Guideline for Optimization of the Radiation Exposure of CT Examinations

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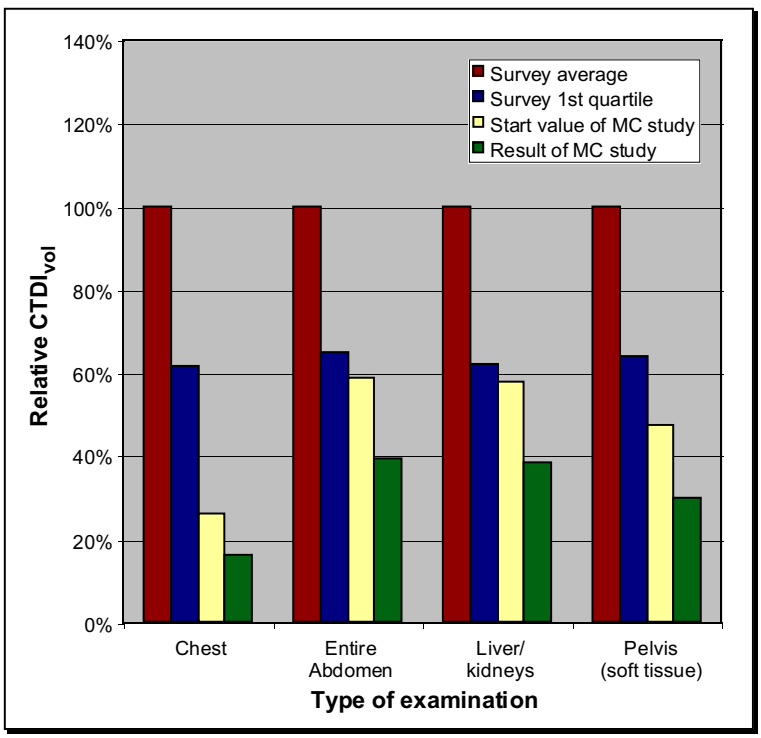
2nd Revised and Updated Edition

Edited by H. D. Nagel



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1. Introduction

Since the results of the UK CT survey in 1989 were published (Shrimpton91), an increasing awareness of the significant radiation exposure to patients undergoing CT examinations and the need for dose optimization has emerged. The best indicator for this change in mind-setting is the large number of publications related to the optimization of dose settings for specific types of examinations, of surveys on CT practice, of multi-centric optimization studies, and of guidelines for good CT practice.

In this guideline, the strategies for dose optimization of CT scan protocols shall be outlined, justified and illustrated by means of an example. Adequate familiarity with the dose descriptors that are appropriate for CT and the fundamental interdependencies between scan parameters, dose and image quality is mandatory. Detailed information on this subject can be found in a dedicated textbook edited by the author of this guideline (Nagel02).

2. Recommendations on Dose Optimization in CT

As a result of the world-wide activities towards dose optimization in recent years, there now exists a number of recommendations for CT. Among them are numerous internet sites offering 'optimized' scan protocol settings (e.g. www.CTisus.com, www.msct.com etc.). From the perspective of a CT user, this information flood often poses more questions than answers, as there is a great variance between these recommendations. At a closer look it turns out the majority of these hints are based on the experience of a single person or a few local users only. Apart from a few exceptions, most of the recommended dose settings are given in terms of mAs that apply for a specific scanner only. And quite often a lack of precision in the terminology used (e.g. 'tube current' specified in 'mAs', 'table speed' in 'mm') and completeness of the parameter sets must be noted that can lead to erroneous protocol set-ups.

The process of dose optimization represents a delicate task, as there are many reasons that prevent a CT user from changing his accustomed attitudes. The most important is his concern of losing diagnostic confidence. Another obstacle is his suspicion in the validity of the recommendations given. And the third is the time required for the optimization procedure. With these challenges in mind, a guide for the evaluation and optimization of CT protocols has been developed in Germany in 2004 as a kind of a 'cookbook' that has recently been updated (Nagel10). The foundation of this guide were the results of the German project *Concerted Action Dose Reduction in CT,* a joint effort of all parties involved in the field of CT that started in 1998:

- The nation-wide surveys on CT practice in 1999 (Galanski01), 2002 (Brix03) and 2005/06 (Galanski07);
- the CT-Expo dose evaluation software developed in 2001 (Stamm02);
- a multi-centre optimization study finished in 2002 (Galanski04), and
- the official German reference dose values for CT released in 2003 (BfS03) and updated recently (BfS10).

In addition, three other important sources were also considered:

- ICRP publication 87 'Managing patient dose in CT' (ICRP01) and ICRP publication 102 'Managing patient dose in multi-detector computed tomography (MDCT)' (ICRP07) providing useful information for various types of examination, and
- the 'Guidelines on patient dose to promote the optimization of protection for diagnostic medical exposures' issued by (NRPB99), introducing the idea of 'achievable doses', i.e. dose settings that can easily be achieved with modern equipment and justifiable optimization efforts.

Finally, the author's own experience as a consultant for the radiological quality assurance committee of the Physicians' Chamber at Hamburg that was gained from the optimization of CT protocols for a larger number of facilities was used in the preparation of the German CT guide. The aim of this guide is to enable all persons dealing with CT in daily practice (radiologists and radiographers, application personal of equipment manufacturers, radiation safety inspectors, and quality assurance committees) to evaluate and optimize the scan protocol settings of the scanner of interest.

3. Results from Surveys on CT Practice

As the exposure practice documented in surveys allows for benchmarking purposes, the results of large-scale surveys that were conducted during the period 1999 to 2005 in Germany, the USA and the United Kindom shall be presented in this section.

3.1 German Survey on CT Practice 1999

In 1999, a nation-wide survey on CT practice in Germany was conducted in a collaborative study by the German Roentgen Society (DRG) and the German Association of Manufacturers of Electromedical Equipment (ZVEI). The survey was based on questionnaires sent to all users of CT scanners in hospitals and private practices (approximately 2000), asking for dose-relevant data on 14 standard CT examinations (scanner data, protocol settings, examination-related parameters, and frequencies of examination). With a return rate of approximately 50%, representative results were obtained for the entire spectrum of areas of application, groups of users, and scanner models.

The majority of scanners covered in this survey were single-slice scanners with the exception of some dual-slice scanners (4%, exclusively Elscint CT Twin). Dose values were assessed individually for each scanner from the protocol settings given in the returned questionnaires by applying the computational methods described in (Nagel02) and by using the basic scanner dose data given in the appendix of this textbook (these algorithms and data were later used to develop the CT dose software CT-Expo). As this study was the first large-scale survey performed since 1989, numerous trends resulting from changes in the design and the use of CT scanners, and their consequences on radiation exposure, could be deduced.

The results of this survey have been documented in a comprehensive report (in German), with numerous interesting details and correlations (Galanski01).

The most essential results are listed in tab. 1. Average dose values are reported in terms of all the relevant dose descriptors, thus allowing comparisons with other published data. While $CTDI_{vol}$ depends only on the scan protocol settings (tube voltage, tube current, exposure time, slice collimation, pitch), DLP_{exam} in addition takes user-specific preferences (scan length and number of scan series (phases)) into account. Moreover, average values for examination-related parameters, such as scan length, pitch factor and number of scan series per examination, are also listed.

3.2 German MSCT Survey in 2002

The German MSCT survey in 2002 was conducted in a

Tab. 1 *Results from the 1999 survey on CT practice in Germany (Galanski01). Average values per scan series for 14 standard CT examinations are listed in terms of CT-relevant dose descriptors (weighted CTDI ($CTDI_w$), volume CTDI ($CTDI_{vol}$),dose-length product (DLP_w) and effective dose (E_{ser})), along with information on some examination-related parameters (scan length, pitch factor, number of scan series per examination). In addition, values of effective dose per examination (E_{exam}) are also given. Note that effective dose refers to the organ weighting scheme of ICRP 60 (ICRP91).*

Examination	Code	Scan Length (cm)	Pitch	Number of Series	$CTDI_w$ (mGy)	$CTDI_{vol}$ (mGy)	DLP_w (1) (mGy·cm)	E_{ser} (1) (mSv)	E_{exam} (2) (mSv)
Routine Brain	BRN	12	1.0	1.5	57	56	676	1.9	2.7
Facial Bone / Sinuses	FB/SIN	11	1.3	1.1	41	37	405	1.2	1.3
Facial Bone / Neck (3)	FB/N	18	1.2	1.2	38	18	603	2.4	2.8
Routine Chest	CHE	27	1.3	1.2	18	15	415	6.4	7.7
Abdomen+Pelvis	ABD+PEL	42	1.3	1.7	21	18	748	12.9	21.4
Pelvis (Soft Tissue)	PEL	24	1.2	1.3	23	20	481	8.2	10.7
Liver / Kidneys	LI/KI	18	1.3	1.9	21	18	327	5.9	11.0
Entire Trunk	TRUNK	66	1.3	1.4	19	16	1040	17.2	24.4
CTA Thoracic Aorta	ATH	26	1.4	1.2	18	14	363	5.9	7.0
CTA Abdominal Aorta	AAB	28	1.4	1.2	19	15	411	7.3	8.9
CTA Pulmonary Vessels	PV	16	1.4	1.1	17	13	213	3.5	3.9
Pelvis (Bone)	OP	22	1.2	1.0	29	27	586	10.4	10.5
Cervical Spine (3)	CSP	4	1.1	1.0	36	35	257	2.4	2.5
Lumbar Spine	LSP	6	1.1	1.1	39	38	231	2.9	2.9

Remarks: (1) per series (2) per examination (3) calculated for body mode

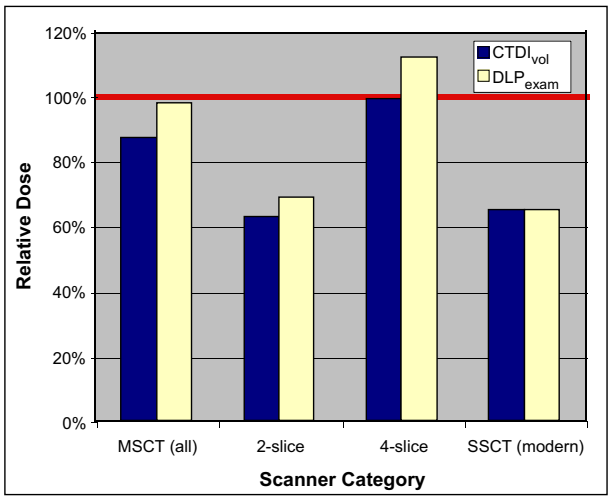

Fig. 1 *Comparison of the average dose levels of MSCT and SSCT scanners in terms of $CTDI_{vol}$ and DLP per examination (DLP_{exam}). A relative dose level of 100% (red line) refers to the overall average of the '99 German survey on SSCT practice.*

collaborative study by the German Roentgen Society (DRG), the Federal Bureau on Radiation Protection (BfS) and the German Association of Manufacturers of Electromedical Equipment (ZVEI). The study was motivated by publications reporting excessive increases in MSCT exposure compared to single-slice scanners (SSCT) operated at the same facility. The survey was organized in the same fashion as the '99 German CT survey, i.e. based on questionnaires sent to all MSCT facilities. At the begin of 2002, a total of 206 MSCT scanners were in operation in Germany, among them 81 two-slice scanners (80% of them being Elscint CT Twin), 123 four-slice scanners (65% of them being Siemens Volume Zoom) and 2 eight-slice scanners (only GE LightSpeed Ultra). The rate of returned questionnaires was 55%. The results of this survey were published as an article in European Radiology (Brix03).

The most interesting question was how MSCT exposure compares with SSCT practice. To answer this question, the average values of the 1999 SSCT survey were used for benchmarking purposes. In order to characterise the dose level by a single value only, the unweighted mean of all 14 standard CT examinations was used. The dose descriptors are the volume CTDI ($CTDI_{vol}$) and the dose-length product per examination (DLP_{exam}).

The relative dose level of all MSCT scanners in terms of $CTDI_{vol}$ was slightly below the mean value of all scanners participating in the '99 survey (fig. 1). While two-slice scanners were found at about 65%, four-slice scanners were operated at the same level as the average SSCT scanner. With DLP_{exam}, the results were similar, but slightly higher owing to the somewhat increased average scan length of examinations carried out with MSCT scanners. These results indicated that there was no dramatic increase in patient exposure following the introduction of MSCT technology as it might have appeared from the studies mentioned above, in which well optimized SSCT protocols were compared to MSCT exposure settings at the begin of their optimization process.

However, as MSCT scanners represent state-of-the-art technology, a comparison with advanced SSCT scanners (i.e. spiral scanners with solid-state detectors) is more appropriate. The typical factory settings of these scanners, when benchmarked in the same fashion, result in overall dose levels of about 65%. The same dose levels were found on average for the users of two-slice scanners in this survey. Compared to this more relevant reference, the overall dose level of four-slice scanners based on DLP per examination was increased by a factor of 1.7. While two-slice scanners (which were in use much longer) were operated at an acceptable dose level, there was obviously a need for the optimization of four-slice scanner protocols.

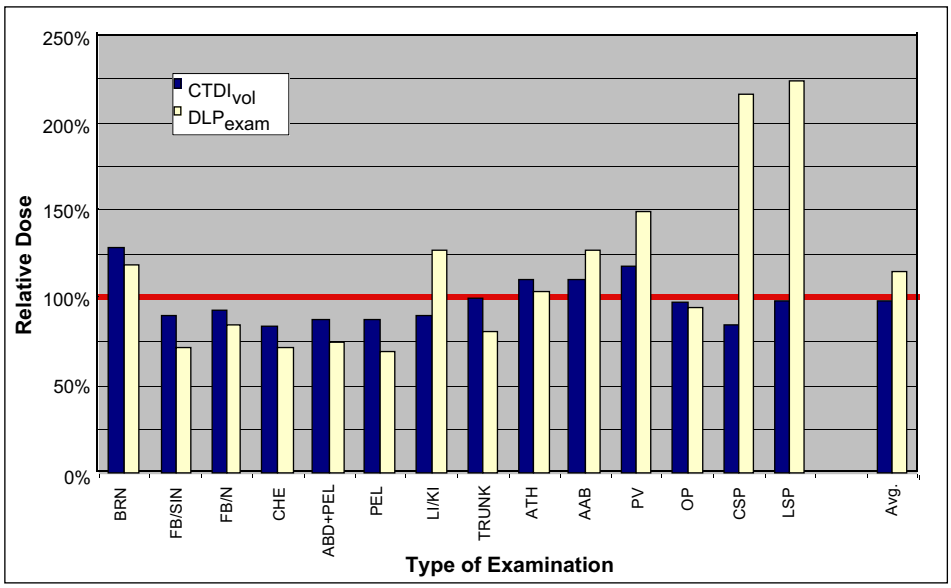

Fig. 2 *Relative dose levels of each particular type of examination, with 100% (red line) being the average value of the German '99 SSCT survey for the corresponding dose descriptor and type of examination. The most significant dose increases were observed for brain, liver/kidneys, CTA, and spine examinations (for abbreviations see tab. 1).*

A closer look at the relative dose levels of each particular type of examinations provides a first indication of the reasons for this (fig. 2). The most significant dose increases were observed for routine brain, liver / kidneys, CT angiography (CTA), and spine examinations. The following circumstances are most likely to explain this increase:

- The majority of participating scanners employed reduced beam filtration in head scanning mode, resulting in increased tube output per mAs. This does not hold for most single-slice scanners.
- In examinations of liver or kidneys, both the average values of scan length and number of scan series were somewhat increased.
- In CTA, the average scan length was also somewhat increased; the main reason, however, was the increase in local dose to compensate for the higher noise levels owing to the selection of much thinner slices.
- In spine examinations, the average scan length had increased considerably, as now there was a clear preference to scan the entire spine section (cervical spine, lumbar spine) instead of selected segments only.

Primarily, four causes have been identified as being responsible for the somewhat increased dose levels associated with the use of four-slice scanners:

- Preference for thinner slices ('isotropic voxels'): Both average slice collimation (h_{col}) and reconstructed slice thickness (h_{rec}) were significantly smaller compared to SSCT practice (2.4 and 4.4 mm vs. 6.4 mm). Obviously, many users felt the need to compensate for the increased noise associated with thinner slices by increasing the dose settings. This, however, can be avoided by accounting for the enhanced contrast of smaller details, as demonstrated in (Wedeg04/1). In addition, overbeaming became a major dose handicap for users of four-slice scanners (note that the overbeaming parameter dz of the majority of quad scanners installed in Germany was comparatively small; therefore the impact of overbeaming might have been even higher in other countries where the spectrum of scanner models differed from Germany).
- Reduced beam filtration in head scanning mode with increased output in terms of dose per mAs, which was not known to the users of these scanners.
- mAs per slice conception: The adaptation of the true (electrical) mAs product to changes in pitch settings was made automatically on the majority of MSCT scanners installed in Germany, so patient dose was no longer reduced with pitch settings above 1. This conception was rarely understood in 2002 (and is still not familiar to a larger number of CT users). As a consequence, users intuitively underestimated the dose in these cases.
- A lack of transparency, resulting from the pitch definition ('volume pitch') used on the majority of MSCT scanners at that time, and an unaccustomed presentation of scan parameters to the user.

3.3 German Paediatric CT Survey in 2005/06

The nation-wide German survey of exposure practice in paediatric CT was conducted in Germany during the period September 2005 to May 2006 by the Medical University Hannover (MHH) on behalf of the ministry for environmental protection, conservation and nuclear safety (BMU). The survey was based on questionnaires that were first sent to 1640 CT facilities in hospitals and private practices, asking for the frequencies of five types of examination, subdivided into five age groups (up to 15 years). In a subsequent second phase, a selected number of 72 users, accounting for about two thirds of the annual paediatric CT examinations reported in phase I, were asked for detailed dose-relevant data. These data were used for dose assessments, depending on the type of scanner and age of the patient. Data evaluation was made in a fashion similar to the two preceding surveys in Germany, with some modifications for the assessment of effective dose based on the data from (Khursheed02)

With return rates of 40% in the first phase and 58% in the second phase of the survey, representative results could be obtained for the five most frequent types of paediatric CT examination. These are documented in a comprehensive report (Galanski07). The most essential results from this survey are listed in tab. 2. Average dose values are reported in terms of all the relevant dose descriptors, thus allowing comparisons with other published data. Moreover, average values for examination-related parameters, such as scan length, pitch factor and number of scan series per examination, are also listed. Conclusions that can be drawn from this study are:

- The fraction of paediatric CT examinations was in the order of only 1% of all CT and thus much smaller than elsewhere (6% on average (UNSCEAR00)).
- The most frequent type of examination was brain (52%), followed by chest (17%) and entire abdomen (7%); other types of examination were quite rare (each less than 5%).
- The age distribution for paediatric CT examinations was almost uniform (40% in the group 0 to 5 years, 28% in the group 6 to 10 years, 32% in the group 11 to 15 years).
- The majority of paediatric CT examinations were conducted in university facilities and with the latest CT technology (multi-slice spiral scanners with solid state detectors and dose display, often also equipped with devices for automatic dose control).
- Exposure settings were generally adapted to the age or

Tab. 2 *Results from the German survey on paediatric CT exposure practice 2005/06 (Galanski07). Average values per scan series for 5 age groups and 5 standard CT examinations are listed in terms of CT-relevant dose descriptors (volume CTDI ($CTDI_{vol}$), dose-length product (DLP) and effective dose (E_{ser})), all per scan series, along with information on some examination-related parameters (net scan length L_{net}, pitch factor, number of scan series per examination). In addition, values of effective dose E_{exam} per examination are also given. For children up to ten years, $CTDI_{vol}$ and DLP are stated both for the 16 cm head phantom (dose-relevant) and the 32 cm body phantom (as displayed at the scanner's console: n.a. = not applicable). Effective dose refers to the organ weighting scheme of ICRP 60 (ICRP91).*

Age Group	Type of Examination	L_{net} (cm)	Pitch	Series (Phases)	$CTDI_{vol16}$ (mGy)	DLP_{16} (mGy·cm)	$CTDI_{vol32}$ (mGy)	DLP_{32} (mGy·cm)	E_{ser} (mSv)	E_{exam} (mSv)
Newborn	Routine Brain	9.8	1.0	1.0	21.9	227	n.a.	n.a.	2.3	2.3
	Facial Bone/Sinuses	8.3	1.4	1.0	10.9	137	n.a.	n.a.	1.3	1.3
	Routine Chest	10.1	1.3	1.0	3.6	46	2.0	25	1.9	1.9
	Abdomen+Pelvis	14.2	1.2	1.1	4.2	71	2.3	39	3.5	3.8
	Lumbar Spine	8.3	1.3	1.0	7.5	90	4.3	52	4.4	4.4
Up to 1 Year	Routine Brain	10.7	1.0	1.0	26.2	302	n.a.	n.a.	2.2	2.4
	Facial Bone/Sinuses	7.3	1.2	1.0	7.7	68	n.a.	n.a.	0.5	0.5
	Routine Chest	12.3	1.2	1.0	5.4	77	2.8	40	2.1	2.2
	Abdomen+Pelvis	19.6	1.2	1.2	6.2	148	3.3	79	4.8	5.7
	Lumbar Spine	9.7	1.1	1.0	23.7	297	12.7	160	11.3	11.3
2 to 5 Years	Routine Brain	11.9	1.0	1.1	35.7	452	n.a.	n.a.	1.9	2.0
	Facial Bone/Sinuses	9.1	1.1	1.0	10.8	116	n.a.	n.a.	0.5	0.5
	Routine Chest	16.4	1.2	1.0	6.1	116	3.2	61	2.5	2.5
	Abdomen+Pelvis	25.1	1.2	1.1	7.9	219	4.1	115	5.4	6.4
	Lumbar Spine	11.1	1.2	1.0	21.9	279	11.7	151	7.9	7.9
6 to 10 Years	Routine Brain	12.8	1.0	1.0	43.7	582	n.a.	n.a.	2.0	2.1
	Facial Bone/Sinuses	9.8	1.2	1.0	13.2	147	n.a.	n.a.	0.5	0.5
	Routine Chest	20.4	1.2	1.0	8.5	194	4.5	102	2.9	3.0
	Abdomen+Pelvis	29.0	1.2	1.2	10.7	342	5.6	180	5.8	6.8
	Lumbar Spine	11.7	1.1	1.0	28.3	383	15.2	208	7.6	7.6
11 to 15 Years	Routine Brain	13.9	1.0	1.1	53.2	764	n.a.	n.a.	2.2	2.4
	Facial Bone/Sinuses	11.4	1.2	1.0	15.4	201	n.a.	n.a.	0.6	0.6
	Routine Chest	26.0	1.2	1.0	n.a.	n.a.	6.2	180	3.3	3.4
	Abdomen+Pelvis	35.9	1.2	1.2	n.a.	n.a.	8.3	328	6.7	8.8
	Lumbar Spine	15.9	1.0	1.0	n.a.	n.a.	16.7	294	6.9	6.9

weight of the patients.

- On average, the adaptation was made in a moderate fashion that is in accordance with specific studies on this topic (e.g. Honnef04, Morgan02, Rogalla04) and tailored more with respect to radiologists' impression of subjective noise than to measured image noise.
- Devices for automatic dose control (ADC) were available on roughly 50% of the scanners, but were not regularly used; compared with manually adapted dose settings, dose values resulting from the use of ADC devices were slightly to significantly higher.
- Patient-size dependent adaptation of exposure settings resulted in a significant dose reduction in terms of $CTDI_{vol}$; with respect to effective dose, however, dose was reduced to a lesser extent or even not at all if the increased risk for induction of malignant tumours in children and newborn was taken into account.

Proposals have been made for diagnostic reference levels that refer to the third quartiles of the observed dose distributions of this survey. In addition, feedback was given to all participants of the survey in such a way that the doses resulting from their scan protocol settings could be benchmarked against the proposed reference dose values.

3.4 NEXT CT Survey in 2000

The NEXT CT survey in 2000 (Stern07) was conducted in the United States almost at the same time as the German survey '99, i.e. based on comparable scanner technology. The survey was organized nation-wide as a representative random sample, comprising 265 facilities (out of an estimated total of 7000 facilities, i.e. 4%) operating 340 scanners (out of an estimated total of 9000 scanners), about 20% of them being MSCT scanners. The average examination frequency was much larger than in Germany (160 vs. 90 annual CT examinations per 1000 inhabitants). Dose assessment was made in a fashion similar to the German CT survey, but with the aid of the ImPACT CT patient dosimetry calculator (ImPACT10). With a few exceptions only, the results in terms of volume CTDI and DLP per examination were not much different from the

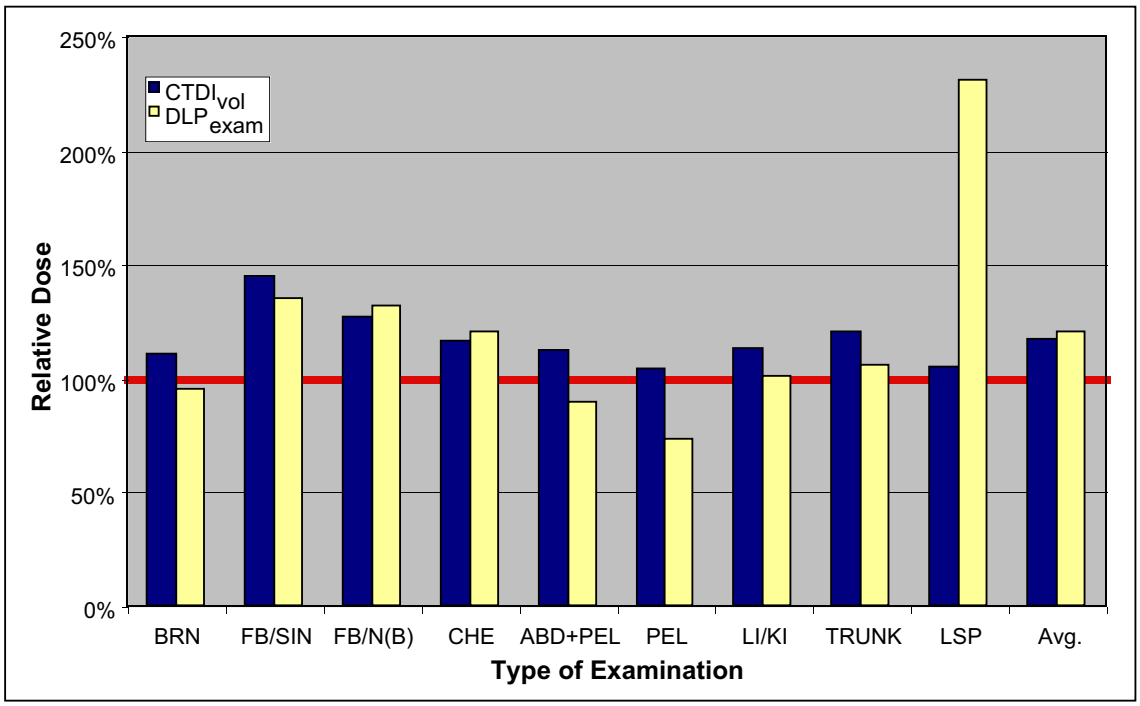

Fig. 3 *Comparison of the results of the NEXT 2000 CT survey with those of the '99 German CT survey. Relative dose values are given for each type of examination in terms of volume CTDI per scan/rotation ($CTDI_{vol}$) and dose-length product per examination (DLP_{exam}). The red line at 100% represents the average of the '99 German CT survey for the pertaining type of examination and dose descriptor (for abbreviations see tab. 1, (B)=body mode).*

'99 German survey (fig. 3). While the dose settings in terms of $CTDI_{vol}$ where slightly higher (by about 15%), relative DLP values differed to a higher degree due to differences in scan length and scan series (phases), with the most apparent difference in the scan length of lumbar spine examinations. On average, DLP per exam was also somewhat higher than in the German survey. According to the dose values reported in (Stern07), the average effective dose per examination (weighted mean) was 8.7 mSv. A reassessment with CT-Expo for a type of scanner with characteristics that are typical for the actual generation of scanners (Philips Tomoscan AV series), using the average exposure settings as stated in the NEXT report, lead to 10.7 mSv. Although this difference is within the error margins of effective dose assessment, it highlights the problem of comparing the results of surveys in terms of effective dose assessed with different methods, which are mainly due to differences in the mean conversion coefficients f_{mean}.

Although the fraction of MSCT scanners in the 2000 NEXT survey was stated as 20%, no distinction was made between single- and multi-slice scanners in the dosimetric data. Hence a dedicated comparison with the NEXT survey for MSCT practice is not possible.

Except for examination frequencies, no specific protocol data were collected for paediatric CT practice in the 2000 NEXT survey. The ratio of paediatric to adult CT examinations was stated as 0.065, i.e. 6.5% of all CT examinations were performed on children (compared to only 1% in Germany). However, it was not stated whether this figure refers to children up to 10 or up to 15 years.

3.5 UK 2003 Survey

The 2003 UK survey (Shrimpton05) was conducted in the United Kingdom as a nation-wide survey by the National Radiological Protection Board (NRPB) in collaboration with the CT users group and the CT evaluation facility ImPACT. The survey involved data collection for a sample of national practice with voluntary data submission (126 out of 471 scanners, i.e. 27%), comprising standard protocols and actual data for individual patients, for a total of 6 types of examination. All of the participating scanners had spiral capability; 37% of them were MSCT scanners. The survey also included data for paediatric CT (three age groups).

For the purpose of comparison with the '99 German survey (fig. 4), only data from single- and dual-slice scanners were taken into account . With the exception of routine brain examinations, the average $CTDI_{vol}$ level amounts to approximately 60% of that in Germany, presumably due to the disappearence of non-spiral scanners in the UK survey and the longer history of CT dose reduction efforts in the UK. The average DLP per examination amounts to only 50% of the German level, mainly due to the lower number of scan series (i.e. phases), as the fraction of mul-

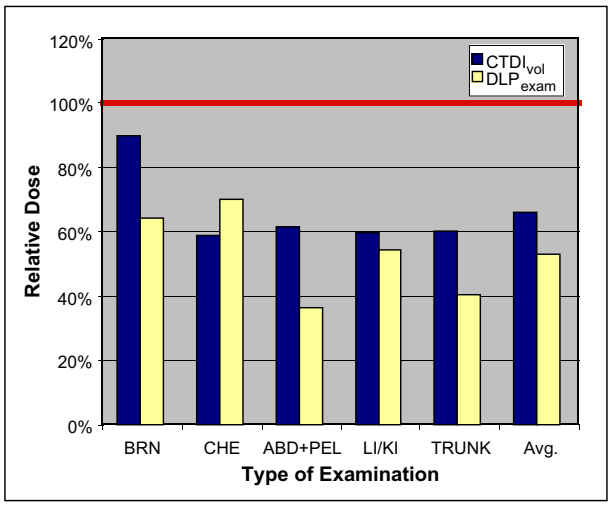

Fig. 4 *Comparison of the results of the 2003 UK CT survey (single- and dual-slice scanners) with those of the '99 German CT survey. Relative dose values are given for each type of examination in terms of volume CTDI per scan/rotation ($CTDI_{vol}$) and dose-length product per examination (DLP_{exam}). The red line at 100% represents the average of the '99 German CT survey for the pertaining type of examination and dose descriptor (for abbreviations see tab.1).*

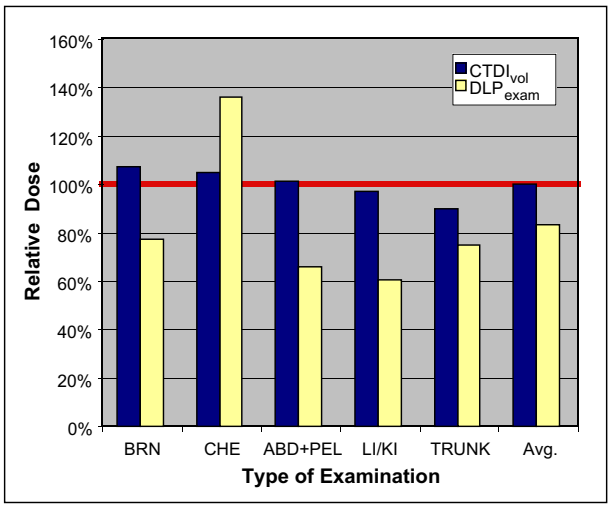

Fig. 5 *Comparison of the results of the 2003 UK CT survey (multi-slice scanner fraction) with those of the German MSCT survey in 2002. Relative dose values are given for each type of examination in terms of volume CTDI per scan/rotation ($CTDI_{vol}$) and dose-length product per examination (DLP_{exam}). The red line at 100% represents the average of the German MSCT survey in 2002 for the pertaining type of examination and dose desciptor (for abbreviations see tab. 1).*

tiphasic examinations in the UK was comparably low.

Effective dose values were assessed using generic mean conversion coefficients independent from the type of scanner that were derived from own Monte-Carlo simulations for general use (Shrimpton04). As with DLP, effective doses were also much lower than the German values. However, the underlying mean conversion coefficients were significantly smaller (15% on average) than the ones obtained with CT-Expo on average. If a correction is made for this systematic difference, the mean effective dose was about 50% lower than in Germany. So the average effective dose per examination is estimated to about 4.3 mSv compared to 8.1 mSv in Germany.

A separate evaluation was made for the 37% fraction of multi-slice scanners with 2 and more slices acquired simultaneously. A comparison of the dose levels with those from the German MSCT survey 2002 is shown in fig. 5. Contrary to the comparison made for single-slice scan-

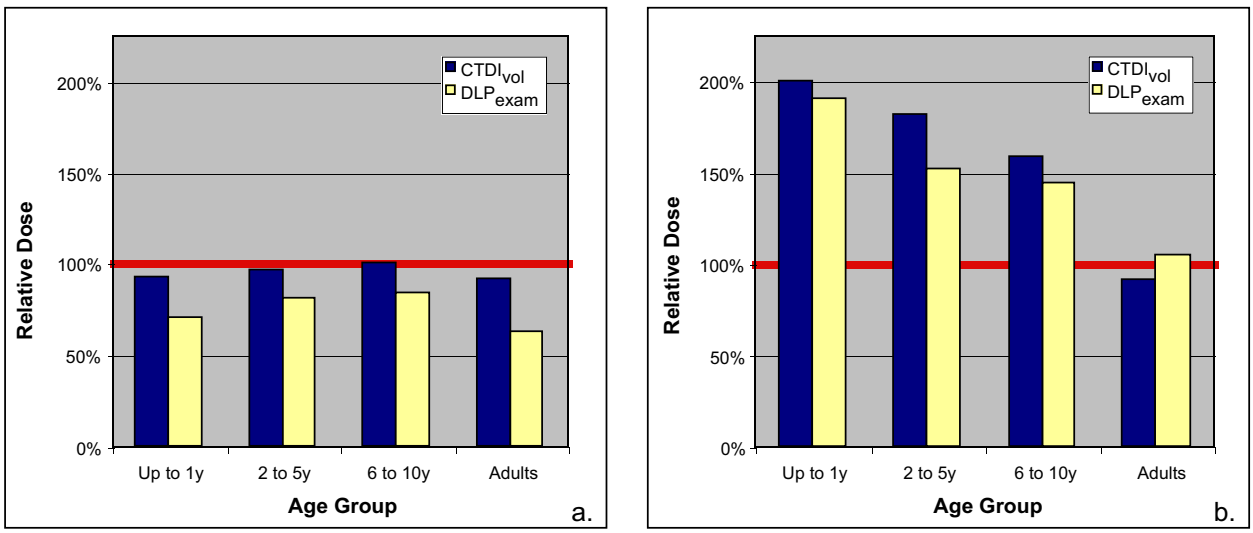

Fig. 6 *Comparison of the results of the 2003 UK CT survey with those of the German paediatric CT survey 2005/06. Relative dose values are given for each age group in terms of volume CTDI per scan/rotation ($CTDI_{vol}$) and dose-length product per examination (DLP_{exam}) for examinations of the head (a.) and the chest (b.). The red line at 100% represents the average of the German paediatric CT survey in 2005/06 for the pertaining age group and dose descriptor (adult data refer to the German MSCT survey 2002).*

ners (fig. 4), the average dose in terms of $CTDI_{vol}$ was almost identical. Except for chest examinations, however, the DLP per examination was significantly lower, which was once again mainly due to differences in the frequency of multi-phasic examinations.

In the 2003 UK CT survey data have also been collected on the dose settings used in paediatric CT examinations, although this included only brain and chest examinations and less age groups (up to 1 year, 2 to 5 years and 6 to 10 years). For examinations of the brain (fig. 6a), $CTDI_{vol16}$ values and their age/weight dependence were quite similar in both surveys. Values of DLP per examination found in the German survey were somewhat higher, which is mainly due to differences in scan length; for adults, differences in the number of scan series (phases) accounted in addition. For examinations of the chest (fig. 6b), $CTDI_{vol32}$ values were significantly higher in the UK survey, and the dose adaptation to body weight was less pronounced; the same pattern held true for DLP per examination. Data on examination frequencies were not collected in the UK 2003 survey, so the fraction of paediatric CT remains unknown.

4. Multi-Centre CT Optimization Study

When the German *Concerted Action Dose Reduction in CT* was founded, one of the highest priorities was given to the assessment of optimized dose settings for a number of standard CT examinations that could commonly be agreed upon. For this purpose, a multi-centre optimization study was conducted by Hannover Medical University, with 12 different facilities (4 universities, 4 large-scale hospitals, 4 private practices) and 32 radiologists (2 - 3 at each facility) participating, distributed all over Germany in order to achieve a representative consensus.

4.1 Study Layout

The principle of finding optimized dose settings is illustrated in fig. 7. When starting with non-optimized dose settings, a reduction of the dose will not change the diagnostic quality until a point is reached where diagnostic confidence will significantly be impaired. The layout of such studies must provide

- a selection of identical images with different dose settings, with the graduation made in equal factors, not in equal steps;
- a sufficient number of observers to avoid any bias,
- criteria for assessment of diagnostic confidence and
- definition of the level of diagnostic confidence that is regarded as sufficient to solve the clinical question.

In this study, patient images acquired with an advanced single-slice spiral scanner with solid-state detector (CT/i, GE Medical Systems) for four types of examination (chest, abdomen+pelvis, liver/kidneys, and pelvis (soft tissue)) were modified to simulate different dose settings without repeated exposure of the patients. This was achieved by retrospectively processing the raw data in such a way that artificial noise was added to the measured data, using the

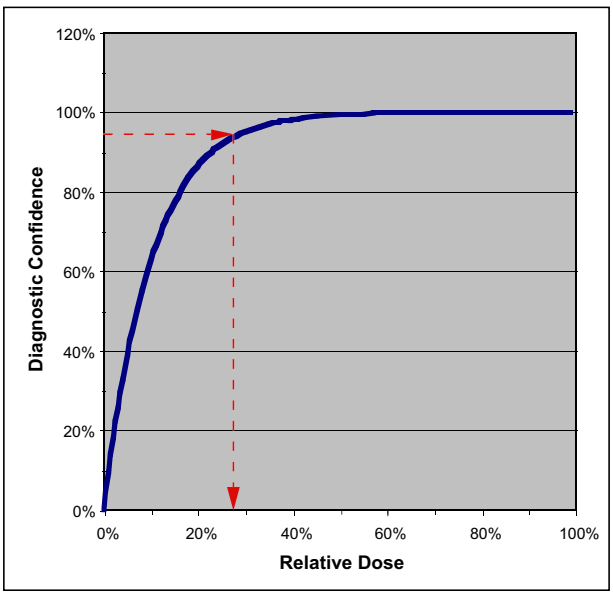

Fig. 7 *Assessment of optimized dose levels (principle) by evaluating the diagnostic confidence for identical images acquired (or simulated) with different dose settings.*

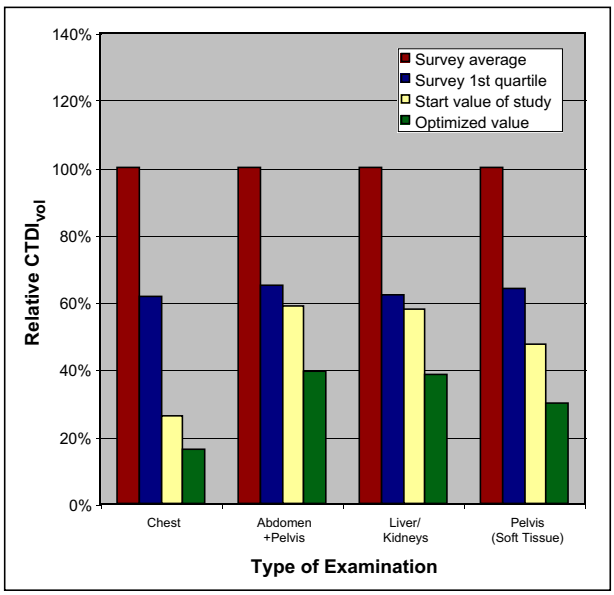

Fig.8 *Illustration of the results of the multi-centre optimization study given in tab. 3 in terms of relative $CTDI_{vol}$ (100% = average of the '99 German CT survey).*

Tab. 3 *Absolute and relative dose values in terms of volume CTDI ($CTDI_{vol}$) after optimization compared to the average and 1st quartile values of the German '99 CT survey and the start values of the multi-centre optimization study. Optimized values refer to an average score of 4 on a 5-point scale (1=poor, 5=excellent).*

Type of Examination	Survey Average	Survey 1st Quartile		Start Value of Study		Optimized Value	
	[mGy]	absolute [mGy]	relative [1]	absolute [mGy]	relative [1]	absolute [mGy]	relative [1]
Chest	15.5	9.5	61%	4	26%	(1 -) 2.5 [2]	(6% -) 16%
Abdomen+Pelvis	17.9	11.6	65%	10.5	59%	7	38%
Liver/Kidneys	18.2	11.3	62%	10.5	58%	7	38%
Pelvis (Soft Tissue)	20.1	12.8	64%	9.5	47%	6	30%

[1] Reference (=100%): average of the German '99 CT survey 1999 for the pertaining type of examination

[2] the lower value of 1 mGy applies to high contrast indications only

experimental software ‚n_sim' supplied by GE Medical Systems. Phantom tests with real and simulated dose variations were made to verify the validity of this approach. So sets of identical images for each type of examination that differed only in the dose settings were presented to each of the participating radiologists and evaluated on a 5-point scale (1 = poor, 5 = excellent) according to a predefined catalogue of diagnostic criteria.

4.2 Results

The consolidated results of this study are summarized in tab. 3 and illustrated in fig. 8. The optimized values that refer to an average score of 4 on the 5-point scale ('image noise noticeable, but not disturbing') indicate that

- a dose reduction in terms of $CTDI_{vol}$ by a factor 2.5 to 3 in relation to the average value of the '99 German CT survey, is feasible with advannnced equipment without losing diagnostic confidence for clinical indications that require sufficient low-contrast resolution;
- even higher dose reductions are possible in clinical indications that are characterised by high contrast (such as lung parenchyma).

4.3 Conclusions from this Study

As a conclusion from this multi-centre optimization study, the 1st quartile values of the German CT survey in 1999 in terms of $CTDI_{vol}$ are well suited for the optimization of scan protocols of advanced scanners with spiral capability and solid state detectors. The dose level of 1st quartile values is about 35% lower than the corresponding average values, leaving room for additional dose reductions. For scanners without these technical features, the 3rd quartile values of the survey, which were the basis for the reference dose values and which are higher than the corresponding 1st quartile values by about a factor 2, should be regarded as an absolute upper limit except for obese patients and other difficult circumstances caused by the patient and the clinical indication.

5. Optimization Strategy

The optimization strategy consists of three steps:

- Registration and evaluation of the scan protocols;
- dose adjustment according to the scanner's capabilities;
- fine tuning according to the clinical question.

The strategy that is described in the following is primarily focussed on the optimization of the dose levels in terms of local dose (i.e. $CTDI_w$ or $CTDI_{vol}$). Beyond that, user-related parameters (scan length and number of scan series (phases)) need to be optimized, too, as they have impact on the integral radiation exposure of the patient (dose-length product and effective dose). However, these parameters are subject to clinical considerations or medical guidelines, so no explicit recommendations shall be given here. Nevertheless, average values from surveys ('99 German CT survey (Galanski01) and 2003 UK CT survey (Shrimpton05)) can be used for orientation.

5.1 Registration and Evaluation of the Scan Protocols

In step one, the dose-relevant parameters of all standard protocols that are used on the pertaining scanner must be registered; these are:

- The tube potential U (in kV);
- the current-time product Q (in mAs) per scan or rotation; alternatively: the tube current I (in mA) and the exposure (or rotation time) t (in s);
- the beam width $N \cdot h_{col}$ (in mm);

Tab. 4 *Recommended overall dose levels according to the technical specifications of the scanner. Relative dose levels refer to the average values for the types of examination assessed in the '99 German CT survey; they apply to $CTDI_w$ (single-slice scanners) or $CTDI_{vol}$ (multi-slice scanners) and DLP_{exam}.*

Scanner Specifications		Relative Dose Level	Remarks
Spiral CT	Detectors		
No	Gas	≤130%	Appr. 3rd quartile
No	Solid state[1]	≤100%	Survey average
Yes	Gas	≤100%	Survey average
Yes	Solid state[1]	≤65%	Appr. 1st quartile

[1] 4th generation scanners with only 1200 detectors same as scanners with gas detectors

- the table feed TF (in mm); alternatively: the pitch factor p;
- the reconstructed slice thickness h_{rec} (in mm);
- the scan length L (in cm), usually available as the difference of the positions of the first and the last slice of the scan series;
- the number of scan series (phases) n_{ser} per examination;
- the scanning mode (sequential/spiral; head/body).

From these data, the corresponding dose values must be assessed for all relevant dose descriptors (at least $CTDI_w$, $CTDI_{vol}$, and DLP_{exam}). The resulting values must then be benchmarked against the pertaining average values of the German '99 CT survey.

A questionionaire for registration of the required scan parameter data along with instructions for use can be found in the appendix.

5.2 Dose Adjustment for Scanner's Capabilities

If necessary, the dose settings ($CTDI_w$ or $CTDI_{vol}$ and DLP_{exam}) for each type of examination are adjusted in step two to a level that accounts for the technical capabilities of the scanner. As there exists no standardized performance parameter like 'dose efficiency', the type of detectors (gas or solid state) and the spiral capability (available or not) are used as dose relevant indicators, as expressed in tab. 4. Starting point is the average value of the German '99 CT survey (= 100%). As the majority of scanners in this survey were spiral scanners with gas detectors, the recommended dose level for this type of scanner is equal to the survey average. On average, solid state detectors are more dose efficient; depending on the quality of gas detectors (depth, gas pressure, thickness of entrance window), the gain in efficiency amounts to approximately 30% to 60%. Therefore, the adequate dose level for spiral scanners with solid state detectors is the 1st quartile of the survey (corresponding to about 65% of the survey average) for the pertaining type of examination. However, this does not hold for those 4th generation scanners equipped with 1200 detectors only. In order to achieve the required spa-

Tab. 5 *Recommendations for the additional dose adjustment ($CTDI_w$ or $CTDI_{vol}$) beyond the appropriate level according to the scanner's specifications (see tab. 4).*

Type of Examination	Code	Recommended Dose Level [1]	Remarks
Routine Brain	BRN	According to scanner specifications [2]	Low contrast
Facial Bones / Sinuses	FB/SIN	$CTDI_w$ = 1/3 BRN ((fractures) = 1/10 BRN(sinuses)	High contrast
Facial Bone+Neck (Body Mode)	FB+N(B)	$CTDI_w$ as abdomen	Low contrast, shoulder
Routine Chest	CHE	$CTDI_w$ as 2/3 abdomen	High contrast, less attenuation
Abdomen + Pelvis	ABD+PE	According to scanner specifications	Soft tisssue contrast
Pelvis (Soft Tissue)	PEL	$CTDI_w$ as 2/3 abdomen	Improved inherent contrast
Liver / Kidneys	LI/KI	$CTDI_w$ as abdomen	Soft tisssue contrast
Entire Trunk	TRUNK	$CTDI_w$ as 2/3 abdomen on average	Lungs, pelvis
CTA Thoracic Aorta	ATH	$CTDI_w$ as 2/3 abdomen (1/3 @ 80 kV)	Less attenuation, optimal contrast @ 80 kV
CTA Abdominal Aorta	AAB	$CTDI_w$ as abdomen (1/2 @ 80 kV)	Optimal contrast @ 80 kV
CTA Pulmonary Vessels	PV	$CTDI_w$ as 2/3 abdomen (1/3 @ 80 kV)	Less attenuation, optimal contrast @ 80 kV
Osseous Pelvis	OP	$CTDI_w$ as 1/3 abdomen	High contrast
Cervical Spine (Disks)	CSP(DI)	According to scanner specifications [2]	Low contrast (Disk), thin slices
Cervical Spine (Bone)	CSP(BO)	$CTDI_w$ as 1/3 CSP (Disk)	High contrast
Lumbar Spine (Disks)	LSP(DI)	According to scanner specifications [2]	Low contrast (Disk), thin slices
Lumbar Spine (Bone)	LSP(BO)	$CTDI_w$ as 1/3 LSP (Disk)	High contrast

[1] max. current reference value [2] increased dose values for neurological examinations independent from type of scanner if image quality not satisfactory

tial resolution, the detectors are partially masked with lead strips. Due to the reduced geometric efficiency, such a scanner must be treated like a scanner with gas detectors. Finally, scanners without spiral capability are usually elder scanners with gas detectors of minor efficiency. The recommended dose level for these scanners is 130%, which approximately corresponds to the pertaining 3rd quartile values of the survey. Dose adjustment for $CTDI_w$ (single-slice scanners) or $CTDI_{vol}$ (multi-slice scanners) is made by altering the mAs settings and - if indicated - the tube potential. Adjustment for the DLP is made via the pitch (single-slice scanners only), the scan length, and the number of scan series (phases).

The reason behind the different treatment of single- and multi-slice scanners ($CTDI_w$ vs. $CTDI_{vol}$) is due to differences in spiral interpolation. As image noise does not depend on pitch for single-slice scanners, $CTDI_w$ is the appropriate dose descriptor for this type of scanner; pitch-related effects are then accounted for at the level of DLP. For multi-slice scanners, image noise depends on the pitch unless mAs settings are adapted accordingly; therefore $CTDI_{vol}$, i.e. the pitch-corrected $CTDI_w$, is the relevant dose descriptor for MSCT scanners.

5.3 Fine Tuning According to the Clinical Indication

Step three consists of an additional adjustment of the dose settings that accounts for the special circumstances of the pertaining type of examination that have not been sufficiently considered in the average and quartile values of the survey. How this additional adjustment should be made is outlined in tab. 5. and shall be described and justified in the following.

The optimization strategy summarized in tab. 3 is based on an analysis of the scan protocols of selected participants of the survey. This approach is supported by recommendations given in the survey report (Galanski01), the multi-centre (MC) optimization study (Galanski04), ICRP publications 87 (ICRP01) and 102 (ICRP07), by the results of the UK survey (Shrimpton05), and scientific publications dealing with dose optimization for specific types of examination.

- Starting point for additional dose adjustments in the trunk region is the abdomen + pelvis examination (ABD+PEL). This type of examination is quite frequent and is characterized by a high integral radiation exposure as well as relatively high requirements for low-contrast resolution (soft tissue contrast). The dose settings should therefore remain at the level that has been adjusted in step 2 according to the scanner's specifications. This is in agreement with the results of the multi-centre optimization study.
- Types of examination characterized by similar requirements for image quality and/or similar attenuating properties should be made with the same dose settings as ABD+PEL. This applies to liver/kidneys (LI/KI, see MC optimization study), facial bone/neck (FB/N), and CTA abdominal aorta (AAB). The dose for neck examinations needs to be relatively high because the shoulder (high attenuation) is included; if feasible, the neck region should be scanned in two steps, with reduced dose settings above the shoulder. In CTA of the abdominal aorta, significant dose reductions (up to 50%) are possible by applying a lower tube potential.
- Neurological indications of the brain (BRN) and the spine (CSP, LSP) require a very good contrast resolution. Dose optimization should be made according to the technical capabilities of the scanner (see e.g. (Gündogdu05) for cranial CT), but no additional dose adjustment should be made. Increased dose settings (however not beyond the reference value) might be necessary independent from the type of scanner if image quality is otherwise not sufficient.
- The reduced attenuation in the chest region allows for significant dose reductions (see MC optimization study) in particular if a wide window setting is used for viewing (lung window). However, to achieve a sufficient quality in the mediastinum and in the lung apices, dose adjustment should only be made to a level that is 35% below that for ABD+PEL. The same applies to CTA examinations in the chest region (thoracic aorta (ATH) and pulmonary vessels (PV)); additional dose reductions (down to 25% of the ABD+PEL level) are possible in CTA by applying a lower tube potential. Much larger adjustments (down to 10 - 20% of the local dose for ABD+PEL) should be made for dedicated high-contrast chest indications (see MC optimization study); for this purpose, an additional scan protocol should be set up.
- Examinations of the pelvis for soft tissue indications (PEL) profit from an increased inherent contrast (skeleton, bladder, colon), so the dose settings can be adjusted to 2/3 of the ABD+PEL level (see ICRP01). The same dose level should be applied on average for examinations of the entire trunk (TRUNK); if feasible, this region should be scanned in three steps, each adjusted for the pertaining section (chest, abdomen, pelvis).
- The osseous pelvis (OP) represents a high-contrast indication that allows for a larger dose adjustment (1/3 of the ABD+PEL level, see (ICRP 01)) that normally is sufficient for an adequate image quality (Wedeg04/2); however, this does not hold for metal implants (e.g. hip joint) with their increased attenuation that requires higher dose settings. The same applies to spine examinations for all other than neurological indications, with separate protocols set up for these purposes.

- Contrary to the brain, the region facial bone/sinuses incorporates a number of clinical indications that are characterized by a higher inherent contrast and viewed with wide window settings. This allows for a significant dose adjustment (Lorenzen05). Two different protocols should be set up, for fractures with 1/3 of the BRN, for sinuses with 1/10 of the BRN dose settings.

The conception outlined here has repeatedly been applied by the author himself to optimize the protocol settings on scanners from different vendors and has been confirmed by positive feedback from their users.

6. Software-assisted Protocol Optimization

6.1 Appropriate Software Tools

Dose optimization of scan protocols can significantly be simplified by using appropriate software tools. The CT-Expo software (Stamm02) is such a tool, as it allows for a quick evaluation of the dose levels (benchmarking) once the relevant parameters have been entered. The software also assists in identifying the potential reasons if dose levels should be unusually high. And finally, dosimetric results are instantaneously provided if parameters are changed during the optimization process.

In the following an example is given how the optimization strategy outlined in the preceding section can be applied with CT-Expo. For this purpose a dedicated module ('Benchmarking') is available. In order to make use of this module, the complete set of parameters listed in section 5.1 is required. Dose values ($CTDI_{vol}$, DLP) that were obtained from the scanner's console alone are not sufficient, as they don't allow identifying the reasons behind dose values that are above average.

6.2 A Practical Example

The example presented here to demonstrate the potential of computer-assisted dose optimization refers to a participant of the '99 German CT survey who operated an advanced single-slice spiral scanner with solid state detectors. Benchmarking of the scan protocols (step 1) results in dose levels in terms of $CTDI_w$ and DLP_{exam} that are slightly above 100%, both on average and for most types of examination (fig. 9 and 10), with 100% being the average of the '99 German CT survey for each type of examination and dose descriptor. Although most values are well below the reference value level (at about 130%), there is a need for optimization, as the adequate dose level for this type of scanner is 65% only (corresponding to the 1st quartile of the survey).

A closer look at the benchmark diagrams for the most relevant parameters (fig. 11 a to d) reveals that the values for scan length (fig. 11a) and number of scan series (fig. 11c) are not unusual and that the selected slice thicknesses (fig. 11d) do not give rise for unduly increased dose settings. Merely the pitch settings (fig. 11b) are unusual in that they were selected as 1 (except for facial bone/neck), while users of single-slice spiral scanners typically apply pitch settings of 1.5 (except for examinations of the brain and the spine, which are predominantly made in sequential scanning mode on SSCT scanners). So the pitch setting is identified as the first reason.

The second reason requires a closer look at the scan parameters (fig. 9): For most scan protocols the selected tube potential is 140 kV. Presumably, these settings were preferred by the user in the belief of saving dose (as accustomed from conventional projection radiography). If this should hold true, this user was not aware that - at that point in time - CT scanners were not equipped with automatic devices that could adapt the mAs settings accordingly. Thus the improved penetration of 140 kV settings was not used for the benefit of the patient. Instead, without mAs adjustment, the output of the x-ray tube is simply increased. In addition, 140 kV settings are by far not optimal in examinations with iodine as contrast agent.

6.3 Protocol Optimization

In step 2 (fig. 12), the protocols are modified as follows:

- All settings for tube potential are changed to 120 kV;
- mAs settings are adjusted until the relative $CTDI_w$ value for the pertaining type of examination amounts to about 65% of the survey average;
- the pitch settings are adjusted to approximately 1.5 (except for BRN, CSP and LSP) by maintaining the table feed and reducing the slice collimation.

These measures already lead to a significant reduction of the average dose levels: from 104% to 65% for $CTDI_w$ and from 109% to 51% for DLP_{exam}. The average effective dose now amounts to only 4.5 mSv compared to 10.2 mSv (-57%).

In step 3 (fig. 13), the mAs settings are fine-tuned as outlined in section 5.3. In addition, the kV settings are modified from 120 to 80 kV for all CTA examinations. These measures result in an additional reduction of the average

Standard Examination		Scan Parameters											Dose Values				Relative Values *			
Name	Abbr.	U [kV]	I [mA]	t [s]	Q_{eff} [mAs]	h_{eff} [mm]	TF [mm]	h_{rec} [mm]	p	L [cm]	Ser.	Spiral Mode	$CTDI_w$ [mGy] (per Scan)	$CTDI_{eff}$ [mGy]	DLP_w [mGy*cm] (per Examination)	E [mSv]	$CTDI_w$ (in % of Survey Average)	$CTDI_{eff}$	DLP_w	E
	Example	*120*	*200*	*1.5*	*300*	*10*	*12*	*10*	*1.2*	*10*	*1*									
Routine Brain	BRN	140	206	1.5	309	8	8	8	1	11.5	1	☐	64.0	64.0	787	2.2	112%	114%	80%	80%
Facial Bone / Sinuses	FB/SIN	120	170	1.5	255	5	5	5	1	9.6	1	☑	37.2	37.2	395	1.1	91%	101%	88%	89%
Facial B.+Neck (Head)	FB+N(H)											☐								
Facial B.+Neck (Body)	FB+N(B)	120	50	1.5	75	3	6	3	2	19	1	☑	6.2	3.1	63	0.5	29%	17%	16%	17%
Routine Chest	CHE	140	240	0.75	180	10	10	10	1	31	1	☑	21.6	21.6	711	12.9	117%	140%	141%	153%
Routine Abdomen (tot.	ABD+PE	140	240	0.75	180	10	10	10	1	37	1.5	☑	21.6	21.6	1261	23.6	103%	121%	102%	111%
Routine Pelvis	PEL	140	240	0.75	180	10	10	10	1	20	1	☑	21.6	21.6	474	8.9	93%	107%	75%	82%
Liver / Kidneys	LI/KI	140	240	0.75	180	10	10	10	1	17	2	☑	21.6	21.6	819	15.9	101%	119%	133%	144%
Whole Trunk	TRUNK	140	240	0.75	180	10	10	10	1	68	1	☑	21.6	21.6	1509	27.9	113%	136%	102%	110%
CTA Thoracic Aorta	ATH	140	240	0.75	180	10	10	10	1	23	1	☑	21.6	21.6	539	10.3	120%	154%	124%	134%
CTA Abdominal Aorta	AAB	140	240	0.75	180	10	10	10	1	25	1	☑	21.6	21.6	582	11.1	115%	147%	115%	125%
Pulmonary Vessels	PV	140	240	0.75	180	8	8	8	1	16	1	☑	21.6	21.6	379	7.5	124%	161%	163%	175%
Osseous Pelvis	OP	140	240	0.75	180	10	10	10	1	22	1	☑	21.6	21.6	517	10.0	74%	81%	87%	95%
Cervical Spine (Head)	CSP(H)											☐								
Cervical Spine (Body)	CSP(B)	140	206	2	412	2	2	2	1	4	1	☐	49.3	49.3	207	2.6	135%	140%	144%	155%
Lumbar Spine	LSP	140	206	2	412	3	3	3	1	7.2	1	☐	49.3	49.3	370	8.0	126%	128%	158%	170%
													Effective dose E refers to ICRP 60							
Average (unweighted!)		137	214	1.1	220	7.8	8.0	7.8	1.1	22.2	1.1		28.6	28.4	615	10.2	104%	119%	109%	117%

Fig. 9 *Step 1: Benchmarking of the scan protocols of a participant in the '99 German CT survey (SSCT spiral scanner with solid state detectors). Although the average dose level is not much above the survey average, most of the protocols need optimization (adequate dose level for this type of scanner: 65%; for terminology see section 5.1).*

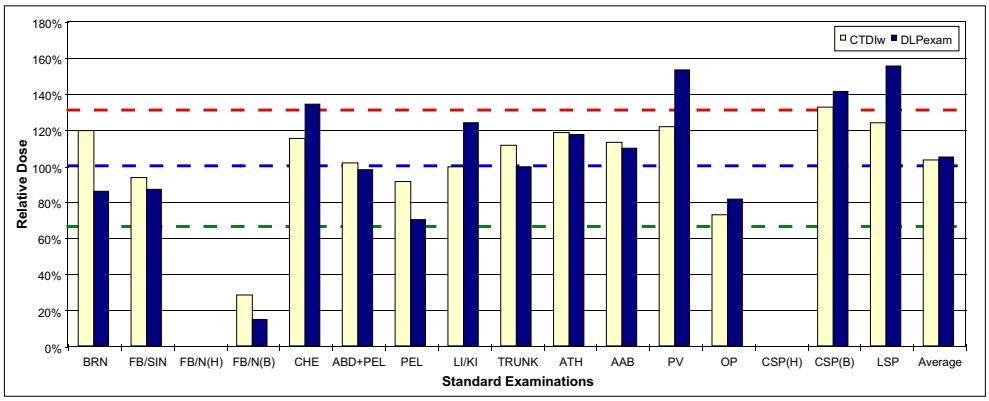

Fig. 10 *Illustration of the relative dose levels from fig. 9 in terms of $CTDI_w$ and DLP_{exam} (for abbreviations see fig. 9) Dashed lines refer to the 3rd quartile (130%, average (100%), and 1st quartile (65%) of the survey .*

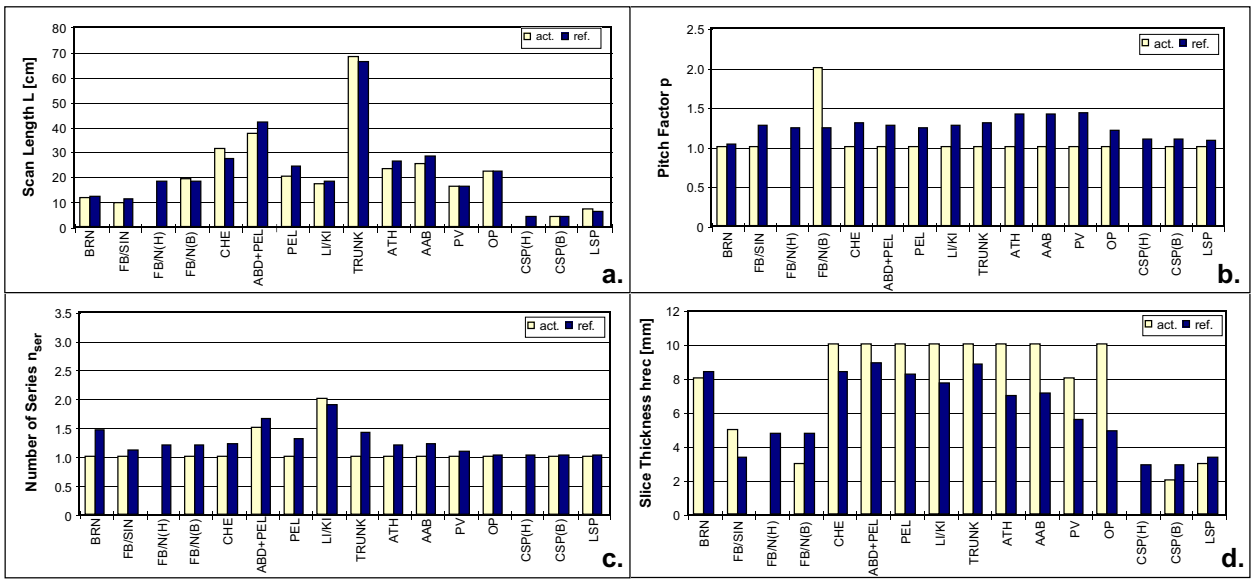

Fig. 11 *Benchmark diagrams for the most relevant parameters: scan length L (a.), pitch factor p (b.), number of scan series n_{ser} (c.) and slice thickness h_{rec} (d.) from tab. 4 (act. = actual values; ref. = survey average).*

Standard Examination		Scan Parameters											Dose Values				Relative Values *			
Name	Abbr.	U [kV]	I [mA]	t [s]	Q_{eff} [mAs]	h_{eff} [mm]	TF [mm]	h_{nom} [mm]	p	L [cm]	Ser.	Spiral Mode	$CTDI_{vol}$ [mGy] (per Scan)	$CTDI_{eff}$ [mGy]	DLP_{exam} [mGy*cm] (per Examination)	E [mSv]	$CTDI_{vol}$ (in % of Survey Average)	$CTDI_{eff}$	DLP_{exam}	E
Example		*120*	*200*	*1.5*	*300*	*10*	*12*	*10*	*1.2*	*10*	*1*									
Routine Brain	BRN	120	170	1.5	255	8	8	8	1	11.5	1	☐	37.2	37.2	458	1.3	65%	66%	47%	47%
Facial Bone / Sinuses	FB/SIN	120	125	1.5	188	3	5	3	1.67	9.6	1	☑	27.4	16.4	174	0.5	67%	45%	39%	39%
Facial B.+Neck (Head)	FB+N(H)											☐								
Facial B.+Neck (Body)	FB+N(B)	120	110	1.5	165	3	5	3	1.67	19	1	☑	13.7	8.2	164	1.2	65%	45%	42%	45%
Routine Chest	CHE	120	195	0.75	146	7	10	7	1.43	31	1	☑	12.1	8.5	280	5.1	66%	55%	55%	60%
Routine Abdomen (tot.	ABD+PE	120	220	0.75	165	7	10	7	1.43	37	1.5	☑	13.7	9.6	561	10.5	66%	54%	45%	49%
Routine Pelvis	PEL	120	240	0.75	180	7	10	7	1.43	20	1	☑	14.9	10.5	230	4.3	64%	52%	36%	40%
Liver / Kidneys	LI/KI	120	220	0.75	165	7	10	7	1.43	17	2	☑	13.7	9.6	364	7.1	64%	53%	59%	64%
Whole Trunk	TRUNK	120	200	0.75	150	7	10	7	1.43	68	1	☑	12.5	8.7	610	11.3	65%	55%	41%	45%
CTA Thoracic Aorta	ATH	120	180	0.75	135	7	10	7	1.43	23	1	☑	11.2	7.8	196	3.8	63%	56%	45%	49%
CTA Abdominal Aorta	AAB	120	200	0.75	150	7	10	7	1.43	25	1	☑	12.5	8.7	235	4.5	66%	59%	47%	50%
Pulmonary Vessels	PV	120	180	0.75	135	5	8	5	1.6	16	1	☑	11.2	7.0	123	2.4	64%	52%	53%	57%
Osseous Pelvis	OP	120	300	0.75	225	7	10	7	1.43	22	1	☑	18.7	13.1	314	6.1	64%	49%	53%	57%
Cervical Spine (Head)	CSP(H)											☐								
Cervical Spine (Body)	CSP(B)	120	145	2	290	2	2	2	1	4	1	☐	24.1	24.1	101	1.3	66%	68%	70%	76%
Lumbar Spine	LSP	120	155	2	310	3	3	3	1	7.2	1	☐	25.7	25.7	193	4.2	66%	67%	82%	89%
													Effective dose E refers to ICRP 60							
Average (unweighted!)		120	189	1.1	190	5.7	7.9	5.7	1.4	22.2	1.1		17.8	13.9	286	4.5	65%	55%	51%	55%

Fig. 12 *Step 2: Adjustment of the $CTDI_w$ values for the scan protocols given in fig. 9 to the level appropriate for the type of scanner (i.e. 65%). Adjustment was made by changing the values for tube potential U, tube current I, and pitch (for terminology see section 5.1). On average, the dose level was reduced by about a factor 2.*

Standard Examination		Scan Parameters											Dose Values				Relative Values *			
Name	Abbr.	U [kV]	I [mA]	t [s]	Q_{eff} [mAs]	h_{eff} [mm]	TF [mm]	h_{nom} [mm]	p	L [cm]	Ser.	Spiral Mode	$CTDI_{vol}$ [mGy] (per Scan)	$CTDI_{eff}$ [mGy]	DLP_{exam} [mGy*cm] (per Examination)	E [mSv]	$CTDI_{vol}$ (in % of Survey Average)	$CTDI_{eff}$	DLP_{exam}	E
Example		*120*	*200*	*1.5*	*300*	*10*	*12*	*10*	*1.2*	*10*	*1*									
Routine Brain	BRN	120	170	1.5	255	8	8	8	1	11.5	1	☐	37.2	37.2	458	1.3	65%	66%	47%	47%
Facial Bone / Sinuses	FB/SIN	120	60	1.5	90	3	5	3	1.67	9.6	1	☑	13.1	7.9	84	0.2	32%	21%	19%	19%
Facial B.+Neck (Head)	FB+N(H)											☐								
Facial B.+Neck (Body)	FB+N(B)	120	110	1.5	165	3	5	3	1.67	19	1	☑	13.7	8.2	164	1.2	65%	45%	42%	45%
Routine Chest	CHE	120	150	0.75	113	7	10	7	1.43	31	1	☑	9.3	6.5	216	3.9	51%	42%	43%	46%
Routine Abdomen (tot.	ABD+PE	120	220	0.75	165	7	10	7	1.43	37	1.5	☑	13.7	9.6	561	10.5	66%	54%	45%	49%
Routine Pelvis	PEL	120	150	0.75	113	7	10	7	1.43	20	1	☑	9.3	6.5	144	2.7	40%	33%	23%	25%
Liver / Kidneys	LI/KI	120	220	0.75	165	7	10	7	1.43	17	2	☑	13.7	9.6	364	7.1	64%	53%	59%	64%
Whole Trunk	TRUNK	120	150	0.75	113	7	10	7	1.43	68	1	☑	9.3	6.5	458	8.5	49%	41%	31%	33%
CTA Thoracic Aorta	ATH	80	250	0.75	188	7	10	7	1.43	23	1	☑	4.6	3.2	81	1.6	26%	23%	19%	20%
CTA Abdominal Aorta	AAB	80	350	0.75	263	7	10	7	1.43	25	1	☑	6.5	4.5	123	2.3	35%	31%	24%	26%
Pulmonary Vessels	PV	80	250	0.75	188	5	8	5	1.6	16	1	☑	4.6	2.9	51	1.0	27%	22%	22%	24%
Osseous Pelvis	OP	120	75	0.75	56	7	10	7	1.43	22	1	☑	4.7	3.3	78	1.5	16%	12%	13%	14%
Cervical Spine (Head)	CSP(H)											☐								
Cervical Spine (Body)	CSP(B)	120	145	2	290	2	2	2	1	4	1	☐	24.1	24.1	101	1.3	66%	68%	70%	76%
Lumbar Spine	LSP	120	155	2	310	3	3	3	1	7.2	1	☐	25.7	25.7	193	4.2	66%	67%	82%	89%
													Effective dose E refers to ICRP 60							
Average (unweighted!)		111	175	1.1	177	5.7	7.9	5.7	1.4	22.2	1.1		13.5	11.1	220	3.4	48%	41%	38%	41%

Fig. 13 *Step 3: Fine tuning of the $CTDI_w$ values for the scan protocols in fig. 12 to the level appropriate for the type of examination as outlined in tab. 5. The overall dose reduction, compared to the inial protocols, is about a factor 3.*

dose level to 48% ($CTDI_w$) and 38% (DLP_{exam}); the average effective dose is further reduced from 4.4 mSv to 3.4 mSv.

Both scan length and the number of scan series have not been modified, as the corresponding values were already in good agreement with the survey average. Nevertheless, it is always worthwhile considering a reduction of both parameters, at least for a fraction of patients where this can be justified.

6.4 Results

By adjusting the scan protocol setting to a level that is adequate for advanced spiral scanners with solid state detectors and by additional fine-tuning, the average dose for the pertaining scanner has been reduced by factor 2.2 in terms of $CTDI_w$ and by factor 2.9 in terms of DLP_{exam}. As the latter is the decisive dose descriptor for the radiation exposure, protocol optimization has lead to a reduction of patient dose by a factor of almost 3 in this particular case.

7. Additional Aspects

7.1 Optimization of Multi-Slice Scanners

The optimization of multi-slice scanners follows the same strategy, with three exceptions, however:

- Instead of $CTDI_w$, the recommended levels for local dose apply to $CTDI_{vol}$ for the reasons already discussed in section 5.2.
- Due to the modified role of pitch, the selection of pitch factors is no longer made with respect to dose, but merely to scan speed and reduction of artefacts.
- As the reconstructed slice thickness h_{rec} is no longer necessarily identical to the slice collimation h_{col} used for data acquisition, the optimization needs to be made with respect to the slice thickness used for diagnosis.

In addition, overranging effects in spiral mode, which were almost negligible in SSCT, need to be taken into account. This applies in particular to examinations with short scan ranges (i.e. spine studies), where it might be preferable not to use the maximal available, but rather a reduced beam width setting. However, this should not be smaller than 10 mm to avoid unduly large overbeaming effects.

7.2 Optimized Dose Settings

Dose settings in absolute terms that result from the recommendations in this guideline are listed in tab. 6. They apply to single- and multi-slice spiral scanners that are equipped with solid-state detectors. Elder scanners with gas detectors or without spiral capabilities require higher dose settings as indicated in tab. 4.

7.3 Adaptation to Patient Size

The recommendations given until here apply to normal and slightly oversized patients (up to BMI 27, but less than 85 kg). Oversized patients require higher dose settings, whereas slim patients can afford less dose. To meet these needs for adults, it is recommended to set up three sub-protocols with different dose settings for each type of examination in the trunk range if the scanner is not equipped with devices for automatic exposure control. Compared to the values given in tab. 6, the dose settings for 'obese' protocols are increased by 40%, while being reduced by 30% for 'slim' protocols. The selection of the appropriate sub-protocol is later made according to the operator's assessment of the patient's habitus. A selection based on BMI or body weight, although more promising, is not better in practice, as both parameters represent the actual attenuating properties only roughly. In the head range, differences in attenuation are comparably small; hence adaptation to patient size it is not necessary.

7.4 Protocol Optimization with Automatic Dose Control

At present, two alternative designs for automatic dose control (ADC) exist that require different strategies for protocol optimization:

- 'Adequate noise systems' with pre-selection of dose (via 'reference mAs' or else) as provided by Philips or Siemens, and
- 'constant noise systems' with pre-selection of image quality (via 'noise index' or else) that can be found in GE's and Toshiba's scanners.

Protocol optimization for 'adequate noise' ADC systems can be accomplished in the same way as for scanners without ADC by using the recommended settings in tab. 6 as 'reference mAs'. Normal sized patiens will then be exposed with these values; for over- or undersized patients the adaptation is made in an infinitely variable fashion. With doubling the mAs by a factor 2 for a difference in tissue-equivalent diameter of between 6 and 10 cm, depending on the type of scanner and the selected ADC characteristic, the adaptation to patient size is more gentle than for constant noise ADC systems that already double the mAs for a difference of almost 4 cm. This 'adequate noise' lay-out is in agreement with relevant studies (e.g. Wilt-

Tab. 6 *Recommended dose settings that apply to single- and multi-slice scanners equipped with solid-state detectors and to normal and slightly oversized patients.*

Type of Exam	Code	SSCT $CTDI_w$ (mGy)	MSCT $CTDI_{vol}$ (mGy)
Routine Brain	BRN	50 [1]	50 [1]
Facial Bones	FB	17 [1]	17 [1]
Sinuses	SIN	5 [1]	5 [1]
Facial Bones+Neck	FB+N	14 [2] (28 [1])	10 [2] (20 [1])
Routine Chest	CHE	9 [2]	7 [2]
Abdomen + Pelvis	ABD+PE	14 [2]	10 [2]
Pelvis (Soft Tissue)	PEL	9 [2]	7 [2]
Liver / Kidneys	LI/KI	14 [2]	10 [2]
Entire Trunk	TRUNK	9-14 [2]	7-10 [2]
CTA Thoracic Aorta	ATH	9 [2] (5 [3])	7 [2] (4 [3])
CTA Abd. Aorta	AAB	14 [2] (8 [3])	10 [2] (6 [3])
CTA Pulm. Vessels	PV	9 [2] (5 [3])	7 [2] (4 [3])
Osseous Pelvis	OP	5 [2]	4 [2]
Cerv. Spine (Disks)	CSP(DI)	25 [2] (50 [1])	25 [2] (50 [1])
Cerv. Spine (Bone)	CSP(BO)	10 [2] (20 [1])	10 [2] (20 [1])
Lumb. Spine (Disks)	LSP(DI)	25 [2]	25 [2]
Lumb. Spine (Bone)	LSP(BO)	10 [2]	10 [2]

[1] CTDIvol16 in head mode [2] CTDIvol32 in body mode [3] @ 80 kV

Routine/ initial procedures	Weight	Noise Index	Minimum mA	Maximum mA	kV	Pink Zone
	0-20 lbs = 0-9 kg	5	65	130	80	
	21-60 lbs = 9.1-27.2 kg	7	80	160	100	
	61-100 lbs = 27.3-45.4 kg	10	95	190	120	
	101-200 lbs = 45.5-90.7kg	12	110	220	120	
	>200 lbs = >90.8 kg	15	125	300	120	

Fig. 14 *Recommendations published by GE (GE09) on how to adapt the pre-selection of noise index as well as minimum and maxium mA settings to patient size (applying to a rotation time of 0.8 s).*

ing01), demonstrating that there is a significant difference between the objective (measured) noise and the radiologist's subjective noise perception when diagnosing images of differently sized patients.

With 'constant noise' ADC systems, protocol optimization is much more complex for the following reasons:

- First of all as a consequence of the need to pre-select noise levels, for which a consensus comparable to dose reference levels does not exist up to now, in combination with the lack of an prospective dose display. Compliance of the selected settings with dose recommendations cannot be verified unless at least 10 examinations have been performed on an almost representative selection of patients.
- Secondly due to the regulation characteristic that is much too steep. This has already been pointed out in a number of publications (e.g. Brisse07, Schindera08). As a consequence, one of the pertaining manufacturers (GE09) has meanwhile released recommendations how to adapt the pre-selection of noise index to patient size (see. fig. 14). Except for the possibility to continue using angular and/or longitudinal dose modulation, this workaround is nothing but a manual adaptation of exposure settings to patient size as described in section 6.3. As a consequence of the steep characteristic, the regulation range must additionally be restricted by setting lower and upper limits for the tube current.
- Thirdly due to the inherent strategy that attempts to maintain image noise when parameters like slice thickness, tube voltage and reconstruction filter are modified. As these parameters not only affect image noise, but also image contrast, positive implications (improved contrast) that often require less or no dose adaptation at all are not taken into account.

From our own experience, the pre-selection of noise indices that result in image noise of 12 HU (abdomen and neck region) and 15 HU (chest region) are in fair agreement with the dose values recommended in this guideline for the following conditions: 120 kV tube voltage, 5 mm slice thickness, and standard reconstruction filter. Under different circumstances, the noise index needs to be modified, taking the changes in image contrast into account. For this purpose, a profound knowledge of the properties of the pertaining ADC system are essential. Up to now, however, there is a lack of literature that supplies this information in sufficient depth (with a few exceptions, such as (Nagel10/2) and (Gosch10)).

As the AEC (automatic dose control) functionality only provides a dose adaptation, dose reductions are thus not achieved. Use of additional ADC functionalities (angular and/or longitudinal dose modulation), however, results in reductions of up to 40%, depending on the scanned region of the body.

8. Recommendations for Paediatric CT

In order to ensure that paediatric CT examinations are carried out in a dose-optimised fashion, the following recommendations that reflect the results from the German paediatric CT survey 2005/06 (Galanski07) should be observed.

8.1 Choice of Equipment

If possible, paediatric CT examinations should be performed on advanced, dose-efficient scanners (spiral scanners with solid-state detectors) only. Multi-slice (MSCT) scanners are advantageous insofar as these allow much shorter scan times compared with single-slice scanners.

8.2 Selection of Tube Potential

Tube voltage settings below 110 kV should be used only if the range of mAs settings is not sufficient to achieve the reduced dose settings desired (e.g. chest examinations on newborn and infants). Otherwise, the standard voltage setting for the particular scanner (between 110 and 130 kV) should be applied.

8.3 Beam Collimation on MSCT Scanners

For paediatric examinations and their associated short scan ranges, a beam width (total collimation) of between 10

Age group	Relative $CTDI_{vol16}$ setting	
	Brain	Facial bone/sinuses
Newborn	45%	15%
< 1 y	55%	18%
2 - 5 y	65%	22%
6 - 10 y	85%	28%
11 - 15 y	100%	33%
> 15 y	100%	33%

Tab. 7 *Age-adapted relative mAs values for paediatric CT examinations of the head region. Starting point (=100%) is the optimised mAs setting for brain examinations on adults, which corresponds to a $CTDI_{vol16}$ of not more that 60 mGy.*

Body weight (kg)	Age (appr.)	Relative $CTDI_{vol32}$ setting		
		Abdomen (w. pelvis)	Chest	Spine
0 - 5	0 - 3 m	10%	7%	25%
6 - 10	4 m - 1 y	17%	10%	50%
11 - 20	2 - 5 y	30%	20%	75%
21 - 40	6 - 12 y	50%	33%	125%
41 - 60	13 - 18 y	75%	50%	200%
61 - 80	>18 y	100%	65%	250%

Tab. 8 *Weight-adapted relative mAs values for paediatric CT examinations of the trunk region. Starting point (=100%) is the optimised mAs setting for abdomen examinations on adults, which corresponds to a $CTDI_{vol32}$ of not more that 15 mGy.*

and 24 mm is optimal. Smaller beam width settings should be avoided, since the patient's exposure will increase excessively due to overbeaming effects (i.e. the portion of the beam not used for imaging). In spiral scanning mode, a much wider beam width should also be avoided since overranging effects (i.e. the consequence of extra rotations) will inevitably become more pronounced.

8.4 Pitch Factor

For single-slice scanners, spiral scans should be made with an increased pitch of 1.5, resulting in a corresponding dose reduction. However, for multi-slice scanners that achieve their mAs settings in terms of 'effective mAs' or 'mAs per slice' (i.e. MSCT scanners from Elscint, Philips and Siemens), dose is no longer affected by the pitch setting, since any modification in the pitch factor is associated with a corresponding adjustment of the electrical mAs product. For these particular scanners, the pitch factor is modified for other reasons (scan speed, reduction of artefacts). In contrast, multi-slice scanners from GE and Toshiba achieve their mAs settings in terms of 'electrical mAs' (similar to single-slice scanners); therefore increased pitch settings will reduce the patient's dose, but at the expense of an increased image noise. Particular attention should be paid if pitch settings below 1 are used for these types of scanner, since the overlapping scans will result in increased dose unless the electrical mAs settings are manually adapted (i.e. reduced). A look at the scanner's dose display (increasing $CTDI_{vol}$ values at pitch settings < 1) reveals whether this aspect is of importance.

8.5 Dose Adaptation

The adaptation of dose settings according to age or body weight should be made in a moderate fashion (factor ±2 for each 8 cm difference in effective body diameter for examinations of the trunk region). The data given in tabs. 7 and 8 can be used to create sets of age- or weight-adapted scan protocols.

8.6 Automatic Dose Control

Automatic dose control should be used only if these devices are designed to provide a moderate dose adaptation. The default dose setting ('reference mAs') for the particular type of examination must be below the reference value for adults and should meet the level appropriate for the type of scanner used. Purely noise-based ADC devices are difficult to handle owing to both their regulation characteristic (mAs factor ±2 per 4 cm difference in effective diameter) and their settings (pre-selection of image quality instead of dose). Therefore manual dose adaptation as described above should be preferred.

8.7 Dose Display

Up to now all scanners display the $CTDI_{vol}$ that relates to the larger body phantom ($CTDI_{vol32}$) if the scan is made in body scanning mode, regardless of the body size. As a consequence, reference values based on $CTDI_{vol32}$ must be used for optimisation purposes (in CT-Expo, $CTDI_{vol16}$ values are used for infants and children of 7 years that allow for the assessment of realistic organ doses). This might change in the future, however, if the dose display is made to refer primarily to the diameter of the scanned body region and not to the scan mode.

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A.1 Questionnaire for the Registration of Scan Protocols

Name of facility	Manufacturer of scanner	Type of ccanner	In operation since
			Month:
			Year :

Contact person for queries (1)	
Phone or e-mail address	

Examination parameters			Scan parameters									Reconstruction & display					Dose indication (14)	
Type of examination	Scan range (approximate) from - to		L (2) [cm]	n_{ser} (3)	U [kV]	I (4) [mA]	t_R (5) [s]	N (6)	h_{col} (7) [mm]	TF (8) [mm]	Spiral? (9)	h_{rec} (10) [mm]	RI (11) [mm]	FK (12)	Window (13) Level	Window (13) Width	$CTDI_{vol}$ [mGy]	DLP_{exam} [mGy · cm]
Routine brain (15)	Vertex to skull base	Brain																
		Posterior fossa																
Facial bone / sinuses (16)	Superior margin of frontal sinus to occlusial plane	Fracture																
		Sinuses																
Facial bonel / neck (17)	Superior margin of frontal sinus to inferior margin of thyorid gland	Neck range																
		Shoulder range																
Routine chest	C7/T1	Sinus																
Abdomen incl. pelvis (18)	Diaphragm to pubic symphysis	Non-contrast series																
		Contrast series																
Pelvis	Inferior extremity of kidney	Pubic symphysis																
Liver / kidneys	Diaphragm	Inferior extremity of kidney																
Entire trunk (19)	C7/T1 to pubic symphysis	Tumour staging																
		Polytrauma																
CTA thoracic aorta	Clavicula	Diaphragm																
CTA abdominal aorta	Diaphragm	Hiop joint																
CTA pulmonary vessels	Clavicula	Diaphragm																
Osseous pelvis	Iliac crest	Ischial tuberosity																
Cervical spine (20)	Dependent on number of segments	Disks																
		Fractures																
Lumbar spine (20)	Dependent on number of segments	Disks																
		Fractures																

Please note:

1. All specifications should refer to standard examinations.

2. Use a separate questionnaire for each of the facility's scanners.

3. Please follow the explanations given in the instruction sheet.
Numbers in brackets (..) refer to this sheet.

Filter kernel (FK)	Code (12)
Very smooth	VSM
Smooth	SMO
Slightly smooth	LSM
Standard	STD
Slightly sharp	LSH
Sharp	SHA
Very sharp	VSH
Special filter	SPF

Specification for mA(s) (4)	
Please indicate:	
mA or	
mAs ?	
True (electrical) mA(s) or	
effective mA(s) (4b) ?	
Fixed mA(s) or	
automatic dose control (4c,d) ?	

A.2 Instructions for Use of the Questionnaire

(1) Nominate a contact person for eventual queries.

(2) Specify the approximate length of the scan range (in cm!), not the length of the scan projection radiograph made for planning purposes! For most scanners the length refers to the difference in position of the first and the last slice. (Note: the anatomical margins should be used as a clue only).

(3) The number of series (n_{ser}) is defined here as the number of times which the same body section (or a part of it) is scanned. Scanning a region (e.g. entire trunk) in multiple sections (e.g. chest + upper abdomen + pelvis) is counted as 1 series. If the body region is only partially scanned in one of two series, specify a value between 1 and 2 that takes into account the different lengths of both scans. If the number of series varies according to the clinical indication, specify a value that corresponds to the average frequency (e.g. routine brain: 80% non-contrast, 20% without + with contrast = 1.25 series).

(4) In field 'I [mA]' specify the tube current (in [mA]) or the current-time product per scan or rotation (not the total mAs!). Specify in the box at the lower right corner of the sheet whether

a) the specification applies to the tube current (mA) or the current-time product (mAs);

b) the scanner displays true (electrical) or effective mAs (i.e. true mAs divided by pitch, also 'mAs per slice');

c) the scanner is equipped with a device for automatic dose control; in this case specify the mA(s) values for an average patient;

d) the scanner makes use of devices that additionally modulate the tube current (angular and/or longitudinal); in this case specify average mA(s) values for an average patient.

(5) t_R is the rotation (or exposure) time, not the total scan time.

(6) In field ‚N' specify the number of separate, non-overlapping slices that are acquired simultaneously per rotation.

(7) In field 'h_{col}' specify the slice collimation used for data acquisition.

(8) In field 'TF' specify the table feed (in [mm] per rotation, not the table speed (in [mm/sec]).

(9) In field 'Spiral' specify whether the scan was made in spiral (by 'Y') or in sequential scanning mode (by 'N').

(10) In field 'h_{rec}' specify the thickness of the reconstructed slices. If the reconstructed slices are not used for diagnosis but added up into thicker slices for this purpose, specify the thickness of the slices used for diagnosis instead.

(11) In field 'RI' specify the reconstruction interval, i.e. the distance between the reconstructed slices.

(12) In field 'FK' specify the filter kernel (reconstruction filter); do not use the vendor's terminology but one of the generic terms given in the box at the lower border of this sheet

(13) In field 'Window' specify the window settings (centre, width) that are routinely used.

(14) The majority of scanners should be equipped with a dose display (at least indication $CTDI_{vol}$, often also DLP); in field 'Dose indication' specify the values provided by the scanner in the units required in this questionnaire per scan/rotation ($CTDI_{vol}$) and for the entire examination (DLP_{exam}); if the scanner should display DLP per scan series only, the contributions from each series must be summed up.

(15) For 'Routine brain' make separate specifications for the (upper) brain and the posterior fossa region.

(16) For 'Facial bone/sinuses' make separate specifications for fracture and sinusitis.

(17) For 'Facial bone/neck' make separate specifications for the neck and the shoulder section.

(18) For 'Abdomen incl. pelvis' make separate specifications for the non-contrast and the contrast-enhanced series.

(19) For 'Trunk' make separate specifications for tumour staging and polytrauma.

(20) For spine examinations specify the length of the entire examination, not for a single segment only, and make separate specifications for disk an fracture protocols.