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Radiation Dose Optimization in CT Planning of Corrective Scoliosis Surgery.

A Phantom Study

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Key words: scoliosis, low dose helical CT, effective dose, dose reduction system (DRS)

SUMMARY – *The aim of the study was to explore the possibility of obtaining a helical CT scan of a long segment of vertebral column, optimally reduce the radiation dose, compare the radiation dose of the low dose helical CT with that of some of the CT protocols used in clinical practice and finally assess the impact of such a dose reduction on the image quality. A chest phantom was examined with a 16-slice CT scanner. Six scans were performed with different radiation doses. The lowest radiation dose which had no impact on image quality with regard to the information required for surgical planning of patients with scoliosis, was 20 times lower than that of routinely used protocol for CT examination of the spine in children (0.38 mSv vs 7.76 mSv). Patients with scoliosis planned for corrective spinal surgery can be examined with low dose helical CT scan. The dose reduction systems (DRS) available in modern CT scanners contribute to dose reduction and should be used.*

Introduction

Adolescent idiopathic scoliosis (AIS) most often affects adolescent girls. The prevalence of AIS exceeding a Cobb angle of 20 degrees is estimated to be in the range of 0.2 %¹. These patients are usually examined initially with lateral and posteroanterior (PA) radiograph. Subsequently the Cobb angle is measured on a single PA radiograph.

The continuous development and improvement of the corrective methods and implementation of new implants make it necessary to obtain a detailed anatomical map of an often large region of interest both before and after corrective spinal surgery. Preoperatively the surgeon needs a precise estimation of the degree of vertebral rotation in order to plan the correct insertion of transpedicular screws at different levels. Furthermore he/she needs information about the width as well as length of the pedicles, not seldom of up to 15 vertebral levels, in order to plan the suitable diameter of screws at various vertebral levels. As such in-

formation cannot be obtained from plain radiograph²; a CT examination of a large segment of the vertebral column is required. Performing such a CT examination of spine, according to CT protocols available in daily clinical practice that are aimed for morphological evaluation of the spine and investigation of different spinal pathology means exposing these young individuals to high radiation dose.

The present availability of multislice scanners and the possibility of reducing and individually adjusting the radiation dose by using the manufacturer's dose reduction system (DRS) (CareDose 4D, Siemens AG, Forchheim, Germany) have enabled us to tailor a very low radiation dose protocol which provides 3D information of relevant segments of the thoracic and lumbar spine. This tube current modulation system includes both angular modulation and z-axis modulation³ with the aim to automatically adapt the tube current to the patient's anatomic configuration and size together with an on-line controlled tube current modulation for each tube rotation⁴. The major aim of this

phantom study was to compare the radiation dose of the here proposed low dose 3D helical CT protocol with that of some of the CT protocols that are routinely used in clinical practice, before implementing this low dose CT protocol in clinical routine.

The other aims of this phantom study were to assess the impact of this optimal dose reduction on image quality and to find the dose level that still allows safe and reliable assessment of the required parameters such as measurement of pedicular width.

Materials and Methods

The anthropomorphic adult chest phantom (PBU-X-21; Kyoto Kagaku CO, Ltd, Kyoto, Japan) was used in this study (figure 1). It contains substitute materials for human soft tissues such as muscles and blood vessels. Bones are simulated by epoxy resins and calcium hydroxyapatite to achieve changes in contrast in the phantom images as in an actual human body.

The examinations were performed on a 16-slice CT scanner (SOMATOM Sensation 16, Siemens AG, Forchheim, Germany).

Following scout view, the phantom was examined with the following scans (table 1 shows scan parameters of every individual scan):

Scan 1: CT spine protocol recommended by the manufacturer for investigation of different spinal pathology in adults⁵.

Scan 2: CT spine protocol recommended by the manufacturer for investigation of different spinal pathology in children with fixed tube voltage of 120 Kv and tube current-time product depending on the body weight. In this study the tube current-time product was 140 mAs (130 mAs recommended by manufacturer for patients with body weight of 35-44 kg)⁵.

Scan 3: "Apical Neutral Vertebra" CT protocol (ANV-protocol). This protocol had been used in our institution to measure the degree of vertebral rotation prior to the planned corrective surgery and to measure the degree and derotation after surgery. It consists of four sequential slices of the apical vertebra (at the scoliotic apex), at the superior and the inferior end vertebra at either end of scoliotic curvature.

Scan 4: The low dose 3D helical CT protocol before applying the DRS.

Scan 5: The low dose 3D helical CT protocol taking advantage the DRS (*the here proposed low dose CT protocol*).

Scan 6: 3D helical CT protocol with the lowest possible radiation dose in our CT system.

For all helical scans, i.e. except scan number 3, the scan length was 36.5 cm. The number of vertebrae included in these scans was 15. Reconstructed slice thickness was 3 mm with increment of 3 mm. Scan number 2 (ANV-protocol) consisted of four sequential slices at the middle of each of the three vertebral bodies imaged (only 1.2 cm of each of the three vertebral bodies has been scanned).

The signal-to-noise ratio (SNR) expressed as the ratio of the mean pixel value (MPV) to the standard deviation (SD) of the pixel values, was estimated at the same level of the vertebral column (L1) for every single scan, using a one cm large region of interest (ROI).

A subjective evaluation of image quality was performed by two readers. All scans were read independently by two senior radiologists who were blinded to scan parameters with the aim of evaluating: (a) the ability of the scan to visualize the vertebral pedicles at different segments of the vertebral column and (b) the possibility of measuring the width of the pedicles. The readers were asked to grade the degree of evaluation reliability in every single scan as: (A) unreliable, (B) relatively reliable or (C) reliable.

For quantitative evaluation of the impact of dose reduction on image quality, 3 mm thick reformatted images from scan 1 (the highest radiation dose tested), from scan 5 (the here proposed low-dose CT protocol) and from scan 6 (the lowest possible radiation dose in our CT system) were blinded to all information related to scan parameters and sent to the Picture Archiving and Communication System (PACS, Agfa IMPAX). Since there was no vertebral rotation in the study phantom, the quantitative evaluation of the impact of dose reduction on image quality was limited to the measurement of the pedicular width. Two independent observers performed measurements of pedicular width of 28 pedicles in every scan (a total of 84 pedicular width measurements per observer and occasion). The same measurements were performed by one observer on two different occasions with a one week interval.

Statistical analysis was performed in SPSS 15. Twenty four paired sample T-tests were performed to explore the inter- and intraobserver variations between measurements done on scans 1, 5 and 6 as well as between measurements done within the same scan by two different observers and by the same observer at two

different occasions. The level significance was decided to be $P \leq 0.01$. The mean value for differences in measurements of pedicular width was expressed as the systematic error while the standard deviation of the aforementioned values was expressed as the random error.

MSCT Dosimetry

The effective mAs concept was introduced with the (SOMATOM Sensation 16, Siemens AG, Forchheim, Germany) MSCT. The effective mAs take into account the influence of pitch on both the image quality and the radiation dose and is defined as tube current-time product/pitch factor⁴. The effective mAs value was recorded for scan 5 i.e. scan with activated DRS (table 1).

$$E = E_{\text{DLP}} \cdot \text{DLP (mSv)}$$

Where E_{DLP} is the region-specific, DLP normalized effective dose (mSv/mGy.cm). General values of the conversion factor, E_{DLP} , appropriate to different anatomical regions of the patient (head, neck, chest, abdomen, pelvis) were taken from European commission 2004 CT Quality Criteria, Appendix A-MSCT Dosimetry⁶. This phantom study included the thoracic and abdominal regions and the conversion factor used was 0.018 (average of 0.019 for the chest and 0.017 for the abdomen).

The effective doses obtained from calculation of the data from this phantom study were compared with the effective doses which were calculated by using Monte Carlo simulation program WINDOSE 3.0 (Scanditronix Wellhöfer, GmbH; Germany).

Table 1 Scan parameters of all scans in the phantom study. The values marked in bold represent the scan parameters of the here proposed low dose CT protocol. Effective tube current-time product shown in column 6 is expressed as IQR mAs and effective mAs, respectively, in scan 5 taking advantage of DRS. (IQR mAs is the Image Quality Reference mAs). (*) Minor modification from the manufacturer's protocol (16x1.5 mm recommended by Siemens). The pitch is however the same as manufacturer's recommendation.

	<i>Slice collimation, mm</i>	<i>Rotation time, sec</i>	<i>Pitch</i>	<i>Tube voltage, Kv</i>	<i>Effective tube current-time product, effective mAs</i>
Scan 1	16×0.75*	0.75	0.75	120	300
Scan 2	16×0.75*	0.75	0.75	120	140
Scan 3	12×1.5	1	1	120	60
Scan 4	16×0.75	0.75	1.5	80	25
Scan 5	16×0.75	0.75	1.5	80	IQR mAs 25 Effective mAs 19
Scan 6	16×0.75	0.50	1.5	80	17

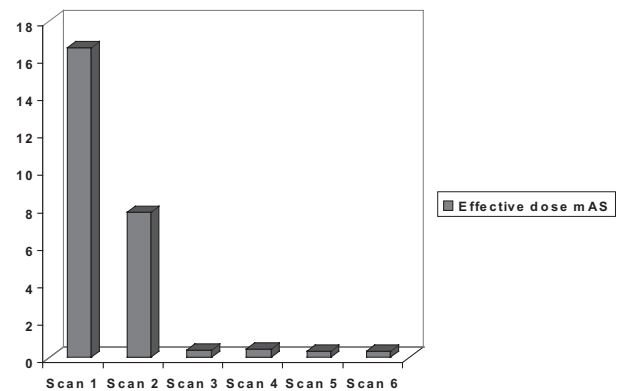
The volume CTDI (CTDI_{vol}) which is a derivative of the computed tomography dose index (CTDI) and the dose length product (DLP) was recorded for every scan included in this study. To allow comparisons with other type of radiological examinations, the effective dose (E) was determined.

The effective dose may be derived from values of DLP for an examination using appropriate conversion factors and the following equation:

Results

The results of measurements of CTDI_{vol} , DLP and the effective doses for scans 1 to 6 are shown in table 2 (columns 2-5). The effective doses of all scans are also shown in figure 2.

The effective dose (table 2, column 4) of the here proposed low-dose 3D helical scan taking advantage of the DRS (Scan 5) was 0.38 mSv which is 44 times lower than that of scan 1 (16.6 mSv), 20 times lower than that of scan 2



↑ Figure 2 The effective radiation dose for all scan settings (scans 1-6).

← Figure 1 The adult phantom used in this study was constructed to contain about 15 vertebral bodies, ribs, two lungs, trachea and soft tissue in the abdomen and in the thoracic and abdominal walls.

Table 2 Results of all scans in the phantom study show the CTDI_{vol}, DLP, mean effective dose, the absorbed dose to the breast and the genital organs as well as image quality (SNR). (*) refers to the estimated effective dose, the absorbed doses to the breast and to the genital organs according to Monte Carlo calculations WINDOSE 3.0. The values marked in bold represent the CTDI_{vol}, DLP, effective dose and the lowest absorbed dose to the breasts and the genital organs in the here proposed low dose CT protocol.

	CTDI _{vol} , mGy	DLP mGy.cm	Effective dose, mSv	Effective dose, mSv*	Absorbed dose to the breasts, mGy*	Absorbed dose to the genital organs, mGy*	SNR= MPV/SD
Scan 1	23.40	920	16.60	18.6	33.3	1.9	167/5
Scan 2	10.92	431	7.76	8.6	15.5	0.9	168/38
Scan 3	4.32	3×8=24	0.43	0.1+ 0.19+ 0.2=0.49	1.31	0.028	166/64
Scan 4	0.65	26	0.47	0.45	0.86	0.037	176/174
Scan 5	0.51	21	0.38	0.34	0.66	0.028	175/182
Scan 6	0.44	19	0.34	0.30	0.55	0.025	160/347

(7.76 mSv) and 12% lower than that of the scan 3/ANV-protocol (0.43 mSv). The latter merely provides few sequential images at only three vertebral levels. Applying the DRS has lowered the effective dose by 19% (from 0.47 mSv in scan 4 to 0.38 mSv in scan 5).

According to the Monte Carlo calculation (table 2, column 5) the effective dose of the here proposed low dose CT protocol of the spine (scan 5) was 0.34 mSv which is 55 times lower than that delivered by scan 1 (18.6 mSv), 25

times lower than that delivered by scan 2 (8.6 mSv) and 30% lower than that of the ANV-protocol (0.49 mSv).

The calculated absorbed dose to the breasts and the genital organs are shown in table 2, columns 6 and 7, respectively. In the CT protocol recommended by the manufacturer for investigation of spinal disease in children (scan 2), the absorbed dose to the breasts and the genital organs was 23 times and 32 times, respectively, higher than that of the here proposed

low-dose CT protocol (scan 5). In the ANV-protocol (scan 3) the absorbed dose to the breasts was twice as high as the here proposed low-dose CT protocol (scan 5) while the absorbed dose to the genital organs was the same in both scans (0.028 mSv).

The readers classified all images of scans 1 to 5 including those of the here proposed low dose CT protocol (scan 5) as reliable with respect to identification of the pedicles, and measuring their width. The overall image quality of scan 6 was classified as unreliable in the lower five vertebral levels and relatively reliable in the upper ten vertebral levels. Due to this difference in overall image quality of scan 6, the statistical test (paired sample T-test) was also performed separately for the lower five vertebral levels (i.e. 10 pedicles out of 28).

The results of the SNR (MPV/SD) calculations are shown in table 2, column 8. The fact that the SNR value of the here proposed low dose CT protocol (scan 5) was 35 times lower than that of scan 1 (with the highest radiation dose) does not seem to affect the reliability of the evaluation of the parameters required. Some examples of images from different scans of this study are shown in figure 3A-D.

The quantitative evaluation of the impact of dose reduction on image quality in scans 1, 5 and 6 is shown in table 3, which shows only the statistically significant results of paired sample T-tests. Five of the 24 performed paired sample T-tests resulted in statistically significant differences in pedicular width measurements. Scan 6 (with lowest possible dose in our CT system) was involved in all five paired tests, out of which three pairs involved differences in pedicular width measurements in the lower five vertebral levels.

Discussion

This study has shown that it would be possible to examine a large segment of the vertebral column (15 vertebrae) with a long helical 3D CT scan while exposing the patient to a markedly lower radiation dose than would do the CT scan performed according to protocols used in daily clinical practice or the previously used CT scan with sequential images over a very limited part of the vertebral column according to the ANV-protocol (table 2 and figure 2). The latter CT protocol merely enabled measurement of the degree of vertebral rotation (preoperatively) and degree of vertebral derotation (post-

operatively) whereas the low-dose helical CT of a considerably larger area of vertebral column gives, in addition, the opportunity to study its morphology. The fact that some pedicles at the apex of the scoliotic curvature can be merely 2-3 mm wide and may have to be subsequently excluded from transpedicular screw insertion makes the reliability of the measurements of pedicular width crucial in the preoperative planning.

Scan 6 (scan with the lowest possible dose in our CT system) is involved in all five paired comparisons with statistically significant differences in pedicular width measurements. This result is compatible with the two reader's subjective classification of images of scan 6 as relatively reliable and of those in the lower five vertebral levels as unreliable. In these five pairs involving scan 6, besides the statistical significance of the differences, the inter- and intraobserver random errors in measuring the pedicular width varied between 1.1 mm and 1.6 mm while the systematic error varied between 1.2 mm and 2.4 mm. The magnitude of the differences exceeding 1 mm also makes the results significant from the clinical point of view as they have a significant influence on the choice of appropriate screw diameter. Unlike the comparisons involving scan 6, none of the comparisons between scan 5 and scan 1 with respect to the inter- and intraobserver random error and the systematic error in measuring the pedicular width resulted in significant differences and were always less than 1 mm (not shown in table 3 because these results were statistically non significant). Taking these statistical findings into consideration, the parameters of the here proposed low dose helical CT protocol (table 1) are to be considered a cut-off value to which the radiation dose can be reduced with no significant impact on image quality required for planning of scoliosis surgery.

In the beginning of 1990s CT constituted about 2-3% of all radiological examinations⁷ and contributed to about 20-30% of the total radiation load from medical use of ionizing radiation⁸. Later reports increased the latter figure to about 50%^{6,9}.

In Germany an overview of MSCT examinations conducted in 2001 showed that the average effective dose to patients had changed from 7.4 mSv at single-slice to 5.5 mSv and 8.1 mSv at dual- and quad-slice scanners, respectively¹⁰. The annual per capita effective dose for the UK in 2001-2002 was estimated to be 0.38 mSv¹¹ and for the Dutch population in 1998 to be 0.59

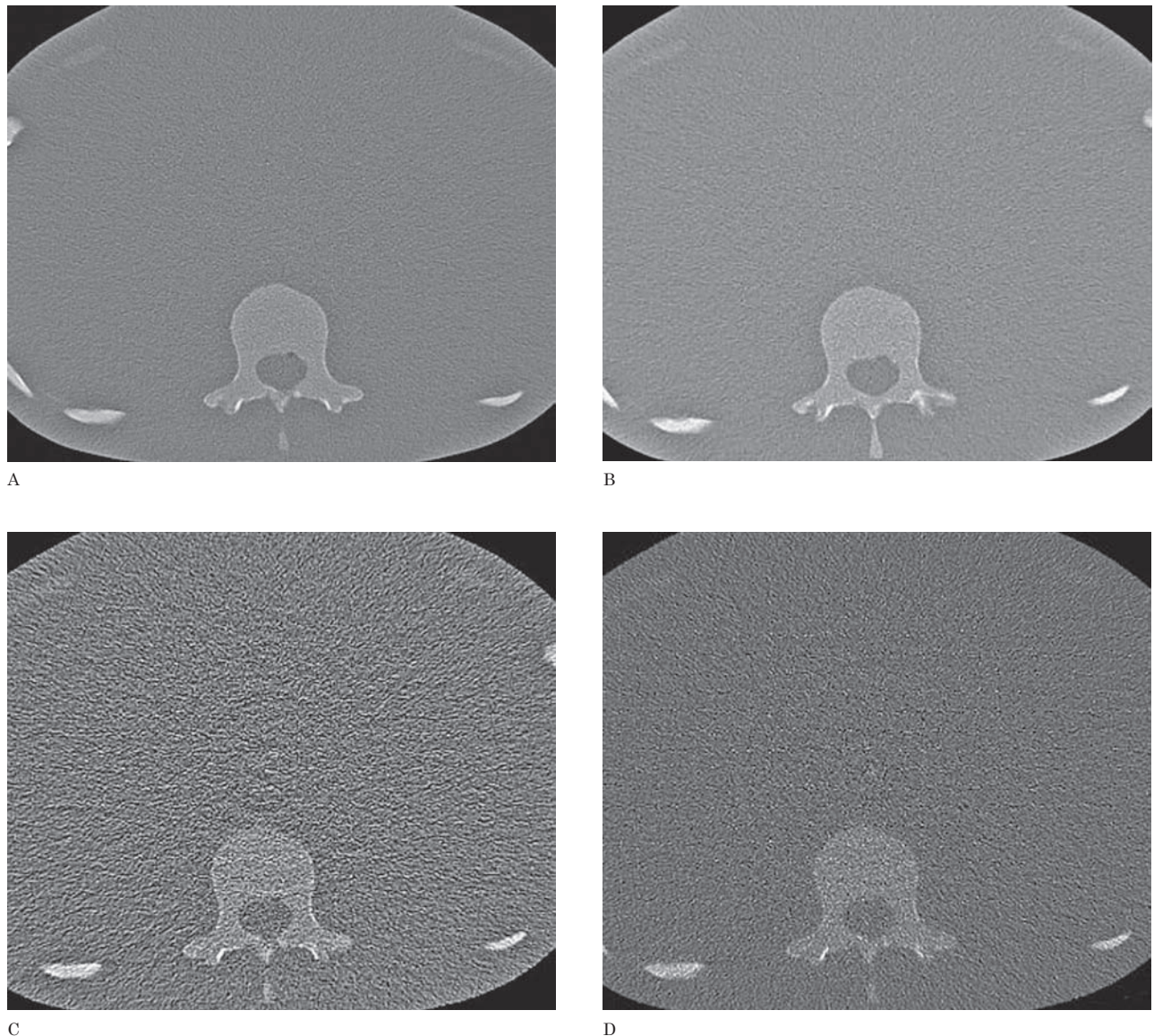


Figure 3 A-D Examples of axial images obtained at the same level of the spine, using different protocols. A) Scan 1 according to the protocol for CT-spine recommended by the manufacturer for investigation of different skeletal spinal pathology in children. B) Scan 3 according to ANV-protocol. C) Scan 5 with the low radiation dose according to the here proposed low dose helical CT protocol. D) Scan 6 with the lowest possible radiation dose in our CT system. Undoubtedly the best image quality is that of image A but the detail in image C allows reliable measurement of the width of the pedicles. The overall image quality in scan 6 (image D) is considered to be unreliable especially in the lumbar region. Note that the cortical delineation of the pedicles in image D, especially on the right side, is indistinct which make the measurements of pedicular width difficult, uncertain and unreliable.

mSv¹². European Commission reference dose levels (EC RDLs) were applied to the routine CT examinations for a random sample of ten patients in the Euromedica medical center in Greece¹³. The mean value of the effective dose was 10.9 mSv for the chest and 7.1 mSv for the abdomen. Both the CTDI vol and the effective dose of the abdomen CT met the EC RDLs criteria¹³. Also the CTDI vol of the scans of the

chest met the EC RDLs dose criteria but the effective dose exceeded the recommended dose. That has been explained by high DLP-value (large irradiation volume length). According to this protocol that had the purpose of applying the EC RDLs criteria, the total effective dose was 18 mSv for the chest- and abdominal scans, a region that corresponds to the region examined in this study with the low dose heli-

Table 3 The results of paired sample T-test on pedicular width measurements performed on scan 1, scan 5 and scan 6 by two observers as well as by one observer on two different occasions. Twenty four paired sample T-tests were performed. Only the statistically significant results are shown in this table. The statistically significant level was set at $P \leq 0.01$

Differences in pedicular width measurements (mm)		Paired differences				Sig. (2-tailed)
		Mean (systematic error)	Std. Deviation (random error)	95% Confidence Interval of the Difference		
				Lower	Upper	
Pair 1	Scan 6, Observer 1, occasion 1 ---- Scan 6, Observer 2	-1,8	1,2	-2,3	-1,3	<0,001
Pair 2	Lower 5 vertebral levels: Scan 6, Observer 1, occasion 1, ---- Scan 6, Observer 2	-2,4	1,6	-3,5	-1,3	0,001
Pair 3	Scan 1, Observer 2 ---- Scan 6, Observer 2	-1,2	1,1	-1,7	-0,8	<0,001
Pair 4	Lower 5 vertebral levels: Scan 1, Observer 1, occasion 1, ---- Scan 6, Observer 1, occasion 1	1,7	1,6	0,5	2,8	0,009
Pair 5	Lower 5 vertebral levels: Scan 1, Observer 1, occasion 2 ---- Scan 6, Observer 1, occasion 2	1,6	1,1	0,9	2,4	0,001

cal CT. That dose is 49 times higher than that of the low dose helical CT protocol of this phantom study.

Even the recent reports using different dose reduction systems record significantly higher radiation doses than that of the here proposed low dose CT protocol. The mean effective dose for CT-lumbar spine after optimization was reported to be 6.9 mSv in one study¹⁴. The mean effective dose for the same region was reported to be 6.69 mSv after angular and z-axis modulation in another study³. These radiation doses are 18 times higher than that of the here proposed low dose helical CT which provides significantly longer scan including most of the thoracic and lumbar spine.

Studies have been done normalizing the effective dose to phantom age and to different body regions (head and neck, and different trunk regions including chest, abdomen, and pelvis). Phantoms corresponding to six age groups have been examined with three different CT scanners¹⁵. In all cases an inverse trend was observed between normalized effective dose and phantom age. The effective dose normalized to age for chest examinations using Siemens DRH-scanner increased from 6 mSv in adult phantom to only 6.3 mSv in phantom corresponding a 15 year old child¹⁵. The difference increased even more in phantoms corresponding to newborn and a one-year-old child resulting in normalized effective doses of 7.8 and 7.1

mSv respectively. In accordance with those results, table 4 in this study shows the effective dose to the adult phantom (according to Monte Carlo calculation) as well as the normalized effective dose to the phantoms corresponding to four different age groups, namely 15 years, ten years, five years, and one year. However, the last three age groups are seldom the object for corrective surgery and consequently rarely subjected to CT examination of the spine. The median age of patients at or just prior to surgery is estimated at 14 to 15 years¹⁶. As the effective dose to the phantom at the age group 15 years was only 1-1.1 times higher than that of the adult phantom (0.34-0.37 mSv versus 0.34 mSv), the results of this study are quite representative for the estimation of the radiation dose in CT-examinations of the spine in adult patients as well as in patients in pubertal age who are often the object for corrective surgery of scoliosis. In lower age groups, e.g. in phantoms corresponding one year old child, the effective dose can be as high as twice the adult dose. However the increase in the effective dose is markedly evident in examinations with originally high radiation dose such as that of scan 1 of this study. In the here proposed low-dose CT protocol the effective dose to a phantom corresponding one-year-old child has been estimated at 0.44-0.68 mSv – a value that still has to be considered a relatively low dose.

A current concept has recently proposed

Table 4 The effective dose (mSv) in the adult phantom and the normalized effective dose (mSv) to the phantoms of four different age groups using the data from the National Radiological Protection Board (NRPB) SP250. The ranges in the age groups other than adult represent the minimum and maximum relative doses. The median age of patients at or just prior to surgery is estimated to be 14-15 years (16). In the here proposed low dose CT-protocol (scan 5), the normalized dose in this age group is almost the same as that of the adults (0.34-0.37 mSv, and 0.34 mSv respectively).

	<i>Adult</i>	<i>15 years</i>	<i>10 years</i>	<i>5 years</i>	<i>1 year</i>
Scan 1	18.6	18.6-20.46	20.46-27.9	22.32-29.76	24.18-37.2
Scan 2	8.6	8.6-9.46	9.46-12.9	10.32-13.76	11.18-17.2
Scan 3	0.49	0.49-0.54	0.54-0.73	0.59-0.78	0.64-0.98
Scan 4	0.45	0.45-0.5	0.5-0.67	0.54-0.72	0.58-0.9
Scan 5	0.34	0.34-0.37	0.37-0.51	0.41-0.54	0.44-0.68
Scan 6	0.30	0.30-0.33	0.33-0.45	0.36-0.48	0.39-0.6

three ways to reduce the overall radiation dose from CT¹⁷. These include a reduction of the number of CT studies prescribed as well as replacing CT examinations with other modalities e.g. MRI. The role of MRI in investigating intraspinal pathologies preoperatively is well known in clinical practice and has been extensively reviewed¹⁸⁻²⁰. In accordance with our recommendation of taking advantage of the dose reduction system available in some scanners, the third proposed way to reduce the population dose from CT was to take advantage of the automatic exposure-control option. However we believe that serious attempts to reduce the radiation dose in CT examinations and efforts to create low dose CT protocols adapted to answer different clinical questions have to be added to the above mentioned methods to reduce the radiation dose from CT examinations.

Applying the here proposed low dose protocol to the CT examination of scoliotic patients who are predominantly thinner than the phantom of this study, will likely enable further reduction of the radiation dose when taking advantage of the dose reduction system of the scanner.

One limitation of this study is that it is a phantom study and the phantom used is an adult phantom. However when normalizing the effective dose to phantom age (table 4), no significant increase in the effective dose could be recorded in the here proposed low dose protocol. The second limitation was inability to assess the degree of vertebral rotation as this was not built into the phantom. Another limitation of this study is that the impact of artifacts from metal implants on the ability to measure the degree of vertebral derotation and the assessment of the hardware status after surgery could not be evaluated. To our knowl-

edge no phantoms with either vertebral torsion or inserted screws are commercially available to test.

Taking the above-mentioned facts in consideration, the medical community has to be concerned about the increasing total radiation load to the population due to the increasing availability of the CT scan and the increasing number of its upcoming new indications and modifications (e.g. CT angiography, high resolution studies, "multiple phase examinations", perfusion studies, etc.). Efforts should be continued to reduce the radiation dose of every single CT by tailoring CT examinations with their radiation doses individually adapted to the purpose of the investigation.

Conclusion

This phantom study has shown that it would be possible to reduce the radiation dose in helical CT examination of the spine in patients planned for corrective surgery of spinal deformities without any significant impact on image quality. To test this possibility we intend to implement the protocol into the preoperative work up of this patient category instead of the ANV-sequential slice method used previously, provided that the radiation doses can be kept at this low level. The results of this study emphasize the importance of tailoring different CT protocols with different radiation doses adapted to answer the clinical question at issue. The dose reduction system of the CT scanner, if available, should be used. When assessing the effective dose the absorbed dose to different organs (e.g. genitals and breasts) should be taken into consideration

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