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Dose reduction in CT examination of children by an attenuation-based on-line modulation of tube current (CARE Dose)

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Abstract In a controlled patient study we investigated the potential of attenuation-based on-line modulation of the tube current to reduce milliampere values (mAs) in CT examinations of children without loss of image quality. mAs can be reduced for non-circular patient cross sections without an increase in noise if tube current is reduced at those angular positions where the patient diameter and, consequently, attenuation are small. We investigated a technical approach with an attenuation-based on-line control for the tube current realised as a work-in-progress implementation. The CT projection data are analysed in real time to determine optimal mAs values for each projection angle. We evaluated mAs reduction for 100 spiral CT examinations with attenuation-based on-line modulation of the tube current in a group of children. Two radiologists evaluated image quality by visual interpretation in consensus. We compared the mAs values read from the CT scanner with preset mAs of a standard protocol. Four different scan regions were

examined in spiral technique (neck, thorax, abdomen, thorax and abdomen). We found the mAs product to be reduced typically by 10–60% depending on patient geometry and anatomical regions. The mean reduction was 22.3% (neck 20%, thorax 23%, abdomen 23%, thorax and abdomen 22%). In general, no deterioration of image quality was observed. There was no correlation between the age and the mean mAs reduction in the different anatomical regions. By classifying the children respectively to their weight, there is a positive trend between increasing weight and mAs reduction. We conclude that mAs in spiral CT examinations of children can be reduced substantially by attenuation-based on-line modulation of the tube current without deterioration of image quality. Attenuation-based on-line modulation of tube current is efficient and practical for reducing dose exposure to children.

Keywords Spiral CT · mAs reduction · Children · Image quality · Exposure to patients

Introduction

Approximately 30% of the radiation exposure from medical imaging modalities is attributable to CT, although CT examinations represent only 4–6% of all X-ray-based imaging studies in Germany [1] and in Britain [2]. Radiation exposure, therefore, remains a predominant issue in

CT. In particular, the potential risk of exposing paediatric patients to ionising radiation has always been of concern to the medical community [3,4], especially because the radiosensitivity of children is higher than that of adults [5]; thus, for paediatric imaging, it is of the utmost importance to reduce radiation exposure to the minimum appropriate for diagnosis. In the United States we

see an increased use of CT in paediatric populations and a concomitant increase in radiation dose and risk of cancer [2, 6]. The reason for the excess radiation dose is the common practice of using the same X-ray exposure factors for CT examinations of children as those used for adults [6]. Paediatric spiral CT parameters are not adjusted on the basis of the examination type or age of the child [7].

This background has motivated us to try to reduce dose in spiral CT examinations of children.

A technical approach to reduce dose was introduced using a software-based modulation of the tube current (SmartScan, General Electric, Milwaukee, Wis.). The local absorption was measured in the 100 central channels of two localiser radiographs (lateral and anteroposterior) and used for sinusoidal modulation of the tube current [8, 9, 10].

In contrast to this, our approach to reduce dose is an attenuation-based on-line modulation of the tube current. In a phantom and a cadaver study [11] and first patient studies [12, 13] we showed that a substantial dose reduction with equal or improved image quality is possible. We observed more homogeneous noise and fewer noise artefacts with attenuation-based on-line modulation of the tube current vs constant tube current [12].

In the past few years, studies have been published about low-dose spiral CT and low-dose high-resolution CT (HRCT) for minimising the dose, also for the thorax region of children [3, 14].

The present study aimed to investigate the possible extent of a reduction of exposure for children in four scan regions. We examined the neck, thorax, abdomen and the thorax and abdomen scan regions.

Materials and methods

Noise in CT images varies proportionately to the square root of the applied dose, i.e. proportionately to the square root of the mAs

product if the tube current is kept constant; however, noise in CT images is dominated by those projections in which attenuation is the highest. For an object with circular cross section, attenuation is constant over all projections, and all measured values contribute equally. For a noncircular cross section, however, attenuation varies strongly, sometimes by more than three orders of magnitude. Noise in the data measured in high-attenuation projections, i.e., mostly in lateral direction, is decisive for the noise level in the CT image. This means that the dose for projections with relatively low attenuation, i.e., mostly in anteroposterior direction, can be reduced substantially without a measurable increase in image noise. The conclusion, and the basic consideration of our approach, is that tube current should be decreased as a function of rotation angle whenever attenuation is low. As a result, we had to develop means for monitoring attenuation on-line and for variation of tube current as a function of projection angle with a delay of 180°. For projections with low attenuation the maximal reduction of the tube current was 90%.

The respective technical solution (attenuation-based on-line modulation of tube current CARE Dose) was implemented as a work-in-progress option on a Somatom Plus 4 (Siemens, Erlangen, Germany).

We performed 100 spiral CT examinations on a group of children without selection. The age ranged from 0 to 18 years. Four different scan regions were examined: spiral CT of the neck ($n=19$); thorax ($n=27$); abdomen ($n=33$); and thorax and abdomen ($n=21$). The scan parameters for the neck was slice thickness 5 mm, feed 5 mm per rotation, reconstruction increment 3 mm and rotation time 0.75 s; for the thorax, abdomen, and thorax and abdomen region parameters were slice thickness 8 mm, feed 10 mm per rotation, reconstruction increment 5 mm and rotation time 0.75 s.

We compared the results of milliamperere (mAs) values read from the CT scanner with preset mAs of a standard protocol adapted to the individual age of the children (Table 1). We correlated the age of the children with the measured mAs reduction. For this purpose we divided the children into three groups: 0–5 years ($n=15$); 6–11 years ($n=44$); and 11–18 years ($n=41$).

We also correlated the weight of the children with the measured mAs reduction. For that we divided the children into four groups: <20, 20–40, 40–60, and >60 kg.

Two experienced radiologists evaluated image quality by visual interpretation in consensus and rated the images as “poor”, “good” and “very good” image quality.

Table 1 Standard protocols (120 kV, 0.75 s rotation time)

Scan region	Age			
	<2 years	2–6 years	6–14 years	14–18 years
Neck				
mAs	90	150	150	150
Slice/feed/increment (mm)	3/5/3	3/5/3	3/5/3	3/5/3
Thorax				
mAs	90	140	170	170
Slice/feed/increment (mm)	3/5/3	5/7.5/3	5/7.5/3	8/10/5
Abdomen				
mAs	90	170	200	280
Slice/feed/increment (mm)	3/5/3	5/7.5/3	5/7.5/3	8/10/5
Thorax/abdomen				
mAs	90	170	200	280
Slice/feed/increment (mm)	3/5/3	5/7.5/3	5/7.5/3	8/10/5

Fig. 1 mAs reduction (mean and range) in four scan regions

Fig. 2 A 5-year-old girl with left kidney nephroblastoma. Image quality was graded as very good. mAs reduction expressed in total mAs was of 27.2%

Fig. 3 mAs reduction (mean) in subject to the age and anatomical region of the children

Results

mAs reduction

The average mAs reduction of all scan regions was 22.3% (maximal 60.0%, minimal 10.7%). The average mAs reduction in the neck scan region was 20%, 23% in the thorax scan region, 23% in the abdomen scan region and 22% in the thorax–abdomen scan region (Fig. 1).

Figure 2 shows a first example from the abdomen scan region.

Correlation between age and dose reduction

The mean mAs reduction in the first group (<6 years) was 18% in the thorax region, 27% in the thorax and abdomen region, and 24% in the abdomen region. In the second group (6–11 years) the mean mAs reduction was 19% in the neck region, 20% in the abdomen region and in the thorax region, and 21% in the combined thorax and abdomen region. In the third group (11–18 years) the mean mAs reduction was 21% in the neck region, 25% in the thorax region, 24% in the thorax and abdomen region, and 27% in the abdomen region. We see no correlation between the age of the children and the mean mAs reduction in the different anatomical regions (Fig. 3).

Table 2 shows the correlation between mAs reduction, age and weight in the different anatomical regions.

Correlation between weight and dose reduction

The mean mAs reduction in the first group (<20 kg) was 20.8%, in the second group (20–40 kg) 20.9%, in the third group (40–60 kg) 24.4% and in the fourth group (>60 kg) 26.8%. We see a positive trend of the mAs re-

Table 2 Correlation between mAs reduction (minimum, mean, maximum, SD, number), age (years) and weight in the different scan regions

Scan region	Age (years)	Weight			
		<20 kg mAs reduction (%) Min., mean, max., SD	20–40 kg mAs reduction (%) Min., mean, max., SD, N	40–60 kg mAs reduction (%) Min., mean, max., SD, N	>60 kg mAs reduction (%) Min., mean, max., SD, N
Neck	0–5	–	–	–	–
	6–10	18, 19.3, 20.2, 0.9, n=5	–, 19.4, –, –, n=1	–	–
	11–18	–	10.7, 17.1, 21.8, 4, n=5	15.7, 22.1, 24.9, 0.03, n=7	–, 25.6, –, –, n=1
Thorax	0–5	16.1, 17.8, 21.6, 2.5, n=4	–	–	–
	6–10	17.8, 18.7, 19.5, 1.2, n=2	16.3, 18.4, 20.2, 1.8, n=4	–, 27.9, –, –, n=1	–
	11–18	–	15.1, 27.3, 57.0, 19.8, n=4	19.3, 24.7, 49.9, 9.8, n=10	23.4, 25.2, 28.0, 2.5, n=3
Thorax/ abdomen	0–5	–, 27.1, –, –, n=1	–	–	–
	6–10	16.3, 19.3, 21.4, 1.9, n=6	15.4, 20.3, 23.5, 3.0, n=5	25.8, 25.9, 26.1, 0.2, n=2	–
	11–18	–	22.7, 23.6, 24.0, 0.7, n=3	–, 20.4, –, –, n=1	23.0, 27.2, 31.3, 5.9, n=2
Abdomen	0–5	16.0, 24.4, 50.8, 9.6, n=10	–	–	–
	6–10	13.5, 19.3, 28.1, 6.0, n=7	14.0, 20.5, 29.9, 5.0, n=8	–	–
	11–18	–	–, 23.0, –, –, n=1	18.0, 28.3, 60.0, 17.9, n=5	22.8, 26.1, 29.4, 4.6, n=2

Fig. 4 mAs reduction (mean and range) in subject to the weight of the children

duction in these four groups regarding the increasing weight of children (Fig. 4).

Assessment of image quality

In all scan regions we evaluated the image quality of the spiral CT with attenuation-based on-line modulation of tube current. With regard to the visual image quality, image noise and contrast resolution the evaluation of image quality resulted in 5% poor images ($n=5$), 11% good images ($n=11$) and 84% very good images ($n=84$; Fig. 5). As we were satisfied with this high image quality, we considered that a second acquisition without CARE Dose was not necessary.

Fig. 5 Proportion of children with image quality in images rated very good, good and poor with attenuation-based on-line tube current modulation

Figure 6 shows an example of the abdomen region of a child with an abscess after pyelonephritis on the left kidney. In this case a mAs reduction of 24.1% was evaluated, and the image quality was very good. Also the MPR showed a very good image quality in which the whole extension of the abscess was better demonstrated.

Discussion

The results of this patient study show that a substantial reduction of the mAs can be achieved in all four scan regions using attenuation-based on-line modulation of the tube current. Our results agree well with previous cadaver examinations [11] and the results of our previous patient studies [12, 13].

For an alternative approach using a sinusoidal tube current modulation based on scout views (SmartScan)

Fig. 6 Image from the abdomen scan region. The mAs reduction was 24.1%. The image quality from the axial scan and also from the MPR was rated as very good

there are no data available for dose reduction in children. Using attenuation-based on-line modulation of tube current, we achieved substantially higher dose reduction in the thorax and the abdomen scan region comparing our own results for children with the results in the same scan region for adults with SmartScan. In the thorax our reduction averaged 22.9%, compared with 3.3% [9], 7% [10] and 15% [8], respectively, with the latter system. In the abdomen the comparable figures were 23% compared with 6% [10], 8.4% [9] and 9%, respectively [8].

In our previous patient study the average mAs reductions for adults were 22% in the thorax scan region and 15% in the abdomen scan region, and 25% in the pelvis scan region [13], respectively, compared with 23% in the thorax and the abdomen scan region for children, and 22% in the combined scan region of thorax and abdomen; thus, we see a comparable mAs reduction for our approach in adults and children.

The large spread of mAs reduction in the present study, especially in the thorax and the abdomen scan region (minimal 13.5%, maximal 60% in the abdomen scan region), results, on one hand, from extremely thin children with a large difference from lateral to anteroposterior cross section and with it a large possibility to reduce mAs with our approach, and on the other hand, from extremely obese children with hardly a difference from lateral to anteroposterior cross section and consequently a small possibility to reduce mAs with our approach.

Monte Carlo dose calculations for scans with attenuation-based on-line modulation of the tube current showed that in fact patient dose is reduced much more strongly than is indicated by the aforementioned mAs reduction [15]. This applies especially for the centre of the

scan object where most of the radiosensitive organs are located [15]; thus, CARE Dose is able to reduce exposure to the most-at-risk organs, e.g. the gonads.

The image quality with attenuation-based on-line modulation of tube current was estimated subjectively in 84% of patients as very good. Also, the image noise shows subjectively no increase. On the contrary, in a previous study [12] we saw that the image quality of a few patients was rated better because the noise contribution was more homogeneous. The quality deficiencies of the single scans evaluated only as good and poor were due to motion artefacts in very young children; yet, these images were also of diagnostic image quality so that no additional studies were necessary. Also, other authors observed only “good” image quality by tachypnoeic infants [14].

With low-dose spiral CT of the thorax region a drastic dose reduction is possible. It was reported that the dose ranged from 3.8 mGy at 25 mAs to 36.5 mGy at 250 mAs measured on a 20-cm round phantom with thermoluminescent dosimeters (TLD) in a paediatric study [3]. Other authors reported on a reduction of the effective dose by spiral CT of the thorax in adults from 9.6 to 0.6 mSv [16]. With the low-dose spiral CT technique you can see an evidently increased image noise noticeable on the mediastinal window setting [3, 16]. While the increasing image noise in the high-contrast resolution (lung window) is of no great relevance, there are mainly effects on the low-contrast resolution (mediastinal window) [3], and the evaluation of the mediastinum is not possible [16].

On the other hand, with attenuation-based on-line modulation of the tube current there is no loss in diagnostics of the mediastinum with, subjectively assessed, no increase in image noise.

Another paediatric study was performed with 80 and 40 mAs for high-resolution low-dose chest CT [14]. Scans performed at 80 mAs showed no loss of pulmona-

ry detail relative to 200- and 140-mAs studies; scans with 40 mAs were noisy but remained acceptable for evaluating parenchymal disease [14].

The positive trend between the weight of the children and the mean mAs reduction that we see agrees well with previous phantom measurements. In these phantom measurements it can be seen that the ratio between lateral attenuation and anterior-posterior attenuation is larger in heavy patients than in thin patients [17]. This correlation is the cause for a potential increase in mAs reduction. In United States there are attempts to adjust the tube current settings based on children's weight with a

profound effect on radiation dose [6, 18]. The major disadvantage of decreasing the mAs, they described, is an increase in noise and the associated potential for degradation of image quality [18]. With our additional approach there is no increase in noise.

We conclude that the use of attenuation-based on-line modulation of the tube current allows a substantial mAs reduction in all four investigated scan regions without a decrease in image quality. This new technique is efficient and practical for minimising dose exposure in spiral CT of children.

References

1. Kaul A, Bauer J, Bernhardt D, Nosske D, Veit R (1997) Effective doses to members of the public from the diagnostic application of the ionizing radiation in Germany. *Eur Radiol* 7:1127–1132
2. Brenner DJ, Elliston CD, Hall EJ, Berdon WE (2001) Estimated risks of radiation-induced fatal cancer from pediatric CT. *AJR* 176:289–296
3. Rogalla P, Stöver B, Scheer I, Juran R, Gaedicke G, Hamm B (1998) Low-dose spiral CT: applicability to paediatric chest imaging. *Pediatr Radiol* 28:565–569
4. Röhrig H, Krupinski E, Hulett R (1997) Reduction of patient exposure in pediatric radiology. *Acad Radiol* 4:547–557
5. Ware D, Huda W, Mergo P, Litwiller A (1999) Radiation effective doses to patients undergoing abdominal CT examinations. *Radiology* 210:645–650
6. Rogers LF (2001) Taking care of children. Check out the parameters used for helical CT. *AJR* 176:287
7. Paterson A, Frush DP, Donnelly LF (2001) Helical CT of the body. Are settings adjusted for pediatric patients? *AJR* 176:297–301
8. Giacomuzzi SM, Erckert B, Freund MC, Schöpf T, Dessl A, Jaschke W (1996) Dosisreduktion in der Computertomographie mit einem neuen Scan-Verfahren. *Akt Radiol* 6:110–113
9. Kopka L, Funke M, Breiter N, Hermann K-P, Vosschenrich R, Grabbe E (1995) Anatomisch adaptierte Variation des Röhrenstroms bei der CT. Untersuchungen zur Strahlendosisreduktion und Bildqualität. *Fortschr Röntgenstr* 163:383–387
10. Lehmann KJ, Wild J, Georgi M (1997) Klinischer Einsatz der software-gesteuerten Röhrenstrommodulation "Smart Scan" in der Spiral-CT. *Akt Radiol* 7:156–158
11. Kalender WA, Wolf H, Suess C, Gies M, Greess H, Bautz WA (1999) Dose reduction in CT by on-line tube current control: principles and validation on phantoms and cadavers. *Eur Radiol* 9:323–328
12. Greess H, Wolf H, Kalender WA, Bautz W (1998) Dose reduction in CT by anatomically adapted tube current modulation: first patient studies. In: Glazer G, Krestin G (eds) *Advances in CT*, vol 4. Springer, Berlin Heidelberg New York, pp 35–40
13. Greess H, Wolf H, Baum U, Lell M, Pirkel M, Kalender W, Bautz W (2000) Dose reduction in computed tomography by attenuation-based on-line modulation of the tube current: evaluation of six anatomical regions. *Eur Radiol* 10:391–394
14. Ambrosino MM, Genieser NB, Roche KJ, Kaul A, Lawrence RM (1994) Feasibility of high-resolution, low-dose chest CT in evaluating the pediatric chest. *Pediatr Radiol* 24:6–10
15. Schmidt B, Schmidt M, Kalender WA (2000) A 3D voxel Monte Carlo program for scanner and patient specific dose calculations in CT. *Eur Radiol* 10 (Suppl 1):304
16. Lenzen H, Roos N, Diederich S, Meier N (1996) Strahlenexposition bei der Niedrigdosiscomputertomographie des Thorax. *Radiologe* 36:483–488
17. Gies M, Kalender WA, Wolf H, Suess C, Madsen MT (1999) Dose reduction in CT by anatomically adapted tube current modulation I. Simulation studies. *Med Phys* 26:2235–2247
18. Donnelly LF, Emery KH, Brody AS, Laor T, Gylys-Morin VM, Anton CG, Thomas SR, Frush DP (2001) Minimizing radiation dose for pediatric body: applications of single-detector helical CT. Strategies at a large children's hospital. *AJR* 176:303–306