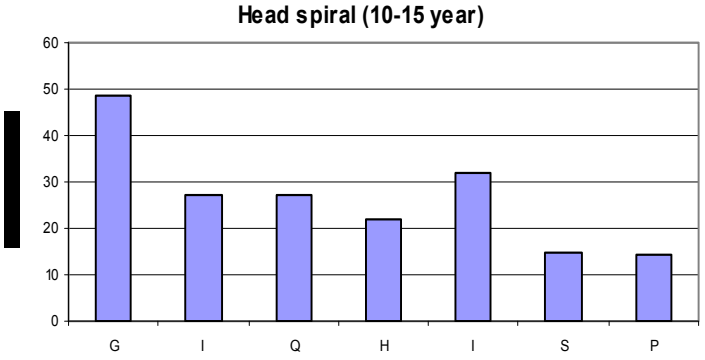
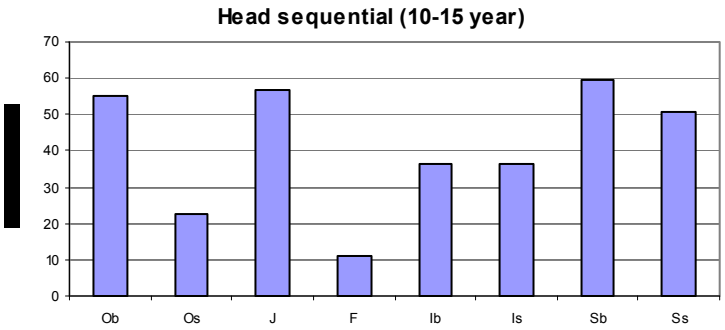
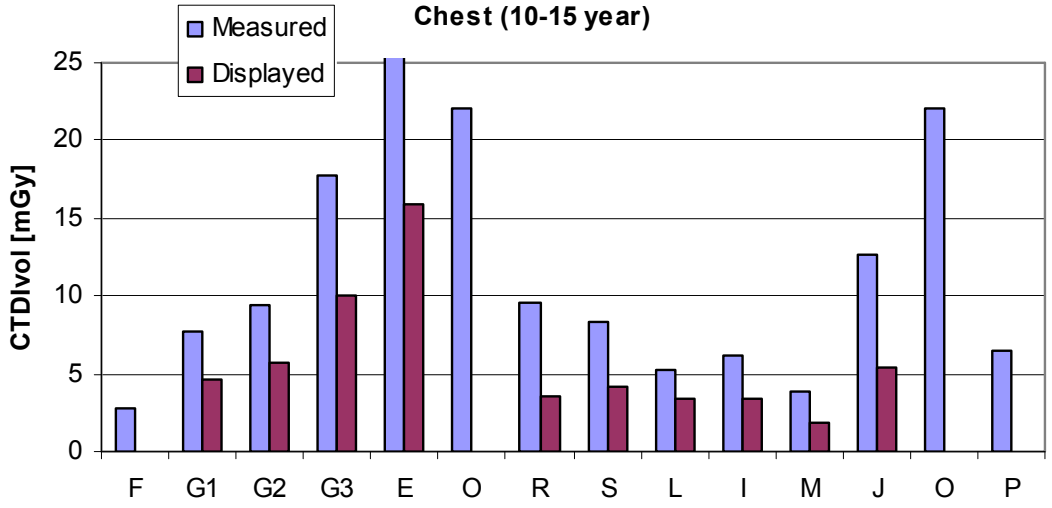


Figure 12. Obtained dose distribution for head, chest and abdomen examinations for age group 10-15 years. Third quartile values are respectively: 50 mGy head, 13 mGy chest and 13 abdomen. For chest protocols, centers F-E use manual mAs. For abdomen protocols, centers F-G2 use manual mAs. All other centers use ATM.







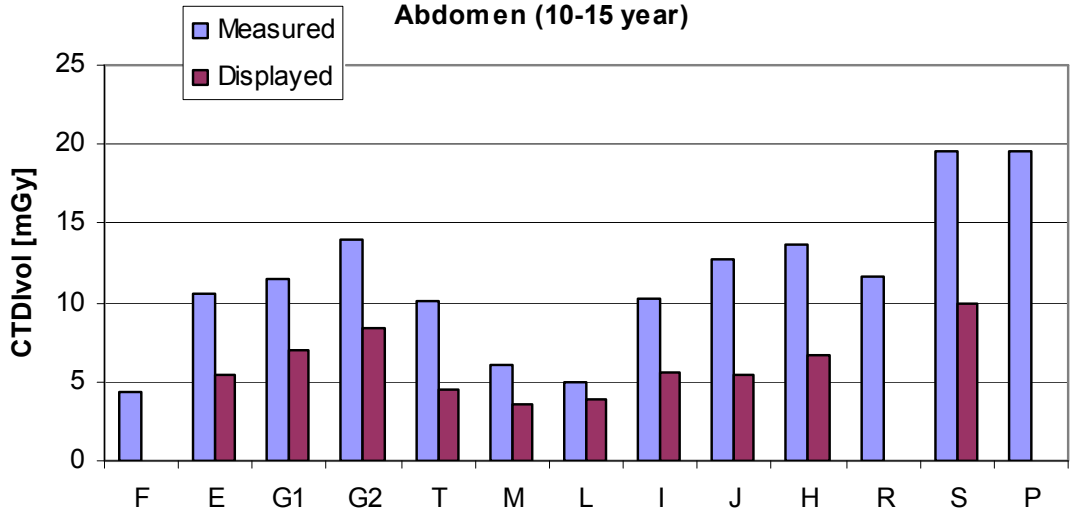
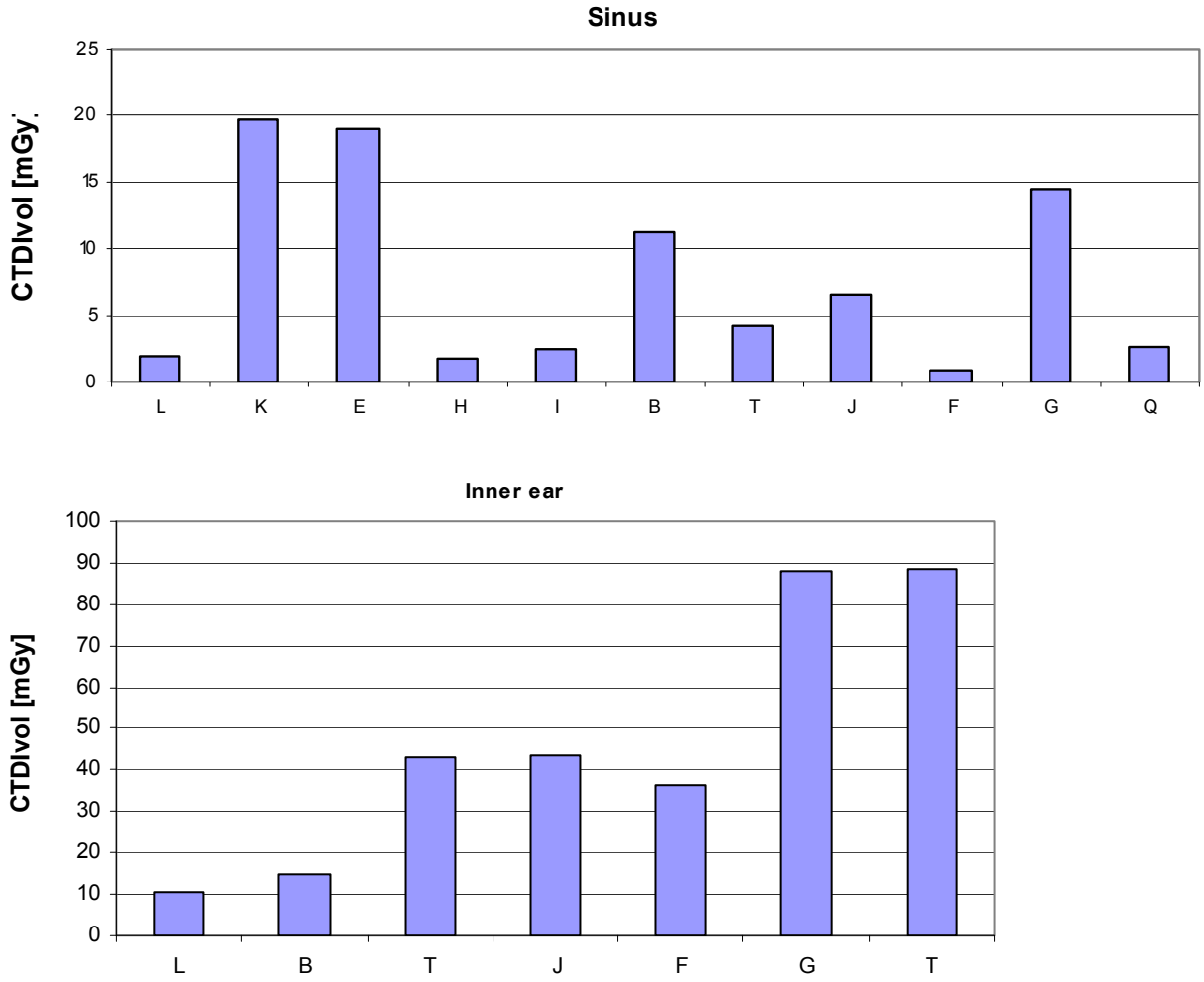


Figure 13. Obtained dose distribution for sinus and inner ear examinations. Third quartile values are respectively: 16 mGy sinus, 66 mGy inner ear. For sinus protocols, centers L-K use spiral scanning. For inner ear protocols, only center L uses spiral scanning. All other centers use sequential scanning.



3.6. *Comparison with other surveys*

Table 12 shows the median and third quartile data of this study (B) compared with data reported from other countries, namely France (F), Greece (Gr), Germany (D), Switzerland (CH) and United Kingdom (UK). A graphical representation is shown in figures 14a-c. Data from Greece is not plotted for clarity. All referred data were reported within the last 5 years. Following references were considered:

B	Belgium, 2010	this study
F	France, 2009	Brisse [20]
Gr	Greece, 2009	Yakoumakis [18]
D	Germany, 2007	Galanski [21]
CH	Switzerland, 2008	Verdun [19]
UK	United Kingdom, 2005	Shrimpton [7]

For reasons of equivalence, all data in the table are expressed as $CTDI_{vol}$, related to the 16 cm dosimetry phantom. For studies that reported $CTDI_{vol}$ data in a 32cm

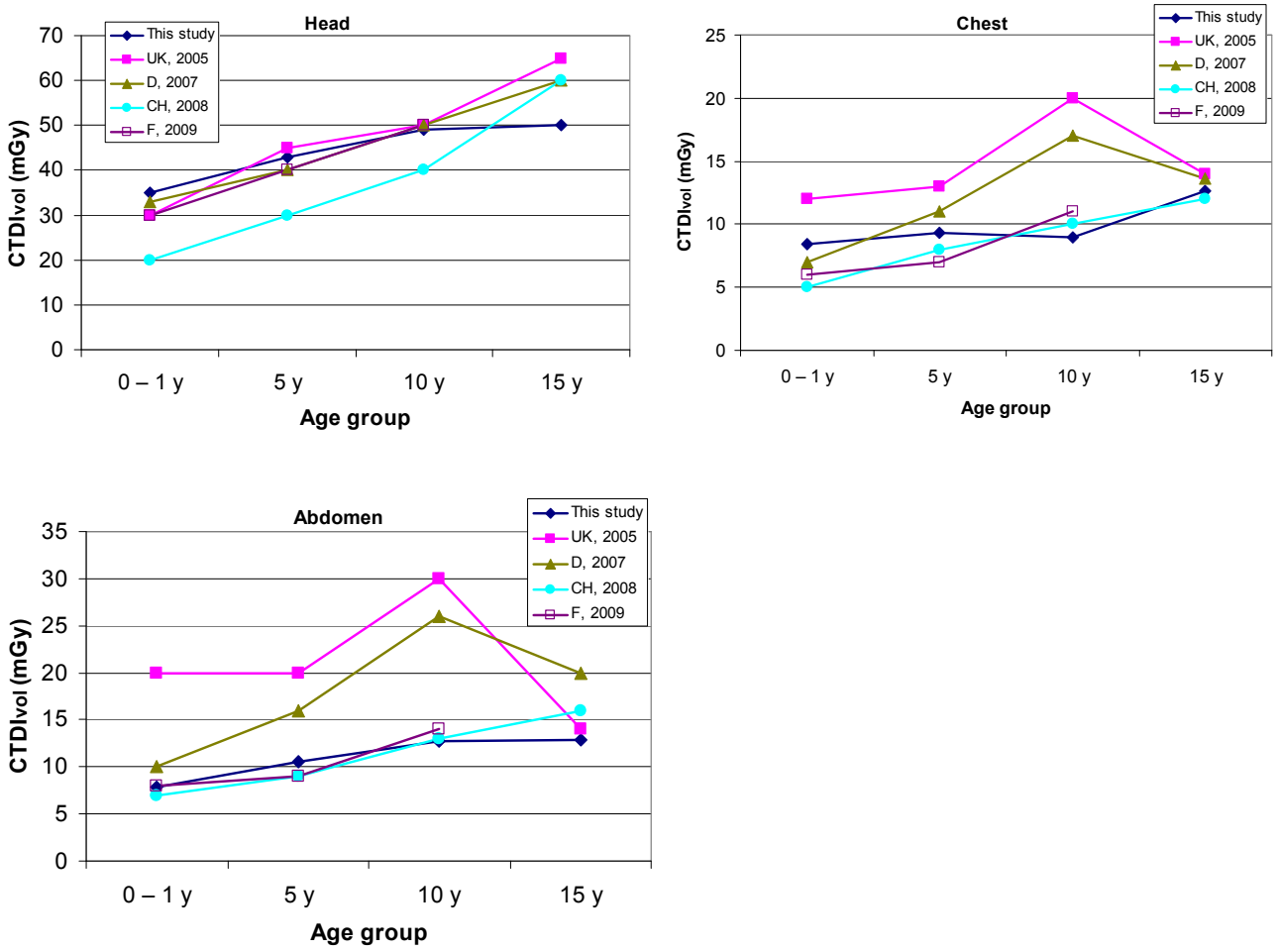
dosimetry phantom (F and D), the $CTDI_{vol}$ for a 16 cm phantom was estimated by doubling the values. For studies that reported $CTDI_w$, the $CTDI_{vol}$ for head examinations was estimated by assuming a pitch factor equal to 1, for body examinations a pitch factor of 1.5 was assumed.
As shown in table 12 and figures 13, the observed values in this study are compatible with the data reported from other countries. In almost all cases they are lower than the UK data. The UK survey by Shrimpton et al was conducted in 2003 before the majority of CT users became aware of the need for appropriately adapted dose settings for paediatric purposes [7]. This might explain that this study reported high doses compared to all subsequent studies except the Greek study from Yakoumakis. The Greek study reported very high doses: for body examinations in the 5-10 year age range even up to threefold the values observed in our study [18]. The main reason for this is that only a few radiology centers in their study adapted scan protocol parameters for children. Also the CT units in their study were not as recent as with other reported data (table 6). For head examinations, the Belgian data is very compatible with the German, French and Swiss data, except for the youngest age group where our values are somewhat higher. It must be noted that the Belgian data contains both spiral and sequential CT and that the doses from spiral CT are substantially lower. When selecting only spiral head CT the 3rd quartile data for the four age groups reduce to respectively: 30 mGy, 32 mGy, 33 mGy and 44 mGy. For chest examinations, the Belgian data shows low doses that agree well with the French and Swiss data, except for the youngest age group. Also for abdomen examinations, the Belgian data is at the low end of the dose range and there is again a very good agreement with the French and Swiss data. For sinus and inner ear examinations, only the French report provides data. For sinus scans they recommend a $CTDI_{vol}$ of 10 mGy which is lower than the 3rd quartile value of 16 mGy that is observed in this study (the median value of this study was 5.4 mGy). For inner ear they recommend $CTDI_{vol}$ values of 45 mGy (1 year), 70 mGy (5 years) and 85 mGy (10 years) which agrees well with the observed 3rd quartile value of 66 mGy observed in this study for all ages.

Table 12. Obtained 3rd quartile CTDIvol (mGy) data in function of age group (years) compared with data reported from other countries.

Age	Head						Chest						Abdomen					
group	B	F	GR	D	CH	UK	B	F	GR	D	CH	UK	B	F	GR	D	CH	UK
<1	35	30	Na	33	20	30	8.4	6	Na	7	5	12	7.8	8	Na	10	7	20
1-5	43	40	50	40	30	45	9.3	7	23	11	8	13	11	9	25	16	9	20
5-10	49	50	65	50	40	50	9.0	11	31	17	10	20	9.5	14	30	26	13	30
10-15	50	Na	Na	65	60	65	13	Na	Na	14	12	14	13	Na	Na	20	16	14

Na: Not available
B: this study, F: France, GR: Greece, D: Germany, CH: Switzerland, UK: United Kingdom

Figure 13. Obtained 3rd quartile CTDIvol (mGy) data in function of age group (years) compared with data reported from other countries for head, chest and abdomen examinations.



3.7. *Comparison with registered data from patient scans*

During the conduct of the study, centers were requested to record dosimetry data of individually scanned patients, together with age, weight and length. Unfortunately, consistent data was only collected from 9 centers, representing a total of 397 dose records (head: 178, chest: 109, abdomen: 57 and sinus: 53). Table 13 compares the data for head, chest and abdomen examinations with the established values from the dose audits (table 11). For sinus examinations the median $CTDI_{vol}$ from the registered data was 6.6 mGy (1.9 – 11 mGy) which agrees well to the median value of 5.4 mGy form the dose audits. Also for chest and abdomen examinations the data agree rather well. For head examinations the registered data shows consistently lower values, except for the oldest age group. This can be explained by the fact that the 16 cm diameter dosimetry phantom overestimates the head size of younger children, as is also indicated by table 4. As a result, it can be expected that data derived from future big patient dose samples will probably be somewhat lower that

the observed dose values for head examinations that are reported from the dose audits in this document.

Table 13. Comparison of obtained median CTDIvol (mGy) values from the dose audits with registered data from patients examinations. Values between brackets show 75 % interpercentile ranges.

Age group	Head		Chest		Abdomen	
	Audit	Registered data	Audit	Registered data	Audit	Registered data
<1	27	19 (12-26)	6.5	5.8 (4.9-6.4)	6.9	Na
1-5	32	21 (9-33)	6.6	6.8 (2.6-8.2)	7.7	6.8 (5.0-8.7)
5-10	36	23 (10–36)	7.5	7.1 (2.6-8.1)	7.7	9.5 (7.4-12)
10-15	34	32 (15–50)	9.0	9.5 (8.5-11.3)	9.3	15 (13-16)

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3.8. *Image quality*

Diagnostic image quality verification was performed for the head, chest and abdominal examinations by a limited observer preference study with two radiologists according to the following quality criteria:

- Head CT
  a. Overall image quality in supratentorial space
  b. Overall image quality in infratentorial space
  c. Cortical grey matter / white matter contrast
  d. Sharpness of cortical surface
  e. Deep grey / white matter contrast
  f. Sharpness of ventricles borders
  g. Supratentorial artifacts: linear streaks (beam hardening)
  h. Supratentorial artifacts : en nappes (cone-beam)
  i. Supratentorial artifacts : circular (calibration)
  j. Infratentorial artifacts: linear streaks (beam hardening)
  k. Infratentorial artifacts: en nappes (cone-beam)
  l. Infratentorial artifacts: circular (calibration)

- Chest CT : without contrast injection? with contrast injection?
  a. Overall image quality
  b. Sharpness of mediastinum
  c. Distinction aorta / pulmonary artery (without contrast injection)
  d. Sharpness of bronchial walls
  e. Sharpness of small vessels
  f. Fissures
  g. Interlobular septum
  h. Artifacts? Type? (cfr. brain CT)

- Abdomen CT : without contrast injection? with contrast injection?
  a. Overall image quality
  b. Borders sharpness (liver, spleen, kidneys)
  c. Parenchyma homogeneity (liver, spleen, kidneys)
  d. Intestinal wall sharpness (stomach, small bowel, large bowel)
  e. Artifacts? Type? (cfr. brain CT)

For this purpose, the centers were requested to submit one set of anonymous patient data for each type of examination and for the different age groups (if available). The patient studies were evaluated on a diagnostic workstation by two independent

radiologists experienced in paediatric CT (P.C. and P.E.). A scoring scale was used between 1 (very poor) and 10 (excellent), and a single result per examination was obtained by consensus between both readers. The results are shown in tables 14a and 14b. As an indication, the observed $CTDI_{vol}$ values from the dose audits are also shown for the particular center. These values, however, do not necessarily correspond with the data of the diagnostic scan and are merely provided as an indication.

Table 14a. Results of the image quality observation on a ten point discrete scale (1 = poor, 10 = excellent) for head and chest examinations of three age ranges (0-1 y, 1-5 y and 5-10 y). CTDIvol (mGy) of the particular center is shown for indication purposes.

Center	Head						Chest					
	Age 0-1 yr		Age 1-5 yr		Age 5-10 yr		Age 0-1 yr		Age 1-5 yr		Age 5-10 yr	
	score	CTDIv	score	CTDIv	score	CTDIv	Score	CTDIv	score	CTDIv	score	CTDIv
L			8	29	5	13						
T	8		6		8		6		5		7	
P	5	14	5	14	5	14	6	1.2	5	4.6	8	4.6
Q	8	27	8	27	7	27			6		7	
M	6		6		6							
J	8	57	7	57	7	57	6	7.5	6	7.5		
E	5	26	5	43	5	48			5	29		
A	8	24	8	32	6				8	11		
N	4	40	6	64	5	64	5	18	6	37	6	37
F	4	11	5	11	5	11	6	2	5	2	6	2.8

Table 14b. Results of the image quality observation on a ten point discrete scale (1 = poor, 10 = excellent) for abdomen examinations of three age ranges (0-1 y, 1-5 y and 5-10 y). CTDIvol (mGy) of the particular center is shown for indication purposes.

Center	Abdomen			
	Age 1-5 yr		Age 5-10 yr	
	score	CTDIv	score	CTDIv
L			5	4.9
T	6	7.1	6	12.5
P	7			
Q	7		8	
M				
J			5	7.5
E	7	8.3	7	9.3
A			8	
N	7	24.8	6	24.8
F	6	4	6	4

The general results of the image quality evaluation shows that the diagnostic quality of the CT scans is better than average. Only two studies were rated poor, these were head examinations of the youngest age group for centers N and F (both a score of 4). All other studies were rated between average (score 5) and very good (score 8). The combination of the results of the image quality evaluation with the dose levels from the audits is not very conclusive due to incomplete data. However, some interesting observations can be made for the head examinations as this represents the most data. For the head examinations, the lower image quality scores agree roughly with the lowest doses. The best image quality scores are achieved from centers with a $CTDI_{vol}$ around 30 mGy, which is also the observed 3rd quartile value

of all centers in the dosimetry audit. Centers with lower $CTDI_{vol}$ (11-13 mGy) consistently represent lower scores of around 5. An exception to this is center N: despite the fact that represents a very high $CTDI_{vol}$, it did not result in good image quality values for all three examination types. This might indicate that the use of high exposure factors (in terms of dose) do not automatically result in very good image quality.

3.10. Future technical developments for dose optimisation

CT manufacturers, together with the radiological community, are continuing to develop radiation protection tools for CT. Besides the recent radiation protection tools that were provided on the CT scanners in this study (such as ATM and dedicated paediatric scan protocols) there are some new promising tools that proved efficient to decrease doses further.
We briefly discuss four of these new tools in development:

The availability of low tube voltages for scanning infants.
A simulation study by Buchenau et al, showed that tube voltages of 80 kV are close to the optimum regarding contrast, noise and dose for soft tissue imaging in paediatric CT. The study also showed that tube voltages of around 60 kV should be made available for scanning infants [27].

Countermeasures for overscanning
Spiral CT scanning requires elongation of the scan range to enable data interpolation at the beginning and at the end of the scan. This represents in an additional exposure. For most CT scanners the elongation of the scan range amounts up to roughly about 1.5 times the total beam width (NxT). Thus, this effect will become more pronounced with the combination of wide MSCT's and the shorter scan ranges that are encountered in paediatric CT (especially with newborns). A recent study by Tzedakis A et al that measured the effect of overscanning in an anthropomorphic paediatric phantom demonstrated that the percentage differences in normalized effective dose data between axial and helical scans may reach 43%, 70%, 36%, and 26% for head-neck, chest, abdomen-pelvis, and trunk studies, respectively [28]. Very recently some CT manufacturers introduced an adaptive collimation system that interferes at the start and end of the spiral acquisition in order to reduce the additional exposure of the overscanning effect [29].

Organ based dose modulation
Such systems apply partial scanning by reducing the output of the x-ray tube when it is directly in front of the breast or other dose-sensitive organs, such as the thyroid gland and eye lens. A study by Vollmar et al demonstrated that by partial CT scanning the dose to the breasts could be reduced typically by 50%. To sustain a constant noise level, an increase of irradiation in the anteroposterior position resulted in a higher dose to the spine [30].

Iterative reconstruction techniques
Iterative reconstruction algorithms are recently being developed and are able to correct image data using a system of models to improve image noise. Such new algorithms have the potential to preserve and enhance the diagnostic capability of CT studies performed at reduced doses compared to the current
filtered back projection reconstruction methods. First clinical studies on patients show significant dose reductions [31].

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